Life cycle greenhouse gas analysis of bioenergy generation alternatives using forest and wood residues in remote locations: a case study in British Columbia, Canada.

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Abstract

Utilization of forest and wood residues as bioenergy feedstock in some remote communities could reduce environmental burdens and increase development opportunities. In a thorough bioenergy project planning, in addition to the economic performance, the potential greenhouse gas (GHG) emissions from investment alternatives should be considered. We present an economic assessment and a life cycle analysis of GHG emissions of alternative bioenergy systems, which include four combustion and gasification technologies with different capacities (0.5 MW, 2 MW and 5 MW), in two remote communities in British Columbia, Canada. In the analysis, all stages from harvesting to energy production are included, and the GHG emissions of the baseline system in each community (the current situation with all the products and services it provides) is used as the reference for comparison. Results of this study show that for small scale alternatives (0.5 MW and 2 MW), cogenerating plants using boiler/steam turbines generate the cheapest electricity, while for larger scale alternatives (5 MW), the most economical plant alternative is a gasification cogeneration system. In the community where all energy needs are currently satisfied using fossil fuels, and all biomass residues (forest and sawmill residues) are currently disposed by burning, net reductions of up to 40,909 t of CO₂ equivalent GHG emissions could be achieved with the installation of a 5 MW boiler/steam turbine cogenerating heat and electricity. In the community where the current energy mix is mostly supplied from other renewable sources (i.e. hydro), and where forest residues are disposed by burning and sawmill residues are landfilled, the net GHG emission reductions that can be achieved with a bioenergy system are considerably lower (2,535 t of CO₂ equivalent emissions with a 5 MW cogenerating gasification system) or null, since the carbon capture of current biomass disposal in landfill outweighs the carbon emission reduction of most bioenergy alternatives.

Keywords:

Life cycle assessment (LCA); greenhouse gas (GHG) emissions; forest residues; wood residues; biomass; bioenergy; remote communities.

Highlights:

- Life cycle GHG of combustion and gasification bioenergy systems is analyzed
- Eight bioenergy systems were compared against current situation in two remote communities
- Biomass boiler/steam turbine systems generated largest non-biogenic carbon emission reductions
- Disposal of unused biomass (burning or landfilling) affected selection of best environmental system

1. Introduction

The lack of access to sustainable electricity restricts the development opportunities and increases the negative environmental impacts in many remote areas around the world (Mahama 2012; Javadi et al. 2013; Cook 2011). The International Energy Agency (IEA) estimated that nearly 1.3 billion people in the world do not have access to an electric utility grid (IEA 2013). Most off-grid remote communities are supplied by small power systems that burn low quality fossil fuels, such as diesel, with adverse environmental effects (Moseley 2006; Thompson and Duggirala 2009). The use of fossil fuels has been recognized as the primary cause of the global increase of greenhouse gases (GHG) concentration in the atmosphere, leading to global warming and climate change that affect human and ecosystems' health, as well as global food and water supply (IPCC 2007). To give remote communities access to more sustainable energy, one of the goals of the United Nations Sustainable Energy for All Initiative (SE4ALL) is the development and implementation of small-scaled renewable energy systems in off-grid regions (United Nations 2012). In remote forestry-dependent regions, this goal can be achieved by converting available forest and wood residues into energy, which consequently supports the economic viability of forest operations (i.e. reducing cost and/or generating new revenue streams for forestry companies) and increases the development opportunities for communities (Borsboom et al. 2002). In addition, previous studies have reported that net GHG emissions of generating electricity from biomass-based sources could be less than 10% of that from fossil fuels, thus the substitution of current low-quality fossil fuels with

forest and wood residues in these regions, could significantly reduce the negative environmental impacts (Cherubini et al. 2009).

In British Columbia, Canada, there are over 70 off-grid communities (Ministry of Energy, Mines and Petroleum Resources 2014). The majority of them rely on diesel for electricity generation at significantly higher costs than the grid (e.g. the electricity rate to customers in off-grid communities in British Columbia is around $\$0.39 \text{ kWh}^{-1}$ versus approximately $\$0.08 \text{ kWh}^{-1}$ paid by on-grid customers) (Ministry of Forests, Lands and Natural Resource Operations 2010). Meanwhile, many of these communities have forestry operations that generate large amounts of biomass such as sawmill wood residues (e.g. chips and hog fuel) and forest harvesting residues (e.g. tops, branches, and non-merchantable logs such as those from trees killed by the pests) that can be used as bioenergy feedstock (Natural Resources Canada 2014). It is estimated that around 8.4 million oven dry metric tonnes (odmt) of forest residues from harvesting are produced per year across the province (Dymond et al. 2010), and there could be around 11 million oven dry metric tonnes of mountain pine beetle-killed logs available until the year 2025 in the interior region of the province (Ralevic 2006).

Current interest in electricity generation from available forest and wood residues in three British Columbia's communities motivated a previous study that identified the most profitable supply chain configuration based on different biomass feedstock types, technologies and plant sizes (Cambero et al. 2015). For the two off-grid communities in the study (Anahim Lake and Hanceville), the results showed that generation of electricity-only in small biomass boilers coupled with steam turbines was the most cost-efficient alternative to replace diesel generation. However, since one of the drivers of supporting the development of bioenergy projects in British Columbia is the interest in reducing GHG emissions from energy generation (Ministry of Energy, Mines and Petroleum Resources 2008), it is important to analyze these alternatives based on their net GHG emissions as well, and analyze the potential utilization of the residual heat to increase the value of sawmill products (e.g. production of dried lumber instead of green lumber).

The main objective of this paper is to support the bioenergy planning process in remote off-grid communities by evaluating the total net GHG emissions associated with equivalent systems using different technologies and plant sizes for the generation of electricity and heat from available forest and wood residues. In each community, the potential GHG emissions associated with installing each technology and plant size depend not only on the conversion efficiency of the technology, but also on the amount and type of available biomass, the demand for bioenergy products, the reference energy sources, and the currently used methods of disposal of unused biomass (e.g. burning or landfilling).

Previous studies have reported life cycle GHG emissions of electricity and cogeneration projects in different regions using forest biomass feedstocks (Cambero and Sowlati 2014). For example, Fan et al. (2011) and Steele et al. (2012) evaluated the GHG emissions of electricity generation through the combustion of bio-oil from the pyrolysis of forest-based biomass in the US; and Froese et al. (2010), Mann and Spath (2001) and Zhang et al. (2010) analyzed the GHG emissions of different forest biomass cofiring rates in large sized coal plants with capacities above 100 MW in North America. Other studies compared GHG emissions of different plant sizes or feedstock types for electricity or heat generation. For example, Guest et al. (2011) and Upadhyay et al. (2012) compared different sizes of cogeneration plants fed with forestry by-products in Norway (plant sizes: 0.1 MW, 1 MW and 50 MW) and Canada (plant sizes: 10 to 300 MW), respectively. Petersen-Raymer (2006) made comparisons among fuel wood, densified biomass products, and sawmill wastes as feedstock for cogeneration in Norway. Puettmann and Lippke (2012) contrasted the use of available sawmill wastes and harvesting residues for heat generation against electricity generation in a typical softwood lumber mill in the US Northwest. A recent study compared combustion and gasification technologies and different biomass types (harvesting residues, small-diameter logs and stumps) for large bioenergy systems in Finland using hydro, peat, coal using the average Finish and European power scenarios as reference systems (Jäppinen et al. 2014). Results of these studies cannot be used to draw general conclusions about the GHG emissions from generating electricity and heat using forest biomass. General characteristics of the analyzed bioenergy systems might

provide planning insights only for cases with similar conditions since results and conclusions vary based on the considered feedstock, technology, and plant size alternatives, as well as the reference energy source to which the system is compared with (Cherubini et al. 2009). However, none of these studies considered the planning of bioenergy systems in remote forest-rich communities, where unused biomass is disposed as waste and off-grid energy sources are used to satisfy energy needs, in order to compare different combustion and gasification technology alternatives for the cogeneration of electricity and heat in small scaled bioenergy systems (under 5 MW) using available forest and wood residues.

2. Materials and methods

2.1. Goal and scope definition

This study aims to fill a gap in the academic literature on the analysis of the net life cycle GHG emissions associated with different small scaled bioenergy technologies (0.5 MW, 2 MW and 5 MW) for the production of heat and electricity from forest and wood residues in remote forest-rich communities. Since the conversion of forest and wood residues produces multiple products (e.g. heat and electricity) and requires inputs from other product's life cycle (e.g. upstream production of logs and lumber), allocation issues arise (Allacker et al. 2014). Based on the recommendations of ISO 14044:2006-07 (ISO 2006), in order to avoid the allocation or partitioning of the emissions associated with downstream generation of multiple products and the upstream biomass production processes (e.g. forest harvesting and sawmilling processes), we used a system expansion approach to include all the associated additional functions (e.g. production of logs and lumber). Thus, the comparison of net GHG emissions is based on the analysis of equivalent systems (baseline system and bioenergy systems) that provide the same products and services to the community (i.e. the equivalent amount of logs, lumber, electricity and heat). The analysis is based on the case of two remote communities in British Columbia, Canada (Anahim Lake and Hanceville).

An attributional life cycle assessment (LCA) approach was used to estimate the net GHG emissions of each bioenergy system alternative compared with a baseline system (current situation). The attributional

approach is useful to estimate the environmental impacts that can be directly credited to each bioenergy system alternative under analysis. However, it assumes that the implementation of such system has no effect on the surrounding market for products (e.g. the potential use of merchantable logs for the production of bioenergy), and thus, the results of this analysis are not intended to advise energy policy-making for which a more suitable approach would be a consequential LCA (Rehl et al. 2012; Pawelzik et al. 2013).

2.1.1. Baseline system

Anahim Lake and Hanceville are two remote forestry-dependent communities located in the Williams Lake timber supply area (TSA). This is one of the largest TSAs in British Columbia, Canada and has been largely affected by the mountain pine beetle (MPB) infestation. Harvesting in the region has been focused on salvage of beetle-killed pine, and the predominant method of harvesting is clearcutting (Ministry of Forests, Lands and Natural Resource Operations 2010). With this harvesting method, merchantable logs are produced as primary products and harvesting residues such as tree tops and branches are aggregated in piles at the roadside and open burned. Because of tree mortality due to the MPB, some whole logs are non-merchantable and are disposed by open burning as well (Friesen 2012).

Currently, there is one sawmill installed in Anahim Lake and another sawmill installed in Hanceville (Marinescu 2012; Marinescu 2013). When in operation, both sawmills produce a surplus of chips and hog fuel (a mix of sawdust, bark and other wood residues) that is disposed as waste due to the high costs of transporting the bulky material to the closest pulp and pellet mills in the region. In Anahim Lake, the sawmill is located in a non-populated area where chips and hog fuel are burnt in an authorized wood residue burner (Ministry of Environment 2015). In Hanceville, sawmill residues must be transported to a landfill located 100 km away from the sawmill to avoid local air pollution.

Anahim Lake has a population of 360 habitants and relies on a diesel generation station that supplies electricity to households (BC Hydro 2013) and on-site diesel generators that supply the entire electricity demand of the local sawmill (Marinescu 2013). Hanceville has a population of 100 habitants (BC Curios Ltd. 2013). This community has limited access to the province's hydropower grid (low-capacity transmission line), and while the electricity needs of the community are satisfied by the province's grid, the local sawmill generates 50% of its power requirements using on-site diesel generators (Marinescu 2012). In both communities, a 5 MW electrical capacity (generating 39,420 MWh per year) would cover the needs of the sawmill and the community (Marinescu 2012; Marinescu 2013). Both sawmills produce green lumber for export, and are evaluating the installation of kilns for lumber drying. The amounts of heat that would be required by each sawmill (70,956 GJ in Anahim Lake and 41,209 GJ of heat in Hanceville) were estimated based on their lumber capacity, and since these two communities have no access to the province's natural gas pipeline, heating oil is the currently used source for industrial heat generation. The baseline systems for both communities and their annual input, output and reference flows are depicted in Fig. 1.

INSERT FIG.1 HERE

Since the goal of this analysis is to compare the net GHG emissions of the baseline system against those of the proposed bioenergy system alternatives, this study does not account for harvesting all the logs around each community, it only accounts the portion of harvesting operations that would generate enough logs to supply the local sawmill in each community, and would produce enough harvesting residues and non-merchantable MPB logs to cover the feedstock demands of the alternative systems presented in section 2.1.2.1 and 2.1.2.2. The annual amount of logs supplied to each sawmill, and the annual amount of available hog fuel (including bark and sawdust) were estimated based on the annual amount of chips available at each sawmill (16,150 odmt in Anahim Lake and 6,000 odmt in Hanceville as reported in (Marinescu 2012; Marinescu 2013)) using sawmill product yields of 56.9% lumber, 26.7% chips and 16.4% hog fuel (Milota et al. 2005). The annual amount of harvested logs includes the logs supplied to

local sawmills and the amount of logs sold to external markets that was estimated considering the amount of non-merchantable MPB logs required by the 5 MW Gas alternative (which is the alternative that demands a larger amount of non-merchantable MPB logs) at each community and assuming harvesting production yields of 57.6% logs, 24.9% residues and 17.6% of non-merchantable MPB logs (based on values reported in Friesen 2012). Note that the amount of logs and residues in Fig. 1 does not represent the total produced amount around each community as more harvesting operations happen at increasingly larger transportation distances around the two communities.

2.1.2. Bioenergy systems

In the bioenergy system alternatives, the system boundaries of the baseline system were extended to include all life cycle stages of procuring forest residues and non-merchantable MPB logs to the bioenergy plants. All reference flows of bioenergy systems are equivalent to those of the baseline system (i.e. same amount of logs to external markets, lumber, electricity and heat). However, input flows (e.g. energy from biomass and from current sources, residues to energy) and waste (e.g. biomass burned or landfilled) are different for each bioenergy system based on the amount of feedstock required for each plant, and the energy conversion efficiency of each technology. All unit processes included within the system boundaries of all bioenergy systems in each location are depicted in Fig. 2, boxes with light shading correspond to added unit processes, and boxes with darker shading correspond to unit processes whose flows might be affected by the introduction of bioenergy plants. Energy and materials used for facility construction and decommission, as well as for the manufacturing of each piece of equipment are not within the scope of this study as recommended in (CORRIM 2010), because while they might be significant for environmental impacts such as mineral extraction and ecotoxicity, they typically do not account for more than 0 to 5% of the total GHG emissions (with global warming potential impact) (refer for example to Ghafghazi et al. 2011) which is the focus of this study.

INSERT FIG. 2 HERE

Fig. 2 illustrates the internal and waste flow amounts specific for a) the 2 MW ST (boiler + steam turbine system for cogeneration of electricity and heat) bioenergy system in Anahim Lake and b) the 0.5 MW ST bioenergy system in Hanceville. All baseline and bioenergy systems and their relevant input and waste flows are introduced in section 2.1.2.1.

2.1.2.1. Technology and plant size alternatives

The installation of a total of 8 bioenergy conversion technologies are considered for each location (2 plant sizes * 4 technologies) (Fig. 3). The plant sizes considered for the bioenergy systems are: small plants (0.5 or 2 MW) to replace diesel generation at the local sawmills (note that a 0.5 MW plant and a 2 MW bioenergy plant would suffice to replace diesel generation at the sawmill in Hanceville and Anahim Lake based on the sawmill size, respectively), and larger plants (5 MW) to supply electricity to local sawmills and the communities. Technologies analyzed are: biomass boilers coupled with steam turbine systems for the generation of electricity-only (ST*), biomass boilers coupled with steam turbine systems for cogeneration of electricity and heat (ST), oil heating boilers coupled with organic rankine cycles for cogeneration of electricity and heat (ORC), and biomass gasifiers with internal combustion engines for cogeneration of electricity and heat (Gas).

INSERT FIG. 3 HERE

2.1.2.2. Biomass mix of each plant alternative

For each bioenergy system alternative, the amount of biomass that is used for bioenergy depends on the technology conversion efficiency (electrical and thermal), the plant size, and the amount of available biomass feedstock as well as its moisture and energy content. Conversion efficiencies of each technology and plant size are listed in Table 1. Note that the electrical and thermal efficiencies of the organic rankine

cycle systems (ORC) and the gasification systems (Gas) are assumed to be fixed regardless of the amount of heat that is recovered from the system. However, when steam turbine systems are designed for electricity-only (ST*), their electrical efficiency is maximized by extracting the largest practical amount of energy from the steam, and when these systems are designed for cogeneration of electricity and heat (ST), the steam is exhausted from the turbine with enough energy to be used for industrial thermal processes, thus reducing their electrical efficiency (EPA 2007). In this study, the heat portion that is not used by the sawmill is considered as waste.

Table 1 Specifications of technologies (from (Cambero et al. 2015))

Technology alternative	Plant size (electrical capacity)	Efficiency	
		Electrical (%)	Thermal (%)
ST*	0.5 MW	18.7%	0.0%
	2 MW	18.7%	0.0%
	5 MW	18.7%	0.0%
ST	0.5 MW	14.5%	21.7%
	2 MW	16.2%	20.2%
	5 MW	18.3%	12.9%
ORC	0.5 MW	11.1%	48.5%
	2 MW	12.0%	52.1%
	5 MW	11.8%	55.5%
Gas	0.5 MW	12.6%	10.3%
	2 MW	19.2%	9.0%
	5 MW	21.2%	8.7%

ST*: boiler + steam turbine, electricity only; ST: boiler + steam turbine, cogeneration; ORC: oil heater + organic rankine cycle, cogeneration; Gas: gasifier + internal combustion engine, cogeneration. Efficiency values refer to the ratio (%) of the energy output (heat or electricity) divided by the energy contained in the input biomass fuel (higher heating value).

The moisture content of the biomass feedstock affects the recoverable energy from the biomass since the process of evaporating water uses some of the heat released by the combustion of the feedstock (Boundy et al. 2011). In addition, every 10% increase in biomass moisture content reduces the burning efficiency of the combustion chamber by around 2% (EPA 2007), thus affecting the electrical and thermal efficiency of the entire system correspondingly. The as-received characteristics of the biomass types considered in this study are presented in Table 2.

Table 2 Biomass characteristics

Biomass type	Moisture content (% wet basis)	Higher heating value (GJ odmt⁻¹)	Bulk density (kg m⁻³)	Ash content (%)
Sawmill chips	33.2 ^a	17.7 ^a	206.7 ^a	0.5 ^a
Sawmill hog fuel	44.9 ^a	17.8 ^a	142.9 ^a	4.8 ^a
Forest harvesting residues	29.8 ^b	19.0 ^b	174.1 ^b	1.0 ^c
Chipped non merchantable MPB logs	29.8 ^b	19.0 ^b	174.1 ^b	1.9 ^d

^a derived from (Kehbila 2010)

^b average from case 3 in (Jafari Naimi et al. 2009)

^c (Badger 2002)

^d sample W6 in (Lehtikangas 2001)

For combustion technologies, all four types of biomass considered in this study can be used. However, for gasification technologies a consistent supply of biomass with a low ash content and a low moisture content (less than 15%) has to be used to achieve an efficient process (Bridgwater et al. 2002). Therefore, only wood chips and chipped non-merchantable MPB logs are considered as potential feedstock for gasification plants, and a portion of the heat generated has to be used to dry the feedstock and achieve the specified moisture content. For combustion technologies, it is assumed that the comminuted biomass is entered into the system as received.

Previous studies that considered different types of biomass (e.g. Petersen-Raymer 2006; Puettmann and Lippke 2012; Jäppinen et al. 2014) assumed that the entire biomass demand could be met by one specific type (e.g. harvesting residues versus small-diameter trees in Jäppinen et al. 2014). However, in a realistic case, the biomass available at a lower cost would be used first, and then, if necessary, more expensive sources would be used to complement the feedstock demand. In this study, we estimated the composition of the feedstock mix for each bioenergy system alternative by selecting the mix of biomass with the lowest cost per net GJ of feedstock procured to the plant.

Under the assumption that the bioenergy plant is an independent economical entity separated from the sawmill, an economic transaction has to be considered for the purchase of sawmill chips and hog fuel. In other communities in the same TSA, the purchase price of sawmill chips and hog fuel when sold to a bioenergy plant are \$25 odmt⁻¹ and \$10 odmt⁻¹, respectively (Cambero et al. 2015). The same values are assumed in this study, and since it is assumed that the bioenergy plants would be installed beside the current sawmills, there are no transportation costs for supplying these sawmill residues to the bioenergy plant. For forest harvesting residues and non-merchantable logs, the stumpage price is \$0.25 m⁻³ of hogged tree material (Ministry of Forest, Lands and Natural Resource Operations (2014)). Based on this stumpage price and the bulk density of the biomass (Table 2), an equivalent price of \$1.44 odmt⁻¹ is assumed for forest residues and chipped non-merchantable logs. In addition to this price, collection and comminuting cost of forest residues and non-merchantable MPB logs is \$20.10 odmt⁻¹ of chipped material (Friesen 2012), and the transportation costs depend on transportation distances from forest blocks to the plants. Average transportation distances required to bring enough material to the bioenergy plants vary among plant alternatives based on their specific feedstock demand (e.g. for gasification technologies only low-ash material is supplied), and varies between locations based on the forest density and the region's harvesting plans for the next 20 years. For example, to get an annual supply of forest residues and non-merchantable MPB logs of 20,000 odmt, average transportation distances of 9.9 km for Anahim Lake and 18.3 km for Hanceville are required during the following 20 years. If only non-merchantable

MPB logs are collected from the residues piles in the forest roadside, these distances increase to 14.3 km and 31.3 km, respectively. The availability of each biomass type in each forest block, the transportation distance and the cost per odmt of biomass transported between each forest block and each plant location were obtained from FPIInterface, a forest operations model developed by FPIInnovations (FPIInnovations 2013).

Based on all the technological considerations in Table 1, the biomass characteristics presented in Table 2, and the biomass procurement costs described above, we estimated the biomass mix that minimizes the overall feedstock costs including feedstock price, collection, comminution, and transportation costs. To estimate the net energy content of the used biomass, the constant 2.45 GJ per tonne of water at 25 °C was used as the latent heat of vaporization of water (Boundy et al. 2011). In addition, technology efficiencies in Table 1 were modified to consider the moisture content of each biomass type entering to the combustion or gasification chamber. The resulting composition and the average procurement cost of the biomass mix of each alternative are presented in Fig.4 for a) Anahim Lake and b) Hanceville.

INSERT FIG. 4 HERE

Sawmill hog fuel is the most economic feedstock ($\$0.60 \text{ GJ}^{-1}$) and is entirely consumed by all combustion alternatives (ST*, ST and ORC), as shown in Fig. 4. Sawmill chips at a cost of $\$1.48 \text{ GJ}^{-1}$, are the second selected feedstock for combustion alternatives, and the base feedstock for the gasification alternatives (Gas). Despite the higher energy content and lower moisture content of forest residues and non-merchantable MPB logs, their collection, chipping and transportation costs make their procurement expensive, and thus they are only included to complement the biomass demand of the plants in both locations. The average feedstock procurement cost for the 0.5 MW plant alternatives in Hanceville is up to 21.1% lower than that for the 2 MW alternatives in Anahim Lake since a largest share of the biomass mix is composed of hog fuel. For 5 MW plant alternatives, the average procurement cost for alternatives in Hanceville are 37.6% to 49.9% higher than that for alternatives in Anahim Lake since Hanceville has a

lower availability of sawmill chips and hog fuel and larger transportation distances for biomass procurement than Anahim Lake.

The unitary feedstock procurement cost (per GJ) for the steam turbine system that produces electricity-only (ST*) is the lowest among all technology alternatives, and the procurement cost of gasification alternatives (Gas) is the highest. It is also noticeable that the unitary biomass procurement cost of small technologies are considerably lower than that of the 5 MW alternatives as they use increasingly more expensive biomass sources. Note that these feedstock procurement costs, however, cannot be used alone to find the most economical bioenergy alternative as larger systems and the cogeneration of heat result in savings per kWh of electricity produced. Fig. 5 shows the estimated costs per kWh of electricity of each alternative based on feedstock procurement cost, as well as other operational and capital costs reported in (Cambero et al. 2015).

INSERT FIG. 5 HERE

To estimate the values presented in Fig. 5, the revenue from the sale of process heat to the sawmill was deducted from the total cost. Note that the unitary cost changes as a function of the plant size, and on the amount of heat recovered and sold. In both locations, in the absence of a heat user (black bars in Fig. 5), the most economical alternative is the 2 MW steam turbine installed for electricity-only, and in the existence of a large heat user (light grey bars in Fig. 5), a 5 MW organic rankine cycle system would generate the best economic performance. However, based on the heat amount that could be used by the sawmills for lumber drying (the only heat user around the plant locations) (dark grey bars in Fig. 5), the alternative with the lowest electricity cost for both sizes is the steam turbine system with cogeneration of heat (ST) in both communities. At small scale (0.5 MW and 2 MW), the lowest cost is \$0.01 kWh⁻¹ in Anahim Lake and \$0.12 kWh⁻¹ in Hanceville, and at larger scales (5 MW), this number increases to \$0.16 kWh⁻¹ and \$0.25 kWh⁻¹, respectively. Based on these results, bioenergy plants could generate electricity at a cost lower than the current average cost of diesel generation in those locations (\$0.39 kWh⁻¹). Note

that the current electricity rate for diesel generation in the region includes a fuel procurement component (30% of the cost based on (Ministry of Forests, Lands and Natural Resource Operations 2010)) plus other operational and capital components such as the levelized capital costs, thus, further analysis should be conducted for a more accurate assessment of the economic impacts of replacing diesel generation plants with bioenergy plants based on the service time of the existing diesel plants.

2.1.2.3. Input and output flows of each bioenergy system

Based on the biomass mix requirements and the output of each bioenergy plant alternative, the relevant input and output flows of each bioenergy system were estimated. Table 3 shows the values for system alternatives in Anahim Lake and Table 4 shows the values for system alternatives in Hanceville.

Table 3 Reference, input and waste flows of baseline and bioenergy system alternatives in Anahim Lake

Description	Baseline	2 MW				5 MW			
		ST*	ST	ORC	Gas	ST*	ST	ORC	Gas
Reference flows									
Logs to external markets (odmt)	10,493	10,493	10,493	10,493	10,493	10,493	10,493	10,493	10,493
Lumber (odmt)	34,417	34,417	34,417	34,417	34,417	34,417	34,417	34,417	34,417
Electricity (MWh)	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420
Heat (GJ)	70,956	70,956	70,956	70,956	70,956	70,956	70,956	70,956	70,956
Input flows									
Logs to local sawmill (odmt)	60,487	60,487	60,487	60,487	60,487	60,487	60,487	60,487	60,487
Electricity from diesel generator (MWh)	39,420	23,652	23,652	23,652	23,652	-	-	-	-
Electricity from British Columbia's	-	-	-	-	-	-	-	-	-

grid (MWh)									
Heat from fuel oil combustion (GJ)	70,956	70,956	175	-	44,433	70,956	-	-	12,882
Sawmill chips to bioenergy (odmt)	-	9,676	12,643	16,150	16,150	16,150	16,150	16,150	16,150
Sawmill hog fuel to bioenergy (odmt)	-	9,920	9,920	9,920	-	9,920	9,920	9,920	-
Residues to bioenergy (odmt)	-	-	-	2,295	-	12,044	12,609	27,178	-
Non-merchantable MPB logs to bioenergy (odmt)	-	-	-	1,621	1,207	8,509	8,909	19,202	21,664
Waste flows									
Sawmill chips to beehive (odmt)	16,150	6,474	3,507	-	-	-	-	-	-
Sawmill hog fuel to beehive (odmt)	9,920	-	-	-	9,920	-	-	-	9,920
Sawmill chips to landfill (odmt)	-	-	-	-	-	-	-	-	-
Sawmill hog fuel to landfill (odmt)	-	-	-	-	-	-	-	-	-
Residues to roadside burning (odmt)	30,663	30,663	30,663	28,369	30,663	18,620	18,054	3,485	30,663
Non-merchantable MPB logs to roadside burning (odmt)	21,664	21,664	21,664	20,043	20,457	13,155	12,755	2,462	-

Table 4 Reference, input and waste flows of baseline and bioenergy system alternatives in Hanceville

Description	Baseline	0.5 MW				5 MW			
		ST*	ST	ORC	Gas	ST*	ST	ORC	Gas
Reference flows									

Logs to external markets (odmt)	79,480	79,480	79,480	79,480	79,480	79,480	79,480	79,480	79,480
Lumber (odmt)	12,787	12,787	12,787	12,787	12,787	12,787	12,787	12,787	12,787
Electricity (MWh)	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420
Heat (GJ)	41,209	41,209	41,209	41,209	41,209	41,209	41,209	41,209	41,209
Input flows									
Logs to local sawmill (odmt)	22,472	22,472	22,472	22,472	22,472	22,472	22,472	22,472	22,472
Electricity from diesel generator (MWh)	3,942	-	-	-	-	-	-	-	-
Electricity from British Columbia's grid (MWh)	35,478	35,478	35,478	35,478	35,478	-	-	-	-
Heat from fuel oil combustion (GJ)	41,209	41,209	19,971	-	29,641	41,209	-	-	-
Sawmill chips to bioenergy (odmt)	-	1,258	2,651	4,550	6,000	6,000	6,000	6,000	6,000
Sawmill hog fuel to bioenergy (odmt)	-	3,685	3,685	3,685	-	3,685	3,685	3,685	-
Residues to bioenergy (odmt)	-	-	-	-	-	20,741	21,307	35,875	-
Non-merchantable MPB logs to bioenergy (odmt)	-	-	-	-	681	14,654	15,053	25,346	31,117
Waste flows									
Sawmill chips to beehive (odmt)	-	-	-	-	-	-	-	-	-
Sawmill hog fuel to beehive (odmt)	-	-	-	-	-	-	-	-	-
Sawmill chips to landfill (odmt)	6,000	-	-	-	-	-	-	-	-
Sawmill hog fuel to	3,685	-	-	-	3,685	-	-	-	3,685

landfill (odmt)										
Residues to roadside burning (odmt)	44,043	44,043	44,043	44,043	44,043	23,302	22,736	8,168	44,043	
Non-merchantable MPB logs to roadside burning (odmt)	31,117	31,117	31,117	31,117	30,436	16,463	16,063	5,771	-	

2.2. Life cycle inventory

In a “cradle-to-grave” life cycle inventory of GHG emissions, all the GHG emissions during the production, use and disposal of products needs to be accounted for. In biomass systems, non-biogenic carbon emissions are generated in activities along the supply chain due to the use of fossil fuels and other materials (e.g. lubricants) required for the operation of equipment and machinery. In addition, biogenic carbon emissions are generated during biomass burning which corresponds to the total amount of carbon that was sequestered during tree growth. Typically, these biogenic emissions are considered to be carbon-neutral (Cherubini et al. 2009). However, when biomass is landfilled, a large amount of the biogenic carbon embedded in the biomass is not released into the atmosphere and remains stored in the landfill (Pawelzik et al. 2013). In this study, since both burning and landfilling activities are included within the compared systems, the total amount of GHG emissions (from biogenic and non-biogenic sources) is accounted for all unit processes to assure equitable comparisons between the baseline and bioenergy systems are performed.

Different data sources were used to compile the life cycle inventories of the baseline system presented in Fig. 1 and the bioenergy systems depicted in Fig. 2, and to estimate the GHG emissions associated with supplementary unit processes such as fossil fuel and lubricants production and use. Whenever available, site specific information was used, otherwise data from relevant published reports were obtained. Specific gases with greenhouse gas effects for which data are compiled in this study include CO₂, CO, CH₄, N₂O, and hydro fluorocarbons (HFC-134a) and were categorized as either biogenic or non-biogenic, where the

latter category might contain trace amounts of biogenic emissions since GHGenius data do not report segregated fossil and biogenic emissions. Information and assumptions used to compile the inventory are described below.

Landfilling: GHG emissions of transporting and disposing wood in a municipal landfill were obtained from the NETL Life Cycle Inventory library (NETL 2013) and modified to consider the disposal of softwood only, with a transportation distance of 100 km, and biomass moisture contents as reported in Table 2. It is assumed that there is no gas recovery for energy in the considered landfill. Data from (NETL 2013), assumes that 98.2% of the carbon in landfilled biomass remains stored within the landfill and only 1.8% is released to the atmosphere: for each t of carbon in landfilled biomass (1.639 t of CO₂ equivalent emissions), only 37.6 kg of CO₂ equivalent emissions are released as CH₄ and 14.8 kg of CO₂ equivalent emissions are released as CO₂, leading to a net GHG capture of 1.587 t of CO₂ equivalent emissions.

Burning at roadside: GHG emissions of burning forest residues (crown wood) and non-merchantable MPB logs (stem wood) were obtained from (NETL 2013), considering the lubricant and diesel consumption for transporting a crew to burn slash in the woods based on (NREL 2012a).

Existing energy system: GHG emissions from the existing energy system depend on the current energy generation profile in each potential location (section 2.1). In this study, it is assumed that the composition of the electricity grid in British Columbia, which covers part of the electricity needs of Hanceville, is based on the province's generation mix which is 94.3% hydro generated electricity, 5.7% from natural gas and 0.1% from other sources (e.g. fuel oil) (production mix in BC) (St. Lawrence 2008). The effect of this assumption is further explored in section 3.3. GHG emissions of current electricity and heat generation were obtained from GHGenius considering electricity generation efficiencies of 34% from diesel (and fuel oil), 45% from natural gas and 100% from hydroelectric plants; and heat generation efficiencies of

95% in heating oil boilers. The grid distribution efficiency in British Columbia used in GHGenius estimations is 92%.

Harvesting: GHG emissions of harvesting come from the combustion of diesel and use of lubricants to operate machinery and transportation equipment. In Western Canada, the average consumption of diesel for harvesting activities is 3.5 l m^{-3} of harvested logs, including pre-harvesting, logging, camping, road construction and silvicultural operations (Sambo 2002). Lubricant required to reduce friction between moving parts of the equipment is assumed to be approximately 0.02% of the amount of diesel consumed (derived from (Johnson et al. 2012)).

Collection and chipping: Tree tops, branches and mountain pine beetle-killed logs are collected from roadside piles, loaded into a grinding unit and conveyed into a truck for transportation. For the operation of hydraulic loaders and grinders, diesel consumption (3.83 l odmt^{-3}) and lubricant use (0.06 l odmt^{-3}) values were obtained from (Johnson et al. 2012).

Biomass transportation: Transportation of chipped harvesting residues from forest to sawmill/bioenergy plant locations is done using three-axle semi-trailers. These trucks have a diesel consumption of 0.68 l km^{-1} (average fuel consumption of loaded and unloaded truck) (Friesen 2012). Lubricant use of 0.01 l km^{-1} was derived from (Johnson et al. 2012). Due to the low bulk density of chipped harvesting residues (around $0.174 \text{ odmt m}^{-3}$), and considering a moisture content of 29.8% (Naimi et al. 2009), the amount of residues that can be loaded in each truck is restricted by the truck's volume capacity of 110 m^3 .

Log transportation: After harvesting, merchantable logs are assumed to be transported to the closest sawmill using three-axle semi-trailers with a load capacity of 28 tonnes (with the same fuel and lubricant requirements of trucks used for biomass transportation). To estimate the amount of GHG that is emitted per odmt km (1 oven dry metric tonne of load transported 1 kilometer), the feedstock densities reported in Table 2 were used. The average hauling distances required to fulfill the log demand (based on the

installed capacity) of sawmills in Anahim Lake and Hanceville are 11.9 km and 14.1 km, respectively over the following 20 years. These distances are based on timber availability estimations (assuming that there is no competition for fibre) from FPIInnovations and are considerably shorter than log procurement distances reported in previous studies (e.g. Sambo 2002), reflecting the significant concentration of timber around these communities. Since bioenergy plants would be installed next to sawmills, no transportation for sawmill by-products to the plant need to be considered.

Sawmill operation: All material and energy inputs (logs, water, lubricants, and fossil fuels such as propane, gasoline and diesel), product yields, and emissions related to the sawmill operation were obtained from a previous study (Milota et al. 2005). In both sawmills, the entire electricity requirement would be met by the proposed bioenergy plants, except for the case when a small 0.5 MW bioenergy plant is installed in Hanceville where 50% of the electricity demand is supplied by the provincial electricity grid.

Combustion, gasification and biomass burning in beehive burner: Wood combustion/burning emissions were taken from the EPA A42 report, and modified based on Pa et al. (2011) to estimate the gasification emissions.

Production and use of fossil fuels and lubricants: GHG emissions related to heavy duty diesel and gasoline engines and trucks were retrieved from GHGenius (S&T Consultants Inc 2014) and included upstream operations and combustion of diesel. Emissions related to the use of lubricants were retrieved from Ecoinvent (Ecoinvent Centre 2015) assuming a lubricant density of 0.882 kg l^{-1} . Lubricants are not consumed during combustion, and are assumed to be recycled after use (Johnson et al. 2012).

2.3. Life cycle impact assessment

All material inputs, energy consumption and emission data for the unit processes depicted in Fig. 1 and Fig. 2, and for the unit processes related with the production and use of fossil fuels and lubricants were

input into the SimaPro v7.0 software (Product Ecology Consultants 2012). This software was used to compute the amounts of CO₂ equivalent GHG emissions of each unit process based on the IMPACT 2002+ v2.1 methodology (Jolliet et al. 2003), the results were then modified to account for biogenic emissions as well. All GHG emissions of each unit process are shown in Table 5, and for those unit process with biogenic emissions, the percentage of emissions that is biogenic is shown within brackets).

Table 5 Results of life cycle inventory: GHG emissions generated per unit process

Unit Process	GHG emissions (kg CO ₂ -eq)	Output
<i>Baseline system</i>		
Landfilling	88.9 (58.90% biogenic)	Per odmt of sawmill chips disposed
	92.7 (56.4% biogenic)	Per odmt of sawmill hog fuel disposed
Burning at roadside	1,630.0 (99.9% biogenic)	Per odmt of forest residues burned
	1,660.0 (99.9% biogenic)	Per odmt of mountain pine beetle logs burned
Burning in beehive burner	1532.7 (100% biogenic)	Per odmt of biomass disposed
Electricity supply from diesel generation	879.0	Per MWh of electricity generated from diesel on-site (cradle-to-grave)
Electricity supply from British Columbia grid	51.7	Per MWh of electricity distributed to end user (cradle-to-grave)
Heat from fuel oil combustion	86.9	Per GJ of heat generated from fuel oil (cradle-to-grave).
<i>Bioenergy systems</i>		
Harvesting	34.6	Per odmt of harvested logs
Log transportation	0.2	Per odmt of logs transported over 1 km in trucks
Sawmill operation	6.3	Per odmt of sawmill by-products produced
Collection and chipping	12.1	Per odmt of chipped harvesting residues and/or chipped mountain pine beetle-killed

		logs
Biomass transportation	0.3	Per odmt of chipped harvesting residues and/or chipped mountain pine beetle-killed logs transported for 1 km using trucks
Biomass combustion	86.0 (100.0% biogenic)	Per GJ of input biomass
Biomass gasification	85.6 (100% biogenic)	Per GJ of input biomass
<hr/> <i>Production and use of fossil fuels and lubricants</i>		
Diesel combustion	2.46	Per liter of diesel combusted in heavy duty engines
Diesel supply	0.68	Per liter of diesel supplied (well to tank)
Gasoline combustion	1.95	Per liter of gasoline combusted in heavy duty engines
Gasoline supply	0.63	Per liter of gasoline supplied (well to tank)
LPG (Propane) combustion	1.14	Per liter of LPG combusted in heavy duty engines
LPG (Propane) supply	0.14	Per liter of LPG supplied (well to tank)
Lubricant oil production	0.85	Per liter of lubricant oil produced

Net emissions of each bioenergy system alternative were calculated and analyzed using a spreadsheet software.

3. Results and discussion

3.1. Net greenhouse gas emissions

The net GHG emissions for the baseline system were 178,631 t of CO₂ equivalent emissions in Anahim Lake, and 143,429 t of CO₂ equivalent emissions in Hanceville. The main difference in emissions is due to the energy mix difference in these two communities. In Anahim Lake, 100% of the electricity comes from diesel generation, while in Hanceville only 10% comes from diesel generation, and the rest is from the province's grid, which is mostly based on hydroelectric generation.

In Anahim Lake, all the analyzed bioenergy alternatives generated less net GHG emissions than the baseline system (Fig. 6a). Depending on the selected bioenergy system alternative, in Anahim Lake, the net GHG emission reductions ranged from 13,964 to 40,909 t of CO₂ equivalent emissions. Fig. 6a shows the most significant differences among alternatives were due to non-biogenic emissions. The total amount of biogenic emissions did not differ significantly among alternatives because it was assumed that all biogenic carbon is released during biomass combustion or burning, regardless of the final use of the generated heat (whether it is used for energy or wasted). Negligible differences appeared among the total biogenic emissions of the alternatives due to the formation of different substances during combustion under the different combustion (or burning) process conditions considered in the data sources. As shown in Fig. 6, the installation of a 2 MW bioenergy system could produce between 13.9 and 20.2 thousand less t of CO₂ equivalent emissions than the baseline system, and a 5 MW system could generate between 34.7 and 40.9 thousand less t of CO₂ equivalent emissions than the baseline system. For both plant sizes, the technology alternative that generated the lowest net GHG emissions was the ST system which has one of the highest electrical efficiencies of all technologies analyzed and was able to fulfill the entire heat demand of the Anahim Lake sawmill. Although the Gas system has a higher electrical efficiency, due to its low thermal efficiency, it was not able to fulfill the entire heat demand regardless of the plant size, thus more GHG emissions were generated as a result of a higher utilization of heating oil.

INSERT FIG. 6 HERE

In Hanceville (Fig. 6b) the baseline system generated less net GHG emissions than most bioenergy systems. Figure 6b shows differences among alternatives in terms of both non-biogenic and biogenic emissions. While all bioenergy systems had less non-biogenic GHG emissions (due to the replacement of current energy sources with bioenergy) than the baseline system, they also generated more biogenic emissions. The increased biogenic emissions in bioenergy systems were due to the release (during combustion) of the biogenic carbon embedded in sawmill residues that was stored in landfills in the baseline system. The increase of biogenic emissions offsets and surpasses the reduction of non-biogenic

emissions in all 0.5 MW bioenergy systems and in the ST*, ST and ORC 5 MW bioenergy systems. The 5 MW Gas system was the only alternative that generated net GHG emission reduction (2.5 thousand less t of CO₂ equivalent emissions than the baseline system) because it has a higher electrical efficiency than the other alternatives and does not utilize sawmill hog fuel (thus, sawmill hog fuel in this alternative is still landfilled).

3.2. Biogenic greenhouse gas emissions

Fig. 7 shows the breakdown of biogenic GHG emissions of the baseline and all bioenergy alternative based on their source: disposal of unused forest residues, disposal of unused sawmill residues, conversion of biomass into bioenergy and other (biogenic emissions in other processes along the supply chain).

INSERT FIG. 7 HERE

In Anahim Lake (Fig. 7a), 85,930 t of CO₂ equivalent emissions are due to the burning of unused forest residues in the forest cut blocks, and 46,889 t of CO₂ equivalent emissions are due to the burning of unused sawmill residues in beehive burners. In the bioenergy systems with 2 MW bioenergy plants, the largest amount of biogenic emissions (above 79,499 t of CO₂ equivalent emissions in all systems) is due to the large amount of forest residues that remains unused and thus are burned in the forest, and is followed by the emissions generated during biomass combustion for bioenergy generation (above 26,460 t of CO₂ equivalent emissions in all systems). For all 5 MW systems, most biogenic emissions are generated at the bioenergy plants (above 59,731 t of CO₂ equivalent emissions in all systems).

In Hanceville, Fig. 7b shows that in the baseline system, almost all biogenic emissions (123,424 t of CO₂ equivalent emissions) are attributed to the burning of unused forest residues, and the biogenic emissions due to landfilling are negligible (2,301 t of CO₂ equivalent emissions). In all 0.5 MW bioenergy systems, since the biomass mixes are mostly composed of sawmill residues, biogenic emissions of residues' burning at the forest do not change compared to the baseline system, but additional biogenic emissions

are generated during the conversion of biomass into bioenergy (above 7,559 t of CO₂ equivalent emissions in all 0.5 MW bioenergy systems). For 5 MW bioenergy systems, biomass conversion is responsible for more than 72,620 t of CO₂ equivalent biogenic GHG emissions.

3.3. Non-biogenic greenhouse gas emission breakdown

Fig. 8 illustrates the breakdown of non-biogenic GHG emissions of the baseline and all bioenergy alternatives based on their source: biomass production (harvesting, log transportation, sawmill operation), biomass supply to bioenergy plants (collection & chipping, biomass transportation), disposal of unused biomass (burning at roadside, landfilling) and provision of heat and electricity from current sources (heat from fuel oil and electricity from diesel or the British Columbia grid). Note that non-biogenic emissions related to the disposal of unused biomass are due to the transportation of a crew to the forest to burn roadside forest residues and to the transportation of sawmill wastes to the landfill.

INSERT FIG. 8 HERE

Since the flows of harvested logs and logs procured to local sawmills were identical for all considered systems in each community (refer to Tables 3 and 4), biomass production emissions remained unchanged across all alternatives. In Anahim Lake (Fig. 8a), biomass production emissions (4,900 t CO₂-eq) were the major contributor of non-biogenic emissions in systems where bioenergy substituted most fossil electricity and heat (5 MW ST, ORC and Gas systems). For other systems existing energy systems contributed to the largest proportion of emissions. For example, diesel generation of electricity was the major contributor to the non-biogenic GHG emissions of the baseline system and the two 2 MW bioenergy alternatives, while heat generation from heating oil was the main contributor to the non-biogenic GHG emissions from the 5 MW ST*. Non-biogenic emissions related with supplying forest residues to the bioenergy plants were significant only for 5 MW systems (from 314 to 749 t of CO₂

equivalent emissions for the ST* and the ORC systems respectively) since 2 MW systems satisfied most of their feedstock demands with sawmill residues available onsite.

In Hanceville alternatives (Fig. 8b), biomass production accounted for a larger proportion of the non-biogenic GHG emissions than in Anahim Lake alternatives for two reasons: (1) the amount of biomass production emissions in Hanceville alternatives (7,087 t CO₂-eq) was larger than those in Anahim Lake alternatives because more harvested logs were included in the analysis (to fulfill the feedstock demand of the bioenergy system with larger demand for non-merchantable MPB logs (the 5 MW Gas system) given that the production of chips in Hanceville is smaller than in Anahim Lake); (2) the amount of non-biogenic emissions from current energy sources in Hanceville was smaller than those in Anahim Lake due to differences in the reference energy systems. Similar to Anahim Lake, in Hanceville non-biogenic emissions related to supplying forest residues to the bioenergy plants were significant only for 5 MW systems (from 687 to 1,303 t of CO₂ equivalent emissions for the ST* and the ORC systems, respectively).

At a 0.5 MW scale, the ORC system generated the lowest amount of non-biogenic GHG emissions because it has the highest thermal efficiency, and was the only technology that satisfied the complete heat demand of the sawmill. In all the other bioenergy alternatives, a fraction of the heat demand had to be supplied by heating oil. For a larger scale plant (5 MW), the ST system was the bioenergy alternative with the lowest amount of non-biogenic GHG emissions. Although the Gas system had a higher electrical efficiency and was able to satisfy the heat demand in Hanceville, additional non-biogenic GHG emissions were generated using the ST system because of the transportation of unused sawmill hog fuel (not suitable for gasification) to the landfill, and the additional transportation and collection operations associated with the procurement of non-merchantable MPB logs to supplement the feedstock demand.

In comparison with the Anahim Lake alternative systems, the disposal of unused biomass had higher impacts in non-biogenic emissions generated in Hanceville, particularly for the baseline system and the

0.5 MW system alternatives, due to the transportation of the unused chips and hog fuel to the landfill. In Hanceville, disposal of unused biomass (mostly landfilling) contributes between 1,374 to 1,494 t of CO₂ equivalent emissions for 0.5 MW bioenergy alternatives, and between 537 and 687 t of CO₂ equivalent emissions for 5 MW bioenergy alternatives (Fig. 8b).

3.4. Sensitivity to British Columbia's electricity mix

In sections 3.1. to 3.3, the results for all alternative systems in Hanceville were based on an electricity mix mostly supplied by hydro generation (94.3%) which assumes a system boundary for the electricity mix covering the electricity produced in the province only. However, British Columbia, as a member of the Western Electric Coordinating Council (WECC, a non-profit organization responsible for assuring a reliable electric system in the Western Interconnection territory covering British Columbia and Alberta, 14 western states in the United States, and Mexico), exports and imports electricity to and from other WECC members (BC Hydro 2015). In order to assess the sensitivity of the alternatives in Hanceville to the composition of the province's electricity consumption mix, an analysis was conducted using the emissions from the British Columbia consumption mix as reported in Ecoinvent (Ecoinvent Centre 2015) (that considers imports from Alberta and U.S. states members of the WECC), and the emissions from the sum of production mixes of the WECC constituents, assuming 5.4% electricity losses as reported in Ecoinvent, and considering the net annual production of each territory based on (BC Hydro 2015; Government of Alberta 2015; and NREL 2012b). Net GHG emissions per MWh of the British Columbia consumption mix and the WECC production mix are 169.56 kg CO₂ eq and 628.89 kg CO₂ eq, respectively. Fig. 9 shows the net GHG emissions of alternative systems in Hanceville under the different assumptions for the British Columbia's electricity mix.

INSERT FIG. 9 HERE

As depicted in Fig. 9, when the BC consumption or the WECC production mixes were considered instead of the BC production mix, the net GHG emissions of the baseline system increased by around 4,182 and 20,477 t of CO₂ equivalent emissions, respectively. The net GHG emissions for all the 0.5 MW bioenergy systems increased the same amounts (4,182 and 20,477 t of CO₂ equivalent emissions using the BC consumption and the WECC production mixes, respectively). This increase of estimated emissions was a result of a larger proportion of fossil electricity sources in regions from where British Columbia receives electricity imports. In Alberta, 52% of the electricity generated comes from coal, 38% from natural gas, and only a 10% comes from renewable low carbon sources such as hydro, wind or biomass (Government of Alberta 2015). In the U.S. states members of the WECC, these proportions are 30.3%, 29.4% and 40.3%, respectively (NREL 2012b). Since a larger plant size of 5 MW would cover the entire electricity demand considered for Hanceville, energy from the current electricity mix is not required to complement the demand, thus the estimated emissions for all 5 MW bioenergy systems remained unchanged regardless of the considered electricity mix.

With the British Columbia production mix, the only system that generated less net GHG emissions than the baseline system was the 5 MW Gas system as explained in section 3.1. However, with the British Columbia consumption mix, the 5 MW ST, ORC and Gas systems generated 684, 298 and 6,717 less t of CO₂ equivalent emissions than the baseline system, respectively. With the WECC production mix, all 5MW systems generated considerably less net emissions than the baseline system (between 13,364 and 23,013 less t of CO₂ equivalent emissions), due to the increased estimated amount of GHG emissions of the baseline system with these electricity mixes.

4. Conclusions

In this study, the life cycle GHG emissions associated with electricity and heat generation in remote communities of Anahim Lake and Hanceville, located in the interior region of British Columbia, Canada were evaluated in order to identify the bioenergy alternatives that generate the highest environmental benefit. In addition, an economic evaluation was included to compare the economic suitability of producing bioenergy in the region. For each community, bioenergy systems with different production scales and conversion technologies were investigated and compared to the baseline system (current scenario). The results of this study showed that the selection of the system with the lowest net GHG emissions depends on whether the unused forest and wood residues are burned or landfilled, as well as the type of energy source used in the current system. When compared with the baseline system in Anahim Lake, a net GHG emission reduction between 13,964 and 40,909 t of CO₂ equivalent emissions was achieved by using available forest and wood residues for the generation of heat and electricity, because currently the residues are burned and fossil fuels are used to generate energy in the community. Under these conditions, in Anahim Lake, the alternative with the lowest GHG emissions was a 5 MW biomass boiler coupled with a steam turbine to cogenerate electricity and heat. However, in Hanceville, where sawmill wood residue is landfilled and the reference electricity mix is mostly based on hydro generation, the net GHG emission reduction that could be achieved by the introduction of a bioenergy system is significantly lower than that in Anahim Lake (2,535 t of CO₂ equivalent emissions in the 5 MW gasification system alternative) or null (for all other alternatives). Results of the sensitivity analysis showed that the composition of the reference electricity mix affected the estimation of net GHG emissions, and impacted the conclusion regarding whether or not the replacement of current electricity sources with bioenergy from forest and wood residues could generate less net GHG emissions. Further work should include other ecological considerations such as the role of harvesting residues in maintaining the health of the forest ecosystem to evaluate the environmental impacts of the alternatives, and the effect

of biomass characteristics such as moisture content and energy value on the overall environmental performance of the system.

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Caption for Figures

Fig.1 Baseline system in a) Anahim Lake and b) Hanceville. Main data sources used to compile the inventory of each unit process are indicated in brackets. MPB refers to mountain pine beetle-killed logs. Odmr refers to oven dry metric tonnes.

Fig. 2 a) 2 MW steam turbine (ST) bioenergy system in Anahim Lake and b) 0.5 MW ST bioenergy system in Hanceville. Main data sources used to compile the inventory of each unit process are indicated in brackets. MPB logs refers to mountain pine beetle-killed logs. Odmr refers to oven dry metric tonnes.

Fig. 3 Technologies and plant sizes evaluated in this study

Fig. 4 Annual biomass demand and average feedstock procurement cost for all bioenergy system alternatives in a) Anahim Lake and b) Hanceville. ST*: boiler + steam turbine, electricity only; ST: boiler + steam turbine, cogeneration; ORC: oil heater + organic rankine cycle, cogeneration; Gas: gasifier + internal combustion engine, cogeneration

Fig. 5 Electricity cost (\$ kWh⁻¹) of the 8 bioenergy alternatives in a) Anahim Lake and b) Hanceville. ST*: boiler + steam turbine, electricity only; ST: boiler + steam turbine, cogeneration; ORC: oil heater + organic rankine cycle, cogeneration; Gas: gasifier + internal combustion engine, cogeneration

Fig. 6 Net GHG emissions of baseline and bioenergy system alternatives in a) Anahim Lake and b) Hanceville. ST*: boiler + steam turbine, electricity only; ST: boiler + steam turbine, cogeneration; ORC: oil heater + organic rankine cycle, cogeneration; Gas: gasifier + internal combustion engine, cogeneration.

Fig. 7 Biogenic GHG emission savings per source of emissions for baseline and bioenergy system alternatives in a) Anahim Lake and b) Hanceville. ST*: boiler + steam turbine, electricity only; ST: boiler

+ steam turbine, cogeneration; ORC: oil heater + organic rankine cycle, cogeneration; Gas: gasifier + internal combustion engine, cogeneration.

Fig. 8 Non-biogenic GHG emissions per source of emissions for baseline and bioenergy system alternatives in (a) Anahim Lake and (b) Hanceville. ST*: boiler + steam turbine, electricity only; ST: boiler + steam turbine, cogeneration; ORC: oil heater + organic rankine cycle, cogeneration; Gas: gasifier + internal combustion engine, cogeneration

Fig. 9 Net GHG emissions for baseline and bioenergy system alternatives in Hanceville under different assumptions for the British Columbia (BC) electricity mix. ST*: boiler + steam turbine, electricity only; ST: boiler + steam turbine, cogeneration; ORC: oil heater + organic rankine cycle, cogeneration; Gas: gasifier + internal combustion engine, cogeneration