Journal of Cleaner Production 165 (2017) 1249–1262

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

A life cycle assessment of oxymethylene ether synthesis from biomass-derived syngas as a diesel additive

Nafisa Mahbub [a], Adetoyese Olajire Oyedun [a], Amit Kumar [a, *], Dorian Oestreich [b], Ulrich Arnold [b], Jörg Sauer [b]

[a] *Department of Mechanical Engineering, 10-263 Donadeo Innovation Centre for Engineering, University of Alberta, Edmonton, Alberta, T6G 1H9, Canada*
[b] *Institute of Catalysis Research and Technology (IKFT), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344, Eggenstein-Leopoldshafen, Germany*

ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form
20 July 2017
Accepted 22 July 2017
Available online 31 July 2017

Keywords:
Life cycle assessment
Oxymethylene ether
Forest biomass
Greenhouse gas emissions
Energy

ABSTRACT

The life cycle energy consumption and greenhouse gas (GHG) emission performances of forest biomass-derived oxymethylene ether (OME) synthesis used as a diesel additive are analyzed in this study. OME, a new alternative liquid fuel, has great miscibility with conventional fuels like diesel. OME can reduce combustion emissions significantly when used as a diesel additive without any modification to the engine. A data-intensive spreadsheet-based life cycle assessment (LCA) model was developed for OME synthesis from woodchips derived from two different kinds of forest biomass, whole tree and forest residue. Woodchip harvesting, chip transportation, chemical synthesis of OME from biomass-derived syngas, OME transportation to blending, and vehicle combustion of this transportation fuel were considered in the system boundary. The results show that the whole tree pathway produces 27 g CO_2eq/MJ of OME, whereas the forest residue pathway produces 18 g CO_2eq/MJ of OME over 20 years of plant life. The difference is mainly due to some emissions-intensive operations involved in biomass harvesting and biomass transportation such as skidding, road construction, etc., in the whole tree pathway. Also, vehicle combustion was found to be the most GHG-intensive unit for both pathways. OME combustion in a vehicle accounts for about 77% and 83% of the total life cycle GHG emissions for the whole tree and forest residue pathways, respectively. This study also compares the diesel life cycle emission numbers with the life cycle emissions of OME derived from forest biomass, and it was observed that GHG emissions can be reduced by 20–21% and soot (black carbon) emissions can be reduced by 30% using a 10% OME blended diesel as a transportation fuel compared with conventional diesel.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Around 46 billion metric tonnes of CO_2eq gases or GHGs were emitted worldwide in 2010, of which an estimated 71% came from energy production and use alone, including fuel combustion in vehicles (EPA, 2014). Canada emitted 702 million tonnes of CO_2eq gases in 2011, and most of these emissions came from Alberta, in particular from the petroleum industry (Environment Canada, 2013). In 2014, Alberta generated 250 Mt of GHGs. If Alberta continues to generate GHGs at this rate, it will produce more than 300 Mt CO_2eq gases per year by 2050, which is alarming (Mahbub and Kumar, 2014; Row and Mohareb, 2014). In 2011, Alberta generated around 239 Mt CO_2eq gases, of which almost 40% came from mining and oil gas extraction and the subsequent use of oil and gas in production, refining, and vehicle combustion (Mahbub and Kumar, 2014; Row and Mohareb, 2014). Vehicle exhaust in the form of CO_2, soot, NO_x, HC, and CO creates environmental pollution. Carbon black, or soot, is considered to be the second largest emission-contributing global warming material after carbon dioxide. It is responsible for producing around 1.1 W/m^2 of warming effect in the atmosphere (Bond et al., 2013). The combustion of fossil fuels in vehicles is one of the highest potential sources of soot or black carbon.

Oxygenated compounds are added to conventional fossil fuels as additives to reduce soot formation (Pellegrini et al., 2012) and make combustion cleaner (Zhang et al., 2014, 2016). Oxymethylene ether (OME) is an emerging fuel that can be used as an alternative transportation fuel or a fuel additive. The composition of oligomer

---

* Corresponding author.
E-mail address: Amit.Kumar@ualberta.ca (A. Kumar).

http://dx.doi.org/10.1016/j.jclepro.2017.07.178
0959-6526/© 2017 Elsevier Ltd. All rights reserved.

Abbreviations

ARP	Acid rain precursors
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2eq	Carbon dioxide equivalent
FU	Functional unit
GHG	Greenhouse gas
GOP	Ground-level ozone precursors
HC	Hydrocarbon
LCA	Life cycle assessment
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MJ	Megajoule
NO_x	Nitrogen oxide
OME	Oxymethylene ether
PM	Particulate matter
VOC	Volatile organic compounds
WTW	Well to wheel

molecules in OMEs can be adjusted to match the distillation range of diesel, thus providing great miscibility with diesel. In addition, OME can be used in old vehicles without altering the engine or using any diesel particulate filter (DPF) or any other expensive maintenance device and can be produced from a range of feedstocks including both fossil sources and biomass (Pellegrini et al., 2013).

To combat the environmental issues arising from fossil fuel combustion and fossil resource depletion, there is a move towards the production and use of alternative fuels (Kajaste, 2014; Nguyen et al., 2013). GHGs can be reduced considerably by replacing fossil sources with bio-based energy sources such as whole tree biomass, forest residue, agricultural residue, etc. (Agbor et al., 2016; Thakur et al., 2014). In Alberta, forests are harvested mainly for pulp and lumber. Since the demand for paper is decreasing, forest biomass can be a potential source of energy that can replace fossil sources (Government of Canada, 2016; Kabir and Kumar, 2012).

Beer and Grant (2007) discussed GHG emissions reduction from the production and use of several biomass-derived alternative fuel blends such as diesohol (15% ethanol blended with low sulfur diesel and an emulsifier), hydrated ethanol (azeotropic ethanol), petrohol (E10, a blend of 10% ethanol and premium unleaded petrol), and E85 (a blend of 85% ethanol, ignition improver, and a denaturant). Pre-combustion and combustion emissions from conventional fuels (i.e., diesel) and several alternative fuels such as CNG, LNG, LPG, ethanol blended with 5% petrol (E95), E10 blend (10% ethanol by volume mixed with gasoline), pure biodiesel (BD100), biodiesel blended with 80% diesel (BD20), and 65% diesel (BD35) have been discussed in the literature (Beer et al., 2002, 2003).

Among the oxygenated compounds, methanol, dimethyl ether (DME), dimethoxymethane (DMM), and OME are the most prominent diesel additives discussed in the literature (Zhang et al., 2014, 2016). Studies have discussed different processes of fuel grade methanol production such as direct conversion of conventional fossil fuels including NG, biomass gasification, CO_2 hydrogenation etc. and analyzed different process parameters on methanol yield (Liu et al., 2016; Riaz et al., 2013). Methanol and dimethyl ether produced from renewable sources like hydrogen from water or wind electrolysis and captured carbon dioxide (Matzen and Demirel, 2016; Van-Dal and Bouallou, 2013) can reduce greenhouse gas emissions by 82–86% compared to conventional fossil fuels. However, due to their chemical properties, DMM and DME require engine modification prior to their use as diesel additives in vehicles whereas OMEs can be used as diesel additives without any engine modification (Pellegrini et al., 2013; Zhang et al., 2016). Burger et al. (2010) discussed the formation of OMEs from DMM and trioxane (TRI) and also investigated the physical and chemical properties of OMEs used as diesel additives.

Zhang et al. (2014) developed a detail process model to produce OMEs from biomass and investigated some of the key parameters affecting the process such as equivalence ratio, H_2/CO ratio, and water flow rates. The authors found that a blend of 20% OME and 80% diesel can reduce soot emissions by 50%. Pellegrini et al. (2013) investigated the performance of neat OME (100%) and blended OME (10% OME blended with 90% diesel) in reducing the combustion emissions from old vehicles. Usually, a 10% blend of any oxygenated component with any conventional transportation fuel is considered the maximum to be used in old cars (Löfvenberg, 2010; Pellegrini et al., 2013). Since the lower heating value (LHV) of OME is significantly less, 100% OME as a transportation fuel is not considered to be strong enough for highway driving conditions (Pellegrini et al., 2013). Pellegrini et al. (2014) further investigated the polyaromatic hydrocarbon (PAH) emissions and particle number size distribution (PNSD) in an old vehicle fueled with 7.5% OME blended in diesel. Zhang et al. (2016) designed an optimal process model for the production of high OMEs (such as OME_3, OME_4, and OME_5) from woody biomass. A number of studies have been conducted on process modelling of OME synthesis from methanol (Zhang et al., 2014, 2016), and there are a few studies on combustion emission performance of OME in vehicles (Pellegrini et al., 2012, 2013). But there is almost no published literature on LCAs or life cycle emission performances of the whole supply chain of OME production from biomass to be used as a diesel additive. This study focuses on the life cycle environmental impacts of the production and combustion of OME from two different types of woody biomass in the western Canadian province of Alberta.

OME as a fuel or fuel additive has not been discussed widely in the literature. Nor is there an LCA of OME, which is essential to determine the environmental impacts of the technology. Therefore, the main objective of this study is to conduct an LCA of energy and emission performance of OMEs from whole tree and forest residue biomass in Western Canada. The specific objectives are to:

- Develop a system boundary diagram showing the production and use of OME from biomass;
- Develop energy consumption estimates of various unit operations for the whole chain of OME production from biomass and the use of OMEs;
- Estimate the life cycle GHG emissions for the whole chain of OME production and use;
- Estimate the life cycle acid rain precursors (ARPs) and the ground-level ozone precursors (GOPs) for the upstream operations;
- Conduct a sensitivity analysis to study the impact of variations in input parameters on overall life cycle GHG emissions.

2. Methodology

The goal of this study is to develop a data-intensive spreadsheet-based LCA model for OME synthesis from woodchips derived from two different types of forest biomass, whole tree and forest residue, and calculate the GHG emissions and net-energy-ratio (NER). The net energy ratio is the ratio of total energy output from the system to the total non-renewable energy input to the system (Shahrukh et al., 2015; Spitzley and Keoleian, 2004).

Information from the literature and Alberta-specific assumptions (such as biomass yield, biomass harvest area, moisture content, and tortuosity factor for biomass transportation distance) and current practices were used to evaluate energy consumption and GHG emissions.

In this study, a life cycle assessment of OME synthesis from two different types of forest biomass was carried out. The system boundary was made up of the following six unit operations for both pathways: biomass production, biomass transportation, chemical conversion, fuel mixing, fuel dispensing, and vehicle combustion. The unit operations were further divided into subunit operations for both biomass feedstock pathways (see Fig. 1). Due to the lack of data and relatively less significance on overall life cycle emissions, the downstream operations such as fuel dispensing, blending, storage, etc., were not included.

The results are given using a functional unit (FU) of 1 MJ of heat produced from OME so that the LCA results can be compared with the results of other LCA studies.

Three gases – carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) – are considered to cause global warming. Their relative impact on global warming is assumed to be 1, 34, and 298 times, respectively (Myhre et al., 2013). A 100-year time horizon is assumed for this impact. The acid rain precursors (ARPs) are sulfur dioxide (SO_2) and nitrogen oxide (NO_x), which are considered mainly responsible for acidification. The weighting factor for ARPs (SO_2eq) is considered to be 1 for SO_2 and 0.7 for NO_x. The ground-level ozone precursor (GOP) was also calculated in this study. GOPs include NO_x and volatile organic compounds (VOC). Both of these compounds have a weighting factor of 1 as GOPs. In the presence of sunlight, NO_x and VOC react with each other chemically and create ground-level ozone (Kabir and Kumar, 2011; Perera and Sanford, 2011).

3. Life cycle inventory

Both pathways studied here involve biomass production, biomass transportation, OME synthesis from biomass-derived syngas, transportation of OME, blending, and fuel combustion in a vehicle. As mentioned above, downstream operations like fuel mixing, storage, distribution, distillation, etc., are not considered in this study. This study considers a plant (gasifier) capacity of 277 t/d for OME synthesis. The GHG emissions are calculated over 20 years of plant life and the results are given in g CO_2eq/MJ of OME. The results are also compared to conventional diesel emission numbers.

3.1. Biomass production

For whole tree harvesting in Alberta, trees are cut in the stand, skidded to the roadside and delimbed, and, eventually, the trunk is used by pulp and paper industries (Pulkki, 1997; Shahrukh et al., 2016b). The biomass harvesting unit operation includes the sub-unit operations felling, skidding, and chipping (Fig. 1). The energy and emission impacts from manufacturing, operations, and disposal of the equipment used (feller, skidder, chipper) are also considered. Silviculture operations, which include fertilizing and pesticide spraying, are not considered in the base model because in Alberta it is assumed that first-generation trees are harvested. However, a case described later in the sensitivity analysis (section 4.4) was developed that includes the energy and emission impacts from silviculture operations.

In Alberta, the rotation of whole tree growth is assumed to be 100 years; this time frame was determined based on weather and soil conditions. Whole forest yield includes both hardwood and softwood. It is assumed in this study that 84 dry tonnes of forest biomass are harvested per hectare and that 20% of whole tree biomass is forest residues (Alberta Energy, 1985; Kumar et al., 2003). Thus the yield of forest harvest residue is assumed 0.247 dry tonnes per hectare over a 100-year rotation. The current trend in Alberta is to burn the residues to prevent forest fires (Shahrukh et al., 2016a). The removal of forest residues removes nutrients required for forest growth that would otherwise be returned to the soil. It is assumed in this study that ash (from the bio-plant) would be returned to the forest floor after the biomass is used for fuel

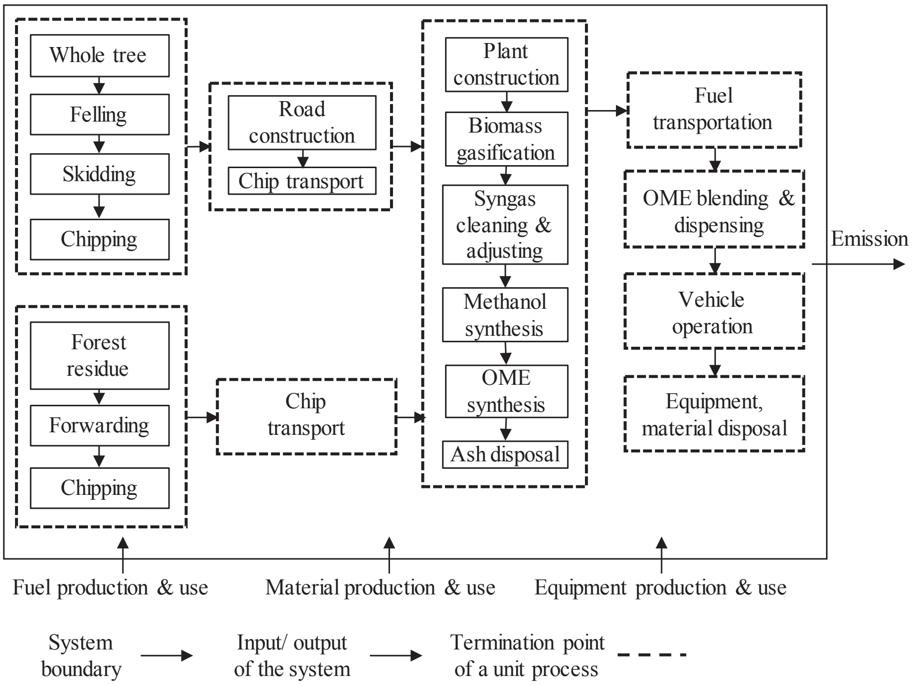


Fig. 1. System boundary for OME synthesis from whole tree and forest residue biomass.

production and thus forest soil nutrients are balanced (Thakur et al., 2014; Wihersaari, 2005). As the nutrient system can be balanced (through ash replacement) and the residues are otherwise considered waste (by their burning), forest harvest residues can be considered a good source for bioenergy production. Table 1 shows the data and assumptions for biomass harvesting for both the whole tree and forest residue pathways.

The forest residue pathway includes forwarding and chipping (See Fig. 1). The energy and emission impacts from production, operations, and disposal of the equipment used (forwarder and chipper) were also considered in this study.

Steel is used in the construction of all types of equipment and machines (e.g., fellers, skidders, forwarders, chippers, and transportation vehicles) considered in this study over the entire life cycle for both pathways.

Diesel is the fuel used to operate the machinery and equipment. Natural gas is used during the conversion of OME from biomass for syngas cleaning. The life cycle energy and combustion emission factors for different material and fuels considered in the system boundary for both pathways were taken from literature (Kabir and Kumar, 2012; Pellegrini et al., 2013; Stripple, 2001). The energy and emission factors are given in Table 2. The specifications of equipment used in biomass processing and harvesting for both pathways are given in Table 3. Energy and emission impacts from construction, operation, and disposal of equipment and machinery were considered in the system boundary.

3.2. Biomass transportation

A circular biomass harvest area is assumed for both pathways. Biomass collection distance depends on two other aspects, tortuosity and geometric factors. The tortuosity factor is the ratio of the distance travelled for biomass collection divided by the visible biomass collection distance, and the geometric factor is used to measure the biomass distribution over the harvest area. A circular harvest area growing only a biomass feedstock has a geometric factor of one, and the tortuosity factor was assumed in this study (for practical transportation assumptions) to be 1.27 (Overend, 1982). We assumed that the preprocessing plant was situated at the center of the harvest area. This methodology has been used in earlier studies (Shahrukh et al., 2016b). With these assumptions, the biomass collection distances used for the whole tree and forest residue pathways were 4.56 km and 21.75 km, respectively (Thakur et al., 2014).

Biomass is transported in heavy capacity trailer trucks. Fourteen tonnes of steel are used to manufacture a trailer truck. A trailer truck can carry 23 wet tonnes of biomass in a single trip and travel up to 2.55 km/L of fuel when empty and 2.12 km/L with a load (Kabir and Kumar, 2012; Mann and Spath, 1997). The energy and emission impacts of truck construction and operation are included in this study.

For the whole tree pathway, road construction was considered as a subunit operation. Forest roads are classified as primary, secondary, and tertiary. Whole trees are usually slid to a primary roadside and chipped, and the chips are transported by truck on primary roads. Other harvesting machinery like fellers, skidders and chippers operate on secondary and tertiary roads on slow speed.

For an OME plant with a capacity of 277 dry tonnes of biomass per day, around 36.48 km of primary road, 42.98 km of secondary road, and 28.65 km of tertiary road construction were assumed for the whole tree pathway in this study. The road construction estimates are based on a discussion with Fulton Smyl (Business Analyst, Alberta Innovates-Technology Futures on June 28, 2016) on Alberta's forest management plans, roads classification, and design specifications. The energy and emission factors for primary road construction – 1731 GJ/km, 403,845 kg CO_2eq/km, 1015 kg SO_2eq/km, and 1155 kg (NOx + VOC)/km – are taken from previous studies (Kabir and Kumar, 2011, 2012; Stripple, 2001). Crawler tractors (140 horsepower/105 kW) are assumed

Table 1
Inventory data and assumptions for biomass harvesting, transportation, and chemical conversion.

Assumptions/Properties	Units	Whole tree	Forest residue	Comments/References
Biomass required over 20 years	t	776,552	1,009,518	Dry basis. Calculated from Zhang et al. (2014); Shahrukh et al. (2016b)
Biomass production	t/ha	84	0.247	Dry basis (Kumar et al., 2003)
Higher heating value	GJ/t	20	20	Dry basis (Kumar et al., 2003)
Moisture content[a]	wt.%	50	45	(Kumar et al., 2003)
Annual biomass requirement	t/y	38,828	50,476	Dry basis. Calculated from (Kabir and Kumar, 2011; Zhang et al., 2014; Shahrukh et al., 2016b)
Harvest area	ha	585	207,158	Calculated from Agbor et al. (2016)
Transportation distance	km	4.56	21.75	Calculated from Agbor et al. (2016)
Ash content	wt.%	1	3	(Kumar et al., 2003)
Pesticide application	kg/ha	0.17	–	(Kabir and Kumar, 2012)
Biomass flow to gasifier	t/d	277	277	Wet basis (Zhang et al., 2014)
Plant life	years	20	20	(Kabir and Kumar, 2011)
Capacity factor				
Year 1		0.7	0.7	(Shahrukh et al., 2016b)
Year 2		0.8	0.8	(Shahrukh et al., 2016b)
Year 3 & onwards		0.85	0.85	(Shahrukh et al., 2016b)
Volumetric truck capacity	m^3	70	70	(Mann and Spath, 1997)
Lifetime of each truck	km	540,715	540,715	(Mann and Spath, 2001)
Dedicated trucks required (WT)		1.56	7.82	Calculated from Mann and Spath (2001; Zhang et al. (2014); Shahrukh et al. (2016b)
Bulk density of whole tree chip	kg/m^3	250	235	(Kabir and Kumar, 2012)
Gross vehicle mass	t	38	38	(Kabir and Kumar, 2012)
Truck payload	t	23	23	(Kabir and Kumar, 2012)
Truck fuel consumptions (empty/full load)	L/km	0.24/0.33	0.24/0.33	(Sultana and Kumar, 2011)
Actual load carried by truck (WT)	t	17.5	16.5	(Kabir and Kumar, 2012)
Road construction required in 20 yrs	km	36.5	N/A	Calculated from Thakur et al. (2014); Winkler (1998)

[a] The moisture content in Table 1 refers to the moisture content of as-received biomass feedstock, and the capacity factors are the conventional ones used for biomass-based plants (Kabir and Kumar, 2012).

Table 2
Energy and emission factors for fuel, materials, and road construction used in the system [derived from Kabir and Kumar (2011, 2012) and Stripple (2001)].

Diesel	HHV (MJ/L)	kg CO_2eq/GJ	kg SO_2eq/GJ	kg (NOx + VOC)/GJ	GJ/GJ
	35.97	100.30	0.39	0.63	1.29
Natural gas	HHV (MJ/kg)	kg CO_2eq/GJ	kg SO_2eq/GJ	kg (NOx + VOC)/GJ	GJ/GJ
	38.26	56.58	0.128	0.22	1.11
Steel	GJ/tonne	kg CO_2eq/GJ	kg SO_2eq/GJ	kg (NOx + VOC)/GJ	–
	34.00	2494.86	21.15	9.66	
Road construction	GJ/km	kg CO_2eq/km	kg SO_2eq/km	kg (NOx + VOC)/km	–
	1731	403,845	1015	1155	

Table 3
Specifications of equipment used in whole tree and forest residue pathways for biomass harvesting, processing, and road construction.

Equipment specification	Value	Unit	Comments/References
Feller (whole tree pathway)			
John Deere 853J	205/274	kW/hp	(MacDonald, 2006)
Feller lifetime productivity	95,812.5	t WF[b]	Dry basis (MacDonald, 2006)
Feller lifetime fuel consumption	514,650	L diesel	(MacDonald, 2006)
Dedicated feller required	18		Calculated from Zhang et al. (2014); Shahrukh et al. (2016b); Kumar et al. (2003)
Steel in each feller	28.84	t	(MacDonald, 2006)
Skidder (whole tree pathway)			
John Deere 748 H	141/189	kW[b]/hp[b]	(Han and Renzie, 2001)
Skidder lifetime productivity	90,000	t WF	Dry basis (Han and Renzie, 2001)
Skidder lifetime fuel consumption	540,000	L diesel	(Han and Renzie, 2001)
Dedicated skidder required	19		Calculated from Zhang et al. (2014); Shahrukh et al. (2016b); Kumar et al. (2003)
Steel in each skidder	14.35	t	(Han and Renzie, 2001)
Chipper (whole tree pathway)			
Morbark 50/48 chipper			(MacDonald, 2006)
Chipper lifetime productivity	270,000	t WF	Dry basis (MacDonald, 2006)
Chipper lifetime fuel consumption	900,000	L[b] diesel	(MacDonald, 2006)
Steel in each chipper	28.16	t	(MacDonald, 2006)
Dedicated chipper required	6		Calculated from Zhang et al. (2014); Shahrukh et al. (2016b); Kumar et al. (2003)
Forwarder (forest residue pathway)			
Wheel loader (Komatsu WA 250-6)	138	hp	Mann and Spath (1997)
Forwarder lifetime productivity	101,200	t FR[b]	Dry basis (MacDonald, 2006)
Forwarder lifetime fuel consumption	416,000	L diesel	(MacDonald, 2006)
Steel in each forwarder	11.58	t	Mann and Spath (1997)
Dedicated forwarder required	17		Calculated from Zhang et al. (2014); Shahrukh et al. (2016b); Kumar et al. (2003)
Chipper (forest residue pathway)			
Nicholson WFP 3A			(Desrochers et al., 1993)
Chipper lifetime productivity	252,000	t FR	Dry basis (Desrochers et al., 1993)
Chipper lifetime fuel consumption	990,000	L diesel	(Desrochers et al., 1993)
Steel in each chipper	57.82	t	(Desrochers et al., 1993)
Dedicated chipper required	7		Calculated from Zhang et al. (2014); Shahrukh et al. (2016b); Kumar et al. (2003)
Crawler tractor (secondary and tertiary road construction)	140/105	hp/kW	(Winkler, 1998)
Tractor lifetime productivity	8000	h	(Winkler, 1998)
Tractor lifetime fuel consumption	184,000	L diesel	(Winkler, 1998)
Operating machine hours (secondary road)	70	h/km	(Winkler, 1998)
Operating machine hours (tertiary road)	100	h/km	(Winkler, 1998)
Dedicated tractor required (secondary and tertiary)	0.73		Calculated from (Thakur et al. (2014); Winkler (1998); Fulton Smyl, Business Analyst, Alberta Innovates-Technology Futures, 2016 on June 28, 2016)

[b] WF = whole forest, FR = forest residue, kW = kilowatt, hp = horsepower, L = litre.

to be used for secondary and tertiary road construction (Winkler, 1998). Primary roads are generally built as permanent roads, whereas secondary roads are built to be semi-permanent and tertiary roads are temporary trails mostly used for harvesting (Ontario Ministry of Natural Resources, 1994). Hence, the tractor operating hours are considered to be 70 h/km for secondary road and 100 h/km for tertiary road construction in this study (Table 3) (Winkler, 1998).

For the forest residue pathway, no road construction is required. The chips are assumed to be transported using the existing road network used by regular logging companies (Kabir and Kumar, 2011, 2012; Shahrukh et al., 2016b).

We calculated truck fuel consumption using a formula from Sultana and Kumar (2011), given in Equation (1). We assumed that a truck carries less than its payload, or volumetric capacity. Truck fuel consumption is calculated as follows:

$$F_a = F_e + \{(F_f - F_e) \times \left(L_a / L_p\right)\} \tag{1}$$

where F_a = actual fuel consumed by a truck while carrying a load L_a (L/km), F_e = fuel consumed by an empty truck (L/km), F_f = fuel consumed by a fully loaded truck (L/km), L_a = actual load transported by a truck (t), and L_p = volumetric capacity of a truck (t). The inventory data for biomass transportation are given in Table 1.

3.3. OME plant construction

An OME plant is assumed to have 20 years of plant life. Due to similarities in the chemical conversion of OME with other fuels like biohydrogen production (such as biomass gasification, syngas cleaning, H_2/CO adjusting, etc.), the scale factor needed to determine the amount of material to construct an OME plant is taken from existing literature on other plants (Moore, 1959; Spath and Mann, 2000). The amount of construction material was determined through Equation (2) obtained from Sarkar and Kumar (2010a, b):

$$C_i/C_o = (S_i/S_o)^n \tag{2}$$

Here, S_i = the size of the OME plant, S_o = the size of reference plant, C_i = the amount of material required for an OME plant, S_o = the amount of material in the reference plant, and n = the scale factor. A scale factor of 0.76 was assumed in this study. The scale factor was taken from Kabir and Kumar (2011) due to similarities in biohydrogen production operations and OME synthesis.

As an example, for a Battelle Columbus Laboratory (BCL) plant with a capacity of 250,200 kg H_2/day, Kabir and Kumar (2011) estimated the amount of steel, concrete, and aluminium to be 5350, 16,535, and 44 t, respectively. We used these values as reference plant material amounts in Equation (2) and a scale factor of 0.76 and estimated the amount of material for an OME plant (capacity 24,746 kg OME/day) to be 922 t steel, 2850 t concrete, and 7.58 t of aluminium. The energy and emission impacts of plant decommissioning and disposal of construction material are also included in the plant construction unit operation. The energy and emission impacts from plant decommissioning are assumed to be 3% of plant construction impacts (Elsayed and Mortimer, 2001; Kabir and Kumar, 2011). The construction materials are assumed to be disposed of in landfills 50 km from the plant (Kabir and Kumar, 2011, 2012; Spath et al., 2005). Heavy capacity trucks used in biomass transportation are used for construction material disposal. All aluminium and concrete material are assumed to be landfilled, but 75% of the steel is recycled and 25% of it is landfilled (Spath et al., 2005; Spath and Mann, 2000). The energy and emission factors for steel and aluminium landfilling are 0.01 tCO_2eq/t material and, for concrete, 0.044 tCO_2eq/t material (Spath et al., 2005; Spath and Mann, 2000).

3.4. Chemical conversion

Five subunit operations are included in the chemical conversion process: gasification, syngas cleaning and H_2/CO adjustment, methanol synthesis, OME synthesis, and ash disposal. Both feedstocks undergo the same process. Biomass conversion is considered to be carbon neutral as all carbon released during the combustion of the woodchips is compensated by the amount of carbon up taken during forest growth (Hartmann and Kaltschmitt, 1999; Liu et al., 2013; Zhang et al., 2009). The input-output mass flow rates for chemical conversion unit operations are given in Table 4. The output includes OMEs 1 to 8 and some untreated gases such as N_2, O_2, water, etc. 6.80 MW of external heat energy, supplied by natural gas, are used in syngas cleaning and H_2/CO adjustment unit operations (Zhang et al., 2016). But this external energy is a small fraction (around 6.57%) of the energy consumed during the whole chemical conversion process. The remaining heat energy is supplied by the combustion of 13–17% of the input biomass depending on the biomass feedstocks as stated by Zhang et al. (2016).

The ash contents in whole tree and forest residue biomass are assumed to be 1% and 3%, respectively (Van den Broek et al., 1995; Kumar et al., 2003). Over 20 years, 16,986 t and 50,957 t of ash are produced through the whole tree and forest residue pathways, respectively. The ash is assumed to be disposed of 50 km away from the plant in the forest area and is usually considered to replace the nutrients removed with the trees and residues (Kumar et al., 2003; Spath et al., 2005). The same heavy capacity trailer trucks used in biomass transportation are used to spread ash. The ash spreading rate is assumed to be 1 t/ha, and a 40′ fertilizer spreader with a capacity of 4.41 ha/h is used (Kabir and Kumar, 2011; Spath et al., 2005). The life cycle energy and emission impacts of trucks and spreaders used for ash transportation and ash spreading are included in this study.

3.5. OME transportation

In this study, we assumed a distance of 300 km to transport OME from the chemical conversion plant to the blending plant. We also assumed that the high capacity trailer trucks used for biomass transportation and ash disposal would be used for OME transportation. The energy and emissions impacts of construction and operation of trucks are considered in this study.

3.6. Vehicle combustion

Combustion emissions and fuel consumption numbers are taken from a study by Pellegrini et al. (2013). They tested an in-use diesel engine car with three different types of fuel, conventional diesel, 100% OME, and a 10% OME diesel blend. The particulate matter (PM) emissions were also calculated, and the PM composition determined the amount of soot emissions. Pellegrini et al. (2013) found that 77% of diesel PM emissions are black carbon/soot whereas in OME, only 33% of PM emissions are black carbon/soot and 50% of the PM emissions come from the volatile organic fractions in lube oil. These figures are used in our model to calculate the soot emissions from vehicle combustion. The soot emissions for 100% OME and a 10% OME blend with diesel as calculated in this model are 0.0011 g/MJ of OME and 0.0071 g/MJ of OME, respectively. When a strong oxidation catalyst and a good synthetic lubricant in vehicles are used, PM emissions can be further reduced. According to the experimental results by Pellegrini et al., using 100% OME as a transportation fuel can reduce soot emissions significantly, although hydrocarbon (HC), carbon monoxide (CO), nitrogen oxides (NOx), and carbon dioxide (CO_2) emissions and fuel consumption increase (Pellegrini et al., 2013). The CO_2eq emissions from the combustion of 100% OME as a transportation fuel are considered to be zero in our model since we assume that the combustion emissions of biomass-derived fuels are compensated by the amount of CO_2 taken up by the tree during its growth. The combustion emissions from a 10% OME blend with diesel are around 0.060 CO_2eq/MJ of OME and come predominantly from the diesel fraction.

Table 4
Input-output data inventory for chemical conversion unit operations.

Chemical conversion units	Inputs	Mass flow rate kg/s	Outputs	Mass flow rate kg/s
Gasification	Air	3.21	Raw syngas	5.35
	Woodchips	3.54		
Syngas cleaning & adjusting	Raw syngas	5.35	Cleaned Syngas	4.09
Methanol synthesis	Cleaned syngas	4.09	Methanol	0.92
OME Synthesis	Methanol	0.92	Total OME	0.29

Table 5
Life cycle energy use and emissions for different upstream unit operations of the whole tree pathway.

Preliminary results	Energy use	GHG emissions	ARP emissions	GOP emissions
Units	GJ/MJ	g CO_2eq/MJ	g SO_2eq/MJ	g(NO_x + VOC)/MJ
Biomass production	0.18	14.25	0.057	0.088
Biomass transportation	0.03	5.41	0.014	0.017
Chemical conversion	1.24	5.61	0.017	0.020
OME transportation ME	0.01	0.50	0.002	0.003

4. Results and discussion

In this section, the results of the life cycle energy and emission impact assessments for both whole tree and forest residue pathways are presented, compared, and discussed. The sensitivity analyses for the different scenarios are also discussed.

4.1. Life cycle energy and emission impacts for the whole tree pathway

Table 5 shows the energy consumptions and GHG emissions results for the upstream operations from whole tree biomass.

Of the upstream unit operations (biomass production, biomass transportation, and chemical conversion), chemical conversion consumes the most energy, almost 85% of the energy consumed in the pathway. The primary energy input for chemical conversion is the heat from the wood chips, which is around 26.37 MW (equivalent to 8.215 MJ/kg). The output from one subunit operation is used as input for the next. About 6.80 MW of fossil heat energy (from natural gas) are used in the syngas cleaning and H_2/CO adjusting subunit operation; this is the only fossil energy considered in chemical conversion operation. Biomass harvesting is the second most energy-intensive unit operation, and biomass transportation consumes the least energy over the entire life cycle of whole tree pathway.

For chemical conversion, OME synthesis in the whole tree pathway consumes the most energy, around 28% of the energy used in the conversion (Fig. 2). The energy required in gasification (around 23% of the energy consumed in chemical conversion) comes primarily from the biomass (wood chips). The fossil energy used in this pathway is around 6.57%, which is supplied by natural gas.

Equipment construction energy is negligible compared to equipment operation energy for all the biomass harvesting equipment considered in this study.

Around 40% of the energy used in the whole tree pathway is consumed in skidding operations. For this study, 19 skidders with a productivity of 7.5 dry tonnes whole trees per hour are required for a plant capacity of 277 t/d over 20 years (Table 3). A skidder's hourly productivity is comparatively much lower than that of a feller (8.75 dry tonnes whole trees per hour) or a chipper (30 dry tonnes whole trees per hour for a high-efficient chipper). But a skidder's life cycle fuel consumption is higher than that of a feller (Table 3), making it the highest energy-consuming unit in biomass production. Only six high-efficient chippers are required over 20 years, hence chipping is the least energy consuming unit (around 22%) throughout the life cycle (Table 3).

Vehicle combustion is the most GHG emissions-intensive unit,

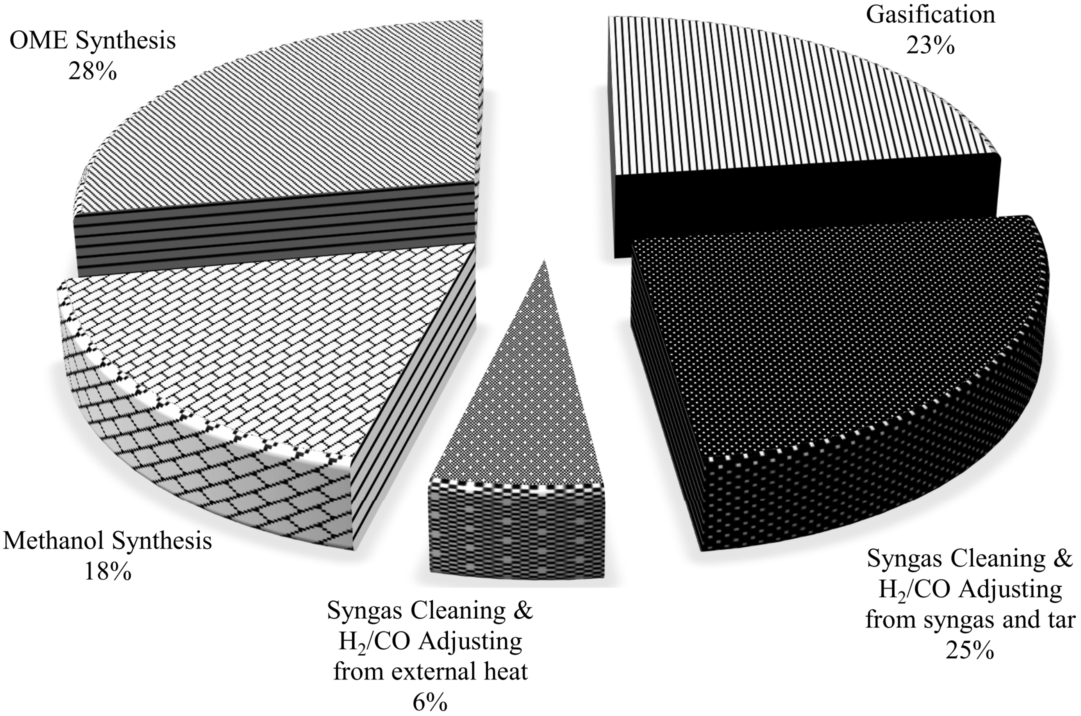


Fig. 2. Energy consumption by sub-unit operations in chemical conversion for the whole tree pathway.

contributing around 77% of life cycle GHG emissions in the whole tree pathway. However, this unit operation is considered to be carbon neutral, thereby nullifying the effect of GHG emissions. Biomass production produces the second highest GHG emissions and contributes 12% of emissions over the life cycle.

In this study, it was assumed that 36.5 km of primary roads were constructed in order to haul whole tree biomass from the forest. This is the third most emissions-intensive unit operation (5.35% of total life cycle GHG emissions) when using whole tree biomass as an energy source. The impact of this subunit operation on the entire life cycle emissions is discussed in the sensitivity analysis.

Biomass production contributes around 12% of the GHG emissions over the entire life cycle for the whole tree pathway. For biomass production, the skidder operation is the most emissions-intensive unit (Fig. 3). Because of its relatively lower productivity and comparatively higher fuel consumption compared to the other unit operations, skidder operations contribute the most GHG emissions over the whole tree pathway life cycle, around 40%. The fellers contribute 36% of the life cycle GHG emissions followed by chipper operation emissions, which are around 22%. Equipment construction emissions are negligible compared to equipment operation emissions.

Over the entire life cycle of the whole tree pathway, the chemical conversion unit process contributes very few GHG emissions (only 4.82%); this result is mainly based on the assumptions that the amount of CO_2 released during the gasification of the forest biomass is equal to the amount of CO_2 taken up by the tree during its growth and the amount of external fossil energy used during chemical conversion is negligible (only 6.57% of life cycle energy consumption). The GHG emissions from ash disposal, including ash transportation and ash spreading, are included in this unit operation. OME transportation emits the fewest GHGs over the entire life cycle, only 0.43% of life cycle GHG emissions.

The biomass production unit operation contributes the highest ARP emissions, around 62% of the life cycle ARP emissions. The biomass transportation, chemical conversion, and OME transportation unit processes contribute around 17%, 18%, and 2% of the life cycle ARP emissions, respectively. Due to the lack of data, ARP and GOP emissions were not calculated for the downstream unit operation, combustion in vehicles, for either pathway.

GOP emissions for biomass production, biomass transportation, and chemical conversion are around 0.09 g (NO_x + VOC)/MJ, 0.018 g (NO_x + VOC)/MJ, and 0.02 g (NO_x + VOC)/MJ respectively. GOP emissions from the OME transportation unit operation are negligible, around 2% of the life cycle GOP emissions.

4.2. Life cycle energy and emission impacts for the forest residue pathway

Table 6 shows the preliminary energy consumption and GHG emissions results for the upstream operations from forest residue biomass.

Whole tree and forest residue biomass feedstocks use the same chemical conversion process. Thus, as for the whole tree pathway, chemical conversion is the highest energy-consuming upstream unit operation in the forest residue pathway, around 89% of the life cycle energy, followed by biomass production, biomass transportation, and OME transportation, which consume around 9%, 1.3%, and 0.47% of the energy, respectively. Among the four unit operations, vehicle combustion emits the most GHGs, around 83% of the life cycle GHG emissions.

Biomass production produces 9.5% of the GHG emissions over the entire life cycle, followed by chemical conversion, biomass transportation, and OME transportation at around 5%, 1.35%, and 0.47% of life cycle GHG emissions, respectively. The transportation emissions are low mainly because no road construction is considered for the forest residue pathway (existing roads built for logging operations are used). Similar to the whole tree pathway, chemical conversion emissions are almost carbon neutral and hence contribute only 5% of the life cycle GHG emissions. Equipment construction emissions are also negligible compared to equipment operation emissions, as for the whole tree pathway. Around 50% of biomass production emissions are from forwarder operation emissions due to the forwarder's low productivity. For an OME plant with a capacity of 277 t/d, around 17 forwarders are required throughout the 20 years of plant life. Six highly productive (more than twice the productivity of a forwarder) chippers are used over 20 years of plant life, producing 47% of the biomass production emissions, almost the same as that from forwarders.

Similar to the whole tree pathway, ARP emissions are highest for the biomass production unit operation (around 61% of the life cycle ARP emissions), followed by the chemical conversion, biomass transportation, and OME transportation operations, which

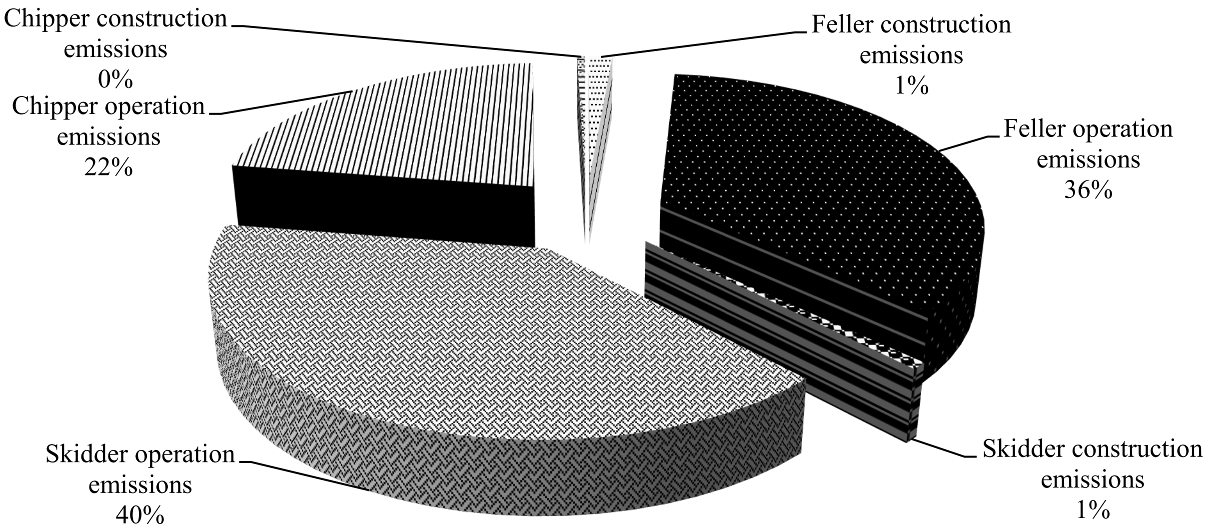


Fig. 3. GHG emissions from different sub-unit operations in biomass production (gCO_2eq/MJ), whole tree pathway.

Table 6
Life cycle energy use and emissions for different upstream operations in the forest residue pathway.

Preliminary results	Energy use	GHG emissions	ARP emissions	GOP emissions
Units	GJ/MJ	gCO_2eq/MJ	gSO_2eq/MJ	g(NO_x + VOC)/MJ
Biomass production	0.13	10.15	0.041	0.063
Biomass transportation	0.02	1.45	0.006	0.009
Chemical conversion	1.24	5.67	0.020	0.021
OME transportation	0.01	0.50	0.002	0.003

contribute around 26%, 9%, and 3% of the total life cycle ARP emissions, respectively.

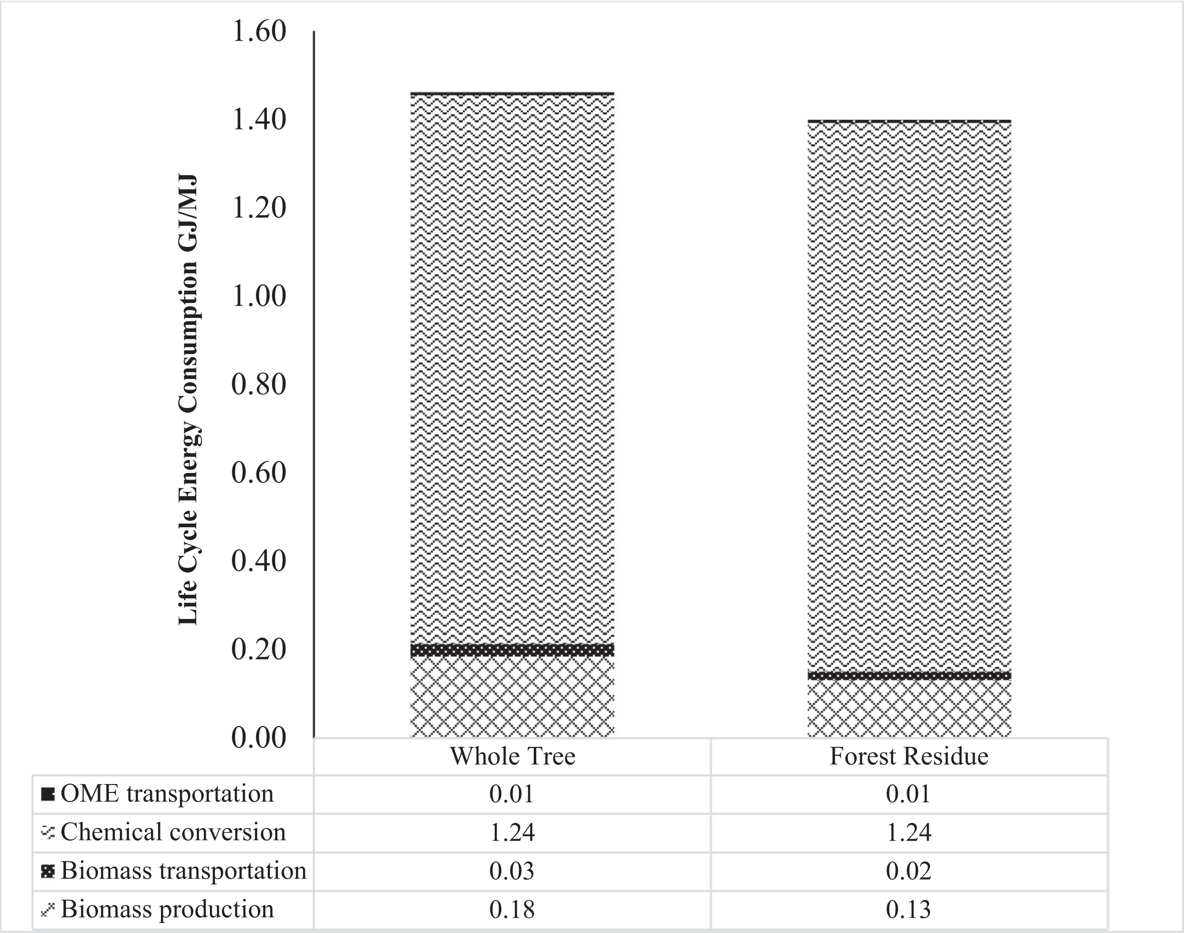
In the forest residue pathway, biomass production GOP emissions are 66% of the total life cycle GOP emissions, and chemical conversion, biomass transportation, and OME transportation contribute around 22%, 9%, and 3% of the life cycle GOP emissions, respectively. OME transportation contributes the lowest GOP emissions, around 0.003 g (NO_x + VOC)/MJ of OME.

4.3. Comparison of life cycle energy and emission impacts between the two pathways

Fig. 4 shows the life cycle energy consumption of four unit operations – biomass production, biomass transportation, chemical conversion, and vehicle combustion – in the whole tree and forest residue pathways.

Both pathways use the same chemical conversion process, and chemical conversion is the most energy-intensive upstream operation for both (around 80–85%). Since road construction is considered in the whole tree and not the forest residue pathway, biomass transportation energy consumption in the whole tree pathway is twice as high as in the forest residue pathway (even though the transportation distance for biomass collection in the forest residue pathway [21.75 km] is almost 5 times higher than in the whole tree pathway [4.56 km]). However, biomass production energy in the whole tree pathway is higher than that of the forest residue pathway. This is due to the effects of the subunit operations involved in biomass production. In the whole tree pathway, biomass production has three subunit operations (skidding, felling, and chipping), and skidding consumes the most energy (almost 40% of the energy consumed in biomass production). In the forest residue pathway, the biomass production unit includes only forwarding and chipping, neither of which consumes large amounts of energy.

For both pathways, vehicle combustion produces the highest GHG emissions, around 89.55 g CO_2eq/MJ of OME. In the whole



	Whole Tree	Forest Residue
■ OME transportation	0.01	0.01
▨ Chemical conversion	1.24	1.24
▩ Biomass transportation	0.03	0.02
▧ Biomass production	0.18	0.13

Fig. 4. Whole tree and forest residue pathways' life cycle energy consumption comparison.

tree pathway, vehicle combustion contributes around 77% of the life cycle GHG emissions and in the forest residue pathway, vehicle combustion is responsible for 83% of the life cycle GHG emissions (see Fig. 5). Since OME is produced from biomass, combustion emissions are considered to be carbon neutral. Hence 83% of life cycle GHG emissions in the forest residue pathway and 77% in the whole tree pathway are considered carbon neutral, and thus the forest residue pathway produces fewer GHGs than the whole tree pathway. In both pathways, the second highest GHG emissions come from biomass production (around 12% of the life cycle emissions from the whole tree and 9.5% from the forest residue pathway). Biomass transportation emissions in the whole tree pathway are almost four times higher than those of the forest residue pathway (Fig. 5). This is mainly due to the emissions-intensive unit operation road construction. About 36.5 km of primary road construction is considered in the whole tree pathway.

Around 12% of life cycle emissions come from biomass production in the whole tree pathway and 9.5% the forest residue pathway. GHG emissions from whole tree and forest residue biomass production are 14.25 g CO_2eq/MJ and 10.15 g CO_2eq/MJ, respectively. GHG emissions from whole tree biomass production are higher because of the differences in biomass production energy consumption, as explained earlier.

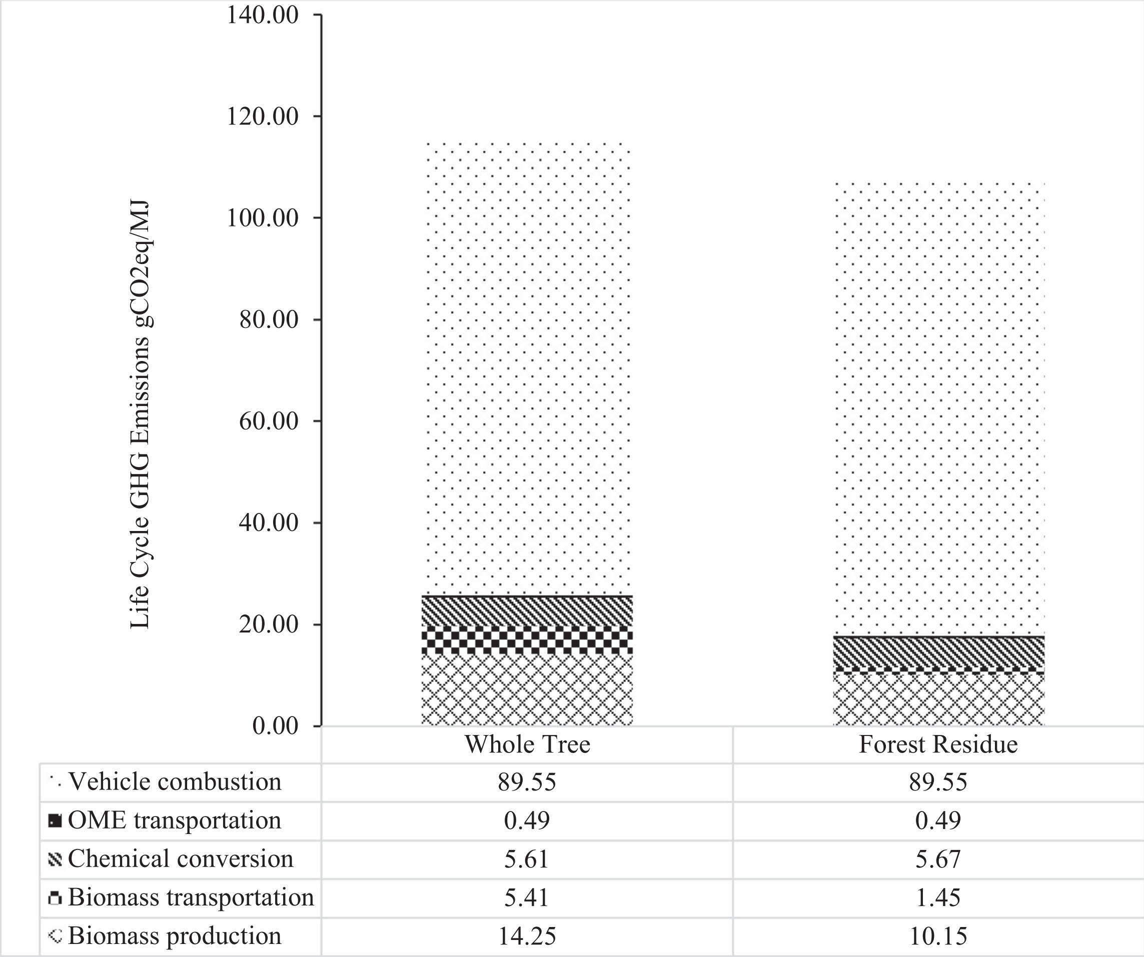
GHG emissions from chemical conversion are around 5.67 g CO_2eq/MJ in the forest residue pathway and 5.61 g CO_2eq/MJ in the whole tree pathway. The difference is due to the higher ash content in forest residues. Because of the higher ash content, this pathway produces more ash than the whole tree pathway, thereby contributing slightly higher GHG emissions.

With respect to ARP emissions, biomass production is the highest contributor in both pathways. Whole tree biomass production produces around 0.06 g SO_2eq/MJ and forest residue biomass production contributes 0.04 g SO_2eq/MJ (see Tables 5 and 6).

The highest GOP emissions come from whole tree biomass production and are around 0.09 g (NO_x + VOC)/MJ (see Table 5). The forest residue pathway also generates the highest GOP emissions from biomass production unit operations; these are around 0.06 g (NO_x + VOC)/MJ (see Table 6).

4.4. Comparison with diesel life cycle energy and emission impacts

We compared life cycle GHG emission numbers of OME derived from forest biomass to those of the conventional fossil fuel diesel. Several LCA studies have been published on diesel life cycle emissions (Garg et al., 2013; Gerdes and Skone, 2009; Rahman et al., 2015). The diesel GHG emission numbers include emissions from crude recovery, crude transportation to the refinery, crude refining, transportation and distribution of finished fuels to the dispensing station, and combustion of fuels in vehicles. The upstream GHG emission numbers, from crude recovery to dispensing fuel, are taken from Rahman et al. (2015), and the combustion emission numbers for diesel are taken from Pellegrini et al. (2013).



	Whole Tree	Forest Residue
⁘ Vehicle combustion	89.55	89.55
■ OME transportation	0.49	0.49
▧ Chemical conversion	5.61	5.67
▦ Biomass transportation	5.41	1.45
▩ Biomass production	14.25	10.15

Fig. 5. Whole tree and forest residue pathways' life cycle GHG emissions comparison.

The well-to-wheel (WTW) diesel life cycle GHG emissions calculated by Rahman et al. (2015)were 126.54 g CO_2eq/MJ, whereas in this study the life cycle GHG emissions from 100% OME as a transportation fuel were found to be 27 g CO_2eq/MJ when OME is produced from whole trees and 18 g CO_2eq/MJ when OME is produced from forest residues (Fig. 6). In the OME pathways, GHG emissions from vehicle combustion are assumed to be carbon neutral and the chemical conversion process is assumed to be almost carbon neutral since only 6.57% of life cycle energy consumption comes from a fossil source. Hence, total life cycle emissions from OME pathways are significantly lower than those of diesel. Total life cycle GHG emissions and percentage reductions in GHGs compared to conventional diesel for 100% OME and a 10% OME blend with diesel to be used as transportation fuels are given in Table 7. The upstream emissions from the forest residue pathway (18 g CO_2eq/MJ) are significantly lower than those of the whole tree pathway (27 g CO_2eq/MJ). Hence, 100% OME as a transportation fuel from the forest residue pathway contributes 86% fewer GHG emissions than diesel, whereas 100% OME from the whole tree pathway contributes 79% fewer GHG emissions than diesel. Similarly, when OME is used as a diesel additive, for the 10% OME blended with 90% diesel, the life cycle GHG emissions are reduced by 5% and 5.35% compared to that of diesel, when OME is produced from the whole tree and forest residue pathways, respectively. Upstream emissions are allocated to the OME blends depending on their mass in the finished fuel.

The soot emissions for 100% OME and a 10% OME blend with diesel as calculated in our model are 0.0011 g/MJ of OME and 0.0071 g/MJ of OME, whereas the soot emissions from diesel are 0.01 g/MJ of diesel (Pellegrini et al., 2013). We compared the soot emissions from a 10% OME blend and 100% OME to the soot emissions from diesel and found that soot emissions decrease by 30% and 89% compared to diesel for a 10% OME blend with diesel and 100% OME, respectively. The soot emissions for all three fuels are shown in Table 7.

4.5. Sensitivity analysis

A number of scenarios were developed for both pathways by varying parameters and assumptions of upstream operations, and the impacts of these variations on life cycle energy and emissions are given in Table 8. The scenarios were developed independently of each other and compared with the base scenario. The downstream operation (vehicle combustion) is not included in this analysis. Four scenarios were developed for the forest residue pathway and six for the whole tree pathway.

In scenario 1, the change in capacity factors for both pathways was analyzed. The pathways were analyzed for two sets of capacity factors: set one at 0.7 for year 1, 0.8 for year 2, 0.95 from year 3 onwards and set two at 0.65 for year 1, 0.7 for year 2, 0.75 from year 3 onwards. Life cycle energy and emissions increased with the increased capacity factors for both pathways, and, in the forest residue pathway, both increase significantly. As an example, GHG emissions increased around 9% over the base scenario in the forest residue pathway with the increased capacity factors (see Table 8). Scenario 2 demonstrates the effects of a 10% increase and decrease in biomass yield. When the yield increases, life cycle energy consumption and emissions drop for both pathways, and when yield decreases, energy consumption and emissions increase. But the changes are insignificant and are within ±1%. Scenario 3 looks at the effects of a 10% increase and a 10% decrease in biomass moisture content for both pathways. The impact is small and is within ±1%. In scenario 4, we analyzed life cycle emission and energy consumption impacts by changing the capacity by ±10%. Overall energy consumption and emissions increase with increased capacity, but the energy consumption per unit output (per tonne of OME produced) decreases as the capacity increases. For the whole tree pathway, a fifth scenario was developed considering silviculture, which involves the application of fertilizer and pesticides and considers machinery fuel consumption. Energy consumption and emissions increases were negligible. Scenario 6 demonstrates the

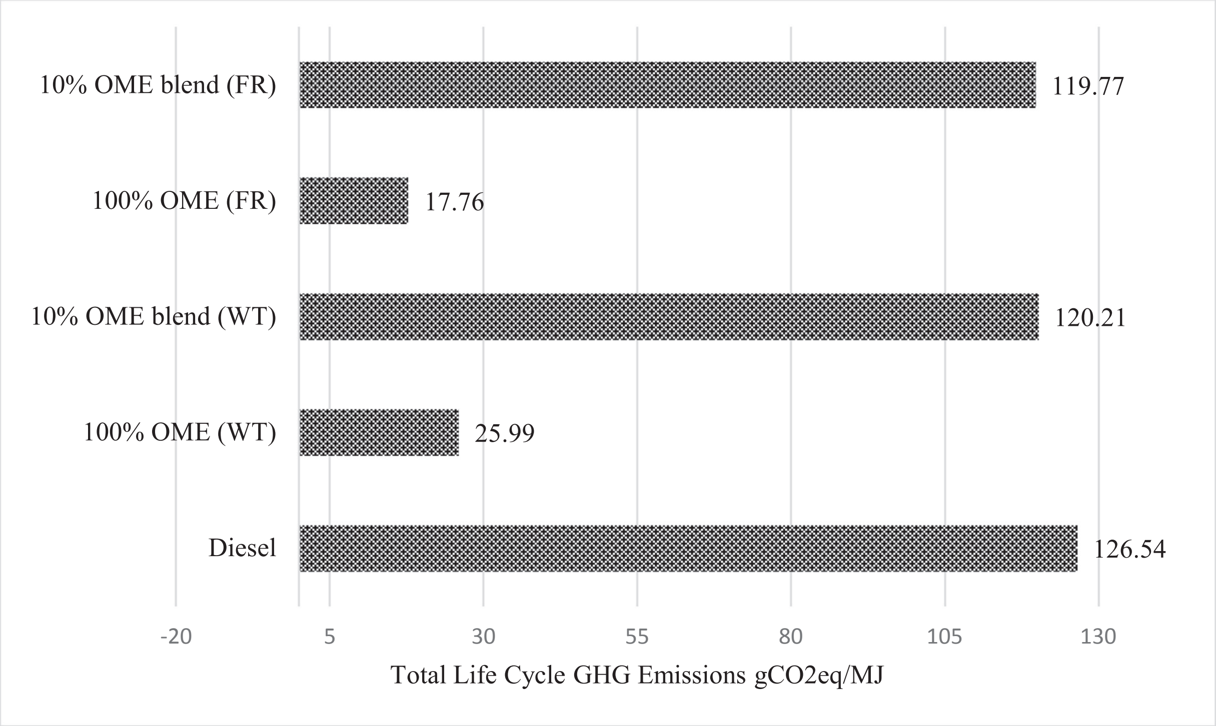


Fig. 6. OME and OME blends from whole tree and forest residue pathways' GHG emissions compared with conventional diesel.

Table 7
Upstream emissions, combustion emissions, total life cycle GHG emissions, total life cycle soot emissions, and reductions in GHG and soot emissions compared to diesel for OME and OME blends with diesel.

Fuels	Upstream emissions g CO_2eq/MJ	Combustion emissions g CO_2eq/MJ	Accountable combustion emissions g CO_2eq/MJ	Total life cycle GHG emissions g CO_2eq/MJ	Reductions compared to diesel (%)	Life cycle soot emission g/MJ	Reductions compared to diesel (%)
Diesel	34.98	91.55	91.55	126.54	N/A	0.0101	N/A
100% OME (a)[c]	25.99	89.55	0	25.99	79.5	0.0011	89
10% OME blend (a)	33.65	91.44	86.56	120.21	5	0.0071	30
100% OME (b)[c]	17.76	89.55	0	17.76	86	0.0011	89
10% OME blend (b)	33.21	91.44	86.56	119.77	5.35	0.0071	30

[c] (a) denotes OME produced from whole tree biomass and (b) denotes OME produced from forest residues.

Table 8
Sensitivity analysis and results.

	Scenario	Energy Use	GHG Emissions	ARP Emissions	GOP Emissions	% Change from Base Case			
		GJ/MJ	g CO_2eq/MJ	g SO_2eq/MJ	g (NOx + VOC)/MJ	Energy Use	GHG Emission	ARP Emission	GOP Emission
FR[d]	1a[d]	1.39	24.52	0.09	0.14	−2.00	−9.37	−10.36	−10.18
	1b[d]	1.33	20.17	0.07	0.11	2.14	10.04	11.09	10.90
WT[d]	1a	1.76	89.92	0.27	0.37	−2.31	−3.54	−4.78	−5.50
	1b	1.68	83.51	0.25	0.33	2.50	3.84	5.17	5.95
FR	2a	1.36	22.31	0.08	0.13	0.11	0.52	0.59	0.56
	2b	1.36	22.56	0.08	0.13	−0.13	−0.61	−0.69	−0.65
WT	2a	1.72	86.83	0.26	0.35	0.00	0.01	0.01	0.01
	2b	0.00	86.85	0.26	0.35	−0.01	−0.01	−0.01	−0.01
FR	3a	1.36	22.32	0.08	0.13	0.10	0.47	0.53	0.50
	3b	1.36	22.52	0.08	0.01	−0.10	−0.45	−0.52	−0.49
WT	3a	1.72	86.83	0.26	0.35	0.01	0.01	0.01	0.01
	3b	1.72	86.85	0.26	0.35	0.00	−0.01	−0.01	−0.01
FR	4a	1.38	24.38	0.09	0.14	−1.87	−8.74	−9.66	−9.49
	4b	1.33	20.48	0.07	0.12	1.85	8.66	9.56	9.40
WT	4a	1.76	89.71	0.27	0.36	−2.15	−3.31	−4.46	−5.13
	4b	1.69	83.97	0.25	0.33	2.15	3.31	4.46	5.13
WT	5	1.72	86.87	0.26	0.35	−0.03	−0.04	−0.05	−0.06
WT	6	1.49	32.81	0.12	0.19	4	33	32	24

The negative sign denotes an increase from the base case and the positive sign denotes a decrease from the base case.

[d] *a* corresponds to a positive change of parameters, *b* corresponds to a negative change of parameters, FR = forest residue pathway and WT = whole tree pathway.

impact of excluding road construction operations in the whole tree pathway. Road construction is assumed to be an emissions-intensive operation in the whole tree pathway. We found that the energy consumption and life cycle emissions dropped significantly compared to the base scenario. The GHG emissions also dropped considerably, by around 33% compared to base scenario, and the other two emissions, ARP and GOP, dropped to 32% and 24% of the base scenario, respectively. Life cycle energy consumption was reduced by 4% from the base scenario (Table 8).

5. Conclusion

This study determined the overall life cycle emissions of OME derived from two different types of forest biomass, whole tree and forest residue, and used as a diesel additive. The life cycle GHG emissions of OME from the whole tree and forest residue pathways are 27 g CO_2eq/MJ and 18 g CO_2eq/MJ, respectively. The results show that a 10% OME blend with diesel reduces GHG and soot emissions by 20–21% and 30%, respectively, compared to 100% diesel. Based on these results, it is obvious that OME, when used as a diesel additive, can decrease GHG emissions significantly compared to conventional diesel. This model can be used to design an optimal process for maximizing OME production and minimizing energy consumption and GHG emissions. The model can also be used to determine the optimum fuel mix (OME-diesel blend) contributing the lowest GHG emissions. We recommend for further studies that the model be extended to include other feedstocks such as agricultural residues, wood waste, or fossil fuels to produce OME and other modes of biomass transportation such as bales, pellets, etc. The results of this study will be of great interest to policy makers, petroleum-based fuel producers, and biofuel companies on the environmental impacts of blending OME with diesel fuels.

Acknowledgements

The authors would like to acknowledge the partners in the Helmholtz-Alberta Initiative, the Helmholtz Association (AE10GREA18), and the University of Alberta, whose financial support has made this research possible. Also the authors would like to acknowledge the researchers of KIT (Karlsruhe Institute of Technology) for their help in providing experimental data. Astrid Blodgett is acknowledged for editorial assistance.

References

Agbor, E., Oyedun, A.O., Zhang, X., Kumar, A., 2016. Integrated techno-economic and environmental assessments of sixty scenarios for co-firing biomass with coal and natural gas. Appl. Energ 169, 433–449.

Alberta Energy, 1985. Alberta Phase 3 Forest Inventory - an Overview. Alberta Energy and Natural Resources. Available from: https://archive.org/details/albertaphase3for00albe. (Accessed 20 October 2016).

Beer, T., Grant, T., 2007. Life-cycle analysis of emissions from fuel ethanol and blends in Australian heavy and light vehicles. J. Clean. Prod. 15, 833–837.

Beer, T., Grant, T., Williams, D., Watson, H., 2002. Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles. Atmos. Environ. 36, 753–763.

Beer, T., Olaru, D., Van der Schoot, M., Grant, T., Keating, B., Hatfield Dodds, S., Smith, C., Azzi, M., Potterton, P., Mitchell, D., 2003. Appropriateness of a 350 Million Litre Biofuels Target: Report to the Australian Government Department of Industry, Tourism and Resources. CSIRO, ABARE, BTRE, Canberra.

Bond, T.C., Doherty, S.J., Fahey, D., Forster, P., Berntsen, T., DeAngelo, B., Flanner, M., Ghan, S., Kärcher, B., Koch, D., 2013. Bounding the role of black carbon in the climate system: a scientific assessment. J. G. R. Atmos. 118, 5380–5552.

Burger, J., Siegert, M., Ströfer, E., Hasse, H., 2010. Poly (oxymethylene) dimethyl ethers as components of tailored diesel fuel: properties, synthesis and purification concepts. Fuel 89, 3315–3319.

Desrochers, L., Puttock, D., Ryans, M., 1993. The economics of chipping logging residues at roadside: a study of three systems. Biomass Bioenerg. 5 (6), 401–411.

Elsayed, M., Mortimer, N., 2001. Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates. Harwell Laboratory, Energy Technology Support Unit. Report No: ESTU B/U1/00644/REP and DTI/Pub URN 01/1342.

Environment Canada, 2013. National Inventory Report: Greenhouse Gas Sources and Sinks in Canada Part 1. Canada's 2013 UNFCCC Submission, pp. 171–197.

EPA, 2014. Climate Change Indicators in the United States: Global Greenhouse Gas Emissions. United States Environmental Protection Agency. Available from: https://www3.epa.gov/climatechange/pdfs/print_global-ghg-emissions-2014.pdf. (Accessed 15 June 2016).

Garg, A., Vishwanathan, S., Avashia, V., 2013. Life cycle greenhouse gas emission assessment of major petroleum oil products for transport and household sectors in India. Energy Policy 58, 38–48.

Gerdes, K., Skone, T., 2009. An Evaluation of the Extraction, Transport and Refining of Imported Crude Oils and the Impact on Life Cycle Greenhouse Gas Emissions. National Energy Technology Laboratory. Report No: DOE/NETL-2009/1362. Available from: http://www.netl.doe.gov/energy analyses/pubs/PetrRefGHGEmiss_ImportSourceSpecific1.pdf. (Accessed 20 April 2016).

Government of Canada, 2016. Forestry: Region of Western Canada and the Territories: 2014-2016. Available from: http://www.edsc.gc.ca/img/edsc-esdc/jobbank/SectoralProfiles/WT/2A71-RPT-SectProf_WT_Forestry_EN–GEN-20150827-VF-MR.pdf. (Accessed 21 October 2016).

Han, H.S., Renzie, C., 2001. Snip & Skid: Partial Cut Logging to Control Mountain Pine Beetle Infestations in British Columbia. University of Northern British Columbia, Prince George, BC. Available from: https://www.researchgate.net/profile/Han_Sup_Han/publication/228732211_Snip_skid_partial_cut_logging_to_control_mountain_pine_beetle_infestations_in_British_Columbia/links/568c091508ae71d5cd04a974.pdf. (Accessed 5 April 2017).

Hartmann, D., Kaltschmitt, M., 1999. Electricity generation from solid biomass via co-combustion with coal: energy and emission balances from a German case study. Biomass Bioenerg. 16, 397–406.

Kabir, M.R., Kumar, A., 2011. Development of net energy ratio and emission factor for biohydrogen production pathways. Bioresour. Technol. 102, 8972–8985.

Kabir, M.R., Kumar, A., 2012. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. Bioresour. Technol. 124, 394–405.

Kajaste, R., 2014. Chemicals from biomass–managing greenhouse gas emissions in biorefinery production chains–a review. J. Clean. Prod. 75, 1–10.

Kumar, A., Cameron, J.B., Flynn, P.C., 2003. Biomass power cost and optimum plant size in western Canada. Biomass Bioenerg. 24, 445–464.

Liu, X., Saydah, B., Eranki, P., Colosi, L.M., Mitchell, B.G., Rhodes, J., Clarens, A.F., 2013. Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction. Bioresour. Technol. 148, 163–171.

Liu, Z., Peng, W., Motahari-Nezhad, M., Shahraki, S., Beheshti, M., 2016. Circulating fluidized bed gasification of biomass for flexible end-use of syngas: a micro and nano scale study for production of bio-methanol. J. Clean. Prod. 129, 249–255.

Löfvenberg, U., 2010. The BEST Experiences with Low Blends in Diesel and Petrol Fuels. Integrated Project (Project No: TREN/05/FP6EN/S07.53807/019854) for BEST (BioEthanol for Sustainable Transport) Deliverable No: D3.15. Available from: http://www.stockholm.se/best-europe.

MacDonald, A.J., 2006. Estimated Costs for Harvesting, Comminuting, and Transporting Beetle-killed Pine in the Quesnel/Nazko Area of Central British Columbia. FERIC Advantage Report, vol. 17, number 16. Forest Engineering Research Institute of Canada (FERIC), Vancouver, BC.

Mahbub, N., Kumar, A., 2014. Co-product use of ethanol produced from wheat grain in Alberta. In: Presented at the 64th Canadian Chemical Engineering Conference, Niagara Falls, Ontario, Canada. http://abstracts.csche2015.ca/00000394.htm.

Mann, M.K., Spath, P.L., 1997. Life Cycle Assessment of a Biomass Gasification Combined-cycle Power System. National Renewable Energy Lab, Golden, CO (US). Report No: 23076. Available from: http://www.nrel.gov/docs/legosti/fy98/23076.pdf.

Mann, M., Spath, P., 2001. A life cycle assessment of biomass cofiring in a coal-fired power plant. Clean. Technol. Environ. 3 (2), 81–91.

Matzen, M., Demirel, Y., 2016. Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: alternative fuels production and life-cycle assessment. J. Clean. Prod. 139, 1068–1077.

Moore, F.T., 1959. Economies of scale: some statistical evidence. Q. J. Econ. 232–245.

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nguyen, T.L.T., Hermansen, J.E., Nielsen, R.G., 2013. Environmental assessment of gasification technology for biomass conversion to energy in comparison with other alternatives: the case of wheat straw. J. Clean. Prod. 53, 138–148.

Ontario Ministry of Natural Resources, 1994. Reasons for Decision and Decision: Class Environmental Assessment by the Ministry of Natural Resources for Timber Management on Crown Lands in Ontario. Environmental Assessment Board: Ontario Ministry of Natural Resources. Available from: http://www.web2.mnr.gov.on.ca/mnr/forests/timberea/decision_pdfs/intro.pdf. (Accessed 26 July 2016).

Overend, R., 1982. The average haul distance and transportation work factors for biomass delivered to a central plant. Biomass 2, 75–79.

Pellegrini, L., Marchionna, M., Patrini, R., Beatrice, C., Giacomo, N.D., Guido, C., 2012. Combustion Behaviour and Emission Performance of Neat and Blended Polyoxymethylene Dimethyl Ethers in a Light-duty Diesel Engine. SAE Technical Paper No: 2012-01-1053.

Pellegrini, L., Marchionna, M., Patrini, R., Salvatore, F., 2013. Emission Performance of Neat and Blended Polyoxymethylene Dimethyl Ethers in an Old Light-duty Diesel Car. SAE Technical Paper No: 2013-01-1035.

Pellegrini, L., Patrini, R., Marchionna, M., 2014. Effect of POMDME Blend on PAH Emissions and Particulate Size Distribution from an In-use Light-duty Diesel Engine. SAE Technical Paper No: 2014-01-1951.

Perera, E., Sanford, T., 2011. Climate Change and Your Health. Rising Temperatures and Worsening Ozone Pollution. The Union of Concerned Scientists. Available from: http://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/climate-change-and-ozone-pollution.pdf. (Accessed 30 August 2016).

Pulkki, R., 1997. Cut-to-length, tree-length or full tree harvesting. Cent. Woodl. 1 (3), 22–27.

Rahman, M.M., Canter, C., Kumar, A., 2015. Well-to-wheel life cycle assessment of transportation fuels derived from different North American conventional crudes. Appl. Energy 156, 159–173.

Riaz, A., Zahedi, G., Klemeš, J.J., 2013. A review of cleaner production methods for the manufacture of methanol. J. Clean. Prod. 57, 19–37.

Row, J., Mohareb, E., 2014. Energy Efficiency Potential in Alberta. Technical Report. Alberta Energy Efficiency Alliance. Available from: http://www.aeea.ca/pdf/ee-potential-in-ab.pdf. (Accessed 20 October 2016).

Sarkar, S., Kumar, A., 2010a. Biohydrogen production from forest and agricultural residues for upgrading of bitumen from oil sands. Energy 35, 582–591.

Sarkar, S., Kumar, A., 2010b. Large-scale biohydrogen production from bio-oil. Bioresour. Technol. 101, 7350–7361.

Shahrukh, H., Oyedun, A.O., Kumar, A., Ghiasi, B., Kumar, L., Sokhansanj, S., 2015. Net energy ratio for the production of steam pretreated biomass-based pellets. Biomass Bioenerg. 80, 286–297.

Shahrukh, H., Oyedun, A.O., Kumar, A., Ghiasi, B., Kumar, L., Sokhansanj, S., 2016a. Comparative net energy ratio analysis of pellet produced from steam pretreated biomass from agricultural residues and energy crops. Biomass Bioenerg. 90, 50–59.

Shahrukh, H., Oyedun, A.O., Kumar, A., Ghiasi, B., Kumar, L., Sokhansanj, S., 2016b. Techno-economic assessment of pellets produced from steam pretreated biomass feedstock. Biomass Bioenerg. 87, 131–143.

Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B., Jechura, J., 2005. Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-heated Gasifier. National Renewable Energy Laboratory, Golden, CO. Report No: NREL/TP-510–37408. Available from: http://www.nrel.gov/docs/fy05osti/37408.pdf.

Spath, P.L., Mann, M.K., 2000. Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming. National Renewable Energy Laboratory, Golden, CO. Report No: NREL/TP-570–27637. Available from: http://pordlabs.ucsd.edu/sgille/mae124_s06/27637.pdf.

Spitzley, D.V., Keoleian, G.A., 2004. Life Cycle Environmental and Economic Assessment of Willow Biomass Electricity: a Comparison with Other Renewable and Non-renewable Sources. Center for Sustainable Systems, University of Michigan, Ann Arbor, MI. Available from: http://css.snre.umich.edu/publication/life-cycle-environmental-and-economic-assessment-willow-biomass-electricity-comparison.

Stripple, H., 2001. Life Cycle Assesment of Road: a Pilot Study for Inventory Analysis. IVL Swedish Environmental Research Institute, Stockholm, Sweden.

Sultana, A., Kumar, A., 2011. Development of energy and emission parameters for densified form of lignocellulosic biomass. Energy 36, 2716–2732.

Thakur, A., Canter, C.E., Kumar, A., 2014. Life-cycle energy and emission analysis of power generation from forest biomass. Appl. Energ 128, 246–253.

Van-Dal, É.S., Bouallou, C., 2013. Design and simulation of a methanol production plant from CO2 hydrogenation. J. Clean. Prod. 57, 38–45.

Van den Broek, R., Faaij, A., Van Wijk, A., 1995. Biomass Combustion Power Generation Technologies. Biomass Combustion Power Generation Technologies: Background Report 41 for the EU Joule 2+ Project: Energy from Biomass: an Assessment of Two Promising Systems for Energy Production (NWS-95029). Netherlands.

Wihersaari, M., 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass Bioenerg. 28, 435–443.

Winkler, N., 1998. A Manual for the Planning, Design and Construction of Forest

Roads in Steep Terrain. Food and Agriculture Organization of the United Nations, Forest Harvesting Case Study 10. Available from: http://www.fao.org/3/a-w8297e/index.html. (Accessed 30 August 2016).

Zhang, X., Kumar, A., Arnold, U., Sauer, J., 2014. Biomass-derived oxymethylene ethers as diesel additives: a thermodynamic analysis. Energy Procedia 61, 1921–1924.

Zhang, X., Oyedun, A.O., Kumar, A., Oestreich, D., Arnold, U., Sauer, J., 2016. An optimized process design for oxymethylene ether production from woody-biomass-derived syngas. Biomass Bioenerg. 90, 7–14.

Zhang, Y., McKechnie, J., Cormier, D., Lyng, R., Mabee, W., Ogino, A., Maclean, H.L., 2009. Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. Environ. Sci. Technol. 44, 538–544.