Life Cycle Assessment of Renewable Diesel Production from Lignocellulosic Biomass

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Abstract

Purpose Governments around the world encourage the use of biofuels through fuel standard policies that require the addition of renewable diesel in diesel fuel from fossil fuels. Environmental impact studies of the conversion of biomass to renewable diesel have been conducted, and life cycle assessments (LCA) of the conversion of lignocellulosic biomass to hydrogenation-derived renewable diesel (HDRD) are limited, especially for countries with cold climates like Canada.

Methods In this study, an LCA was conducted on converting lignocellulosic biomass to HDRD by estimating the well-to-wheel greenhouse gas (GHG) emissions and fossil fuel energy input of the production of biomass and its conversion to HDRD. The approach to conduct this LCA includes defining the goal and scope, compiling a life cycle inventory, conducting a life cycle impact assessment, and executing a life cycle interpretation. All GHG emissions and fossil fuel energy inputs were based on a fast pyrolysis plant capacity of 2000 dry tonnes biomass/day. A functional unit of 1 MJ of HDRD produced was adopted as a common unit for data inputs of the life cycle inventory. To interpret the results, a sensitivity analysis was performed to measure the impact of variables involved, and an uncertainty analysis was performed to assess the confidence of the results.

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Results and discussion The GHG emissions of three feedstocks studied – whole tree (*i*.e., chips from cutting the whole tree), forest residues (i.e., chips from branches and tops generated from logging operations), and agricultural residues (i.e., straw from wheat and barley) – range from 35.4-42.3 $gCO_{2,eq}$/MJ of HDRD (i.e., lowest for agricultural residue- and highest for forest residue-based HDRD); this is 53.4-61.1% lower than fossil-based diesel. The net energy ratios range from 1.55-1.90 MJ/MJ (i.e., lowest for forest residue- and highest for agricultural residue-based HDRD) for HDRD production. The difference in results among feedstocks is due to differing energy requirements to harvest and pre-treat biomass. The energy-intensive hydroprocessing stage is responsible for most of the GHG emissions produced for the entire conversion pathway.

Conclusions Comparing feedstocks showed the significance of the efficiency in the equipment used and the physical properties of biomass in the production of HDRD. The overall results show the importance of efficiency at the hydroprocessing stage. These findings indicate significant GHG mitigation benefits for the oil refining industry using available lignocellulosic biomass to produce HDRD for transportation fuel.

Keywords: Life cycle assessment · Renewable diesel · Lignocellulosic biomass · Greenhouse gas · Fast pyrolysis · Bio-oil · Hydrogenation-derived

1 Introduction

Fossil fuel combustion has led to an increase of carbon dioxide to a concentration of 385 ppm, causing global warming (IPCC 2007; Hansen et al. 2008). Global warming issues caused by greenhouse gas (GHG) emissions from fossil fuels can be mitigated through the use of biofuels. Biofuels are considered to be nearly carbon-neutral as the carbon generated from the combustion of biofuels is originally derived from the carbon dioxide (CO_2) in the atmosphere when a plant absorbs CO_2 during photosynthesis (Raymer 2006). This biofuel carbon neutral idea has been challenged by some researchers who believe that there is an amount difference between carbon sequestration from the biomass growing stage and carbon emissions from the biomass harvest and use stages. However, using biofuel can still lead to a significant GHG emission reduction with accounting a global warming bio-factor (GWP_{bio}) of 0.08 for a 500-year global warming potential (GWP) or 0.43 for a 100-year GWP (Cherubini et al. 2011). In an effort to promote wise energy use and responsible development, the governments of various countries, such as the United States of America, the United Kingdom, and Canada, have come up with renewable fuel regulations (Environmental Protection Agency 2015; Department for Transport 2007; Environment Canada 2015). Although biofuels are regarded as carbon-neutral, the biofuel production process produces GHG emissions and has other environmental impacts. Biofuels characteristics and environmental impacts vary based on conversion pathways and biomass type, and these variations result in different amounts of energy use and GHG emissions (Larson 2006; Papong et al. 2010).

Lignocellulosic biomass from forests and agricultural land provides a source of biomass for HDRD production sufficient to meet the demand initiated by the various renewable fuel regulations in various jurisdictions (Environmental Protection Agency 2015; Department for Transport 2007; Environment Canada 2015). Apart from energy use, lignocellulosic biomass has been proven to have the potential to achieve environmental benefits by replacing fossil fuel-dependent products when made into products (Helin et al. 2013; Perez-Garcia et al. 2005). Although biodiesel is able to fulfill government regulations, the chemical composition of biodiesel and HDRD is different (Natural Resources Canada 2012). Biodiesel is produced through transesterification and contains straight-chain fatty acid alkyl esters, while HDRD is produced through hydroprocessing and contains components such as alkanes, aromatic compounds, and alkyl side chains (Knothe 2010). These chemical structures of biodiesel and HDRD determine the physical properties of biodiesel and HDRD (Knothe 2010). Due to the chemical composition differences between biodiesel and HDRD, biodiesel has a higher cloud point than HDRD, and this poses a problem for blending with fossil fuel diesel, especially in colder climates (Natural Resources Canada 2012). Furthermore, the cloud point of HDRD can be lowered by altering the isomerization or hydrocracking process to make it ideal for blending with fossil fuel diesel (Natural Resources Canada 2012). Besides the cloud point of fuel, other physical properties, such as cetane number and cold flow properties, make HDRD a more suitable alternative to fossil fuel diesel than biodiesel (Natural Resources Canada 2012). Therefore, we have focussed on HDRD instead of biodiesel due to its more favorable physical properties to allow this study to be applicable to colder climates. Biofuel use is expected to grow further as a means of mitigating GHG emissions (European Biomass Association 2007; Government of Canada 2011), thus it will be important to increase our understanding of the environmental impact of HDRD production from lignocellulosic biomass if HDRD is to help meet the growing demand for biofuels.

Studies based on various technologies currently available have been done on converting biomass to renewable diesel. Papong et al. looked into the net energy ratio (NER) (the ratio of energy output to fossil-fuel energy input) of biodiesel from palm oil; this biodiesel has a NER of 2.5 MJ/MJ, making the production of this biodiesel efficient in terms of energy (Papong et al. 2010). However, that study did not include an environmental impact analysis. Peters et al. simulated the fast pyrolysis and hydro-upgrading processes to convert poplar into HDRD using data specific to Spain (Peters et al. 2015). In their study, both processes showed 54.5% GHG reductions compared to fossil gasoline and diesel (Peters et al. 2015). Peters et al. also mentioned biomass drying as the major energy consumer and direct emissions from pyrolysis and hydroprocessing plants were the main GHG emissions contributors (Peters et al. 2015). Han et al. performed a life cycle analysis on the well-to-wheel process of forest residues and corn stover conversion to gasoline and diesel via pyrolysis and hydroprocessing based on research data specific to the United States of America (Han et al. 2013). In their study, pyrolysis yields from woody biomass range from 50-70% while yields from agricultural residues range from 30-60% (Han et al. 2013). Han et al. also concluded that GHG emissions reductions range from 55-64% when natural gas is used to produce hydrogen for hydroprocessing (Han et al. 2013).

With relatively few LCAs conducted on lignocellulosic biomass conversion to HDRD and no Canada-based research, this paper serves to fill this gap in the literature. The overall objective of this research is to conduct the LCA of HDRD production from lignocellulosic biomass for Canada. The specific objectives are:

- To develop a model to estimate the energy input to produce HDRD from lignocellulosic biomass in Canada.

- To quantify GHG emissions for each stage of lignocellulosic biomass harvesting to delivering produced renewable diesel to consumers.
- To conduct an uncertainty analysis of the results based on the Monte Carlo simulation.
- To assist the oil refining industry and government in making decisions on future implementations of HDRD related to sustainability.

2 Methodology

The LCA conducted in this study followed the four steps given in ISO 14040: a goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation (International Organization for Standardization 2006). The goal and scope of the paper are clearly defined by stating the intended audience as well as the system boundary set for the study. A detailed inventory of GHG emissions and energy inputs for lignocellulosic biomass to HDRD are compiled for the assessment required in the second and third steps of a life cycle assessment. Data inputs from sources that reflect the conditions of Western Canada were used in this study to increase accuracy and flexibility in the computation of the life cycle inventory. Subsequently, global warming potentials were allocated to the respective GHG emissions for an impact assessment before the results were interpreted further; the interpretation is shared in the results and discussion section of the paper.

This study was based on several assumptions. First, the locations of pyrolysis plants and hydroprocessing plants are based on the locations of biomass availability and the current locations of oil and gas processing facilities. Traveling distance is then determined according to these designated locations. Second, it is assumed that soil nutrient content and carbon concentration remain the same following fertilization, reforestation, and cultivation of agricultural crops.

2.1 Goal and scope

The first step of an LCA, goal and scope, states the objective, boundary, and functional unit of the study.

2.1.1 Goal

The LCA model developed in this study, a well-to-wheel approach, helps analyze whether it is more environmentally friendly to use HDRD than its conventional fossil fuel alternatives. With site-specific data and pathways, this model is more precise than LCA models currently available in the public domain. The amount of GHG emissions from the production of HDRD from forest biomass and agricultural residues is estimated (in the model) in order to quantify the feasibility of using the biomass available in Alberta, a province in Western Canada, as feedstock in an effort to mitigate GHG emissions. As part of the LCA, the net energy ratio (NER) is estimated to determine the ratio of energy output to fossil fuel energy input ($\sum E_{out}/\sum E_{in}$). The NER quantifies the effectiveness of energy use in HDRD production from forest biomass and agricultural residues (Kabir & Kumar 2011). The values of GHG emissions and the NER derived in this LCA can then be used as a reference to benefit industry for the commercialization of HDRD plants.

2.1.2 Scope

Emissions and energy use are calculated for the following key stages: (i) logging trees, harvesting forest and agricultural residues, (ii) transportation of whole trees, forest residues, and agricultural residues in the form of chips and bales, (iii) pyrolysis of biomass, (iv) transportation of bio-oil to the hydrotreating plant, distillation, and hydrocracking plant, (v) HDRD production, (vi) transportation of HDRD to the refinery for blending and finally delivery to consumers, and (vii) combustion of HDRD by consumers. Carbon emissions from the combustion of biomass are absorbed during plant growth, rendering the emissions from the combustion of biomass carbon-neutral (Raymer 2006).

2.1.3 System boundary, functional unit, and GHGs

A detailed illustration of the system boundary is provided in Figure 1. The system boundary encompasses the direct inputs of fossil fuel in each stage of HDRD production for the whole life cycle assessment. The indirect inputs (i.e., manufacturing trucks for transporting feedstock and building factories for feedstock conversion) are not considered in the study as these are a small percentage of the overall emissions (Kabir & Kumar 2011). The functional unit, the unit used as the basis for analysis, is a unit of energy (1 MJ) of the renewable diesel produced based on lower heating value. The GHGs considered in terms of their contribution to global warming are CO_2, CH_4, and N_2O, which have global warming potentials (GWP) ($CO_{2,\ \mathrm{equivalent}}$) of 1, 34, and 298, respectively; these figures are based on a 100-year time horizon and adopted by the Intergovernmental Panel on Climate Change (IPCC) and the Alberta Government (IPCC 2013; Alberta Government 2014).

2.1.4 Allocation method

An allocation method is needed to distribute the inputs and outputs of each product in the system and its respective environmental impact (Diego et al. 2012). Energy allocation, an allocation method wherein environmental impacts are allocated based on the energy contents of products formed in the system studied, is used here because HDRD and co-products are energy sources and are used as products for their energy content. Energy allocation is widely used as an allocation method for bioenergy-related LCAs (Cherubini et al. 2011). Furthermore, energy allocation does not change with time as calorific values of products are not dependent on time (Ric et al. 2010). In addition, comparisons between our work and other published energy allocation-based results can be made. Other methods such as displacement and economic allocation are not applicable as, in the first instance, there is no prevalent equivalent product in the market for displacement, and the second applies when economic concerns are the main driver (Diego et al. 2011).

3 Life cycle inventory

This inventory encompasses the necessary direct energy inputs, GHG emissions, and the materials required for all unit operations from the production of biomass to its conversion to HDRD.

3.1 Availability of biomass

The large areas of Alberta covered by forests provide a sufficient amount of trees for a biomass feedstock supply if sustainable forest management practices are carried out. The main harvests in Alberta's forestry industry are coniferous and deciduous trees, and thus this study focuses on these tree types (Government of Alberta 2013). To fully tap the resources of the forest, the entire tree is used for biomass feedstock; this includes the tops and branches, which constitute around 15-25% of the tree biomass (Kumar et al. 2003). The harvest of forest residues such as branches and tree tops contributes about 3.29 million dry tonnes of wood biomass generated predominantly from logging operations (Kabir & Kumar 2011). To increase the energy density of forest residues, the residues can be densified through pyrolysis to bio-oil, before stabilization and hydrocracking, followed by conversion into gasoline and diesel blend components (U.S. Department of Energy 2009).

Pyrolysis plants are assumed to be located in the center of a circular biomass collection area; hence the locations of pyrolysis plants in Alberta depend on the availability of biomass. With respect to whole tree feedstock, regions within Alberta's Land-use Framework where the province's main timber harvesting activities occur are the Lower Peace, Upper Peace, Lower Athabasca, and Upper Athabasca (Alberta Environment and Sustainable Resource Development 2012). Similarly, forest residues are primarily available in the Lower Peace and Upper Athabasca (Alberta Environment and Sustainable Resource Development 2010). Based on statistics available from Alberta Environment and Sustainable Resource Development, the Lower Peace and Upper Athabasca regions are able to meet biomass demand for a 2000 dry tonnes/day capacity pyrolysis plant (Alberta Environment and Sustainable Resource Development 2012; Alberta Environment and Sustainable Resource Development 2010). Therefore, locations of pyrolysis plants for wood chips are assumed to be in the Lower Peace and Upper Athabasca regions.

In Alberta, wheat and barley constitute the bulk of the agricultural harvest (Alberta Agriculture and Rural Development 2012). From 1997 to 2008, the combined average annual yield of wheat, barley, and oats was approximately 12.72 million tonnes/year (Alberta Agriculture and Rural Development 2014). With straw-to-grain ratios of 1.1 for wheat, 0.8 for barley, and 1.1 for oats (Sultana et al. 2010), a large amount of straw can be used as biomass for HDRD production. This straw is normally left in the fields to decompose and in the process releases CO_2 into the atmosphere. A portion of agricultural residues must be left in the fields to prevent soil erosion and some agricultural residues are used for animal feed and bedding. For average grain productions of 6.9 million tonnes/yr, 5.1 million tonnes/yr, and 0.72 million tonnes/yr during the period 1997-2008 for wheat, barley, and oats, respectively, an average straw yield of 2.70 tonnes of straw/ha is available in the field (Alberta Agriculture and Rural Development 2014). With an additional 0.75 tonnes/ha of the residues left in the field to prevent erosion, harvesting equipment capable of harvesting 70% of the residues available in the field, and 0.66 tonnes/ha to be used as feedstock and bedding, 0.517 dry tonnes/ha is available for biomass conversion to HDRD (Sultana et al. 2010).

For a 2000 dry tonnes/day agricultural residue biomass pyrolysis plant, the southeast region of the province (demarcated by Statistics Canada), according to Alberta Agriculture and Rural Development, is able to supply that demand with agricultural straw (Alberta Agriculture and Rural Development 2014; Agriculture Financial Services Corporation 2013). A location in southeast Alberta is assumed for a pyrolysis plant using agricultural straw as feedstock. The collection of agricultural residues is assumed to be done based on a square-shaped collection area of farmland in the middle of which the pyrolysis plant is located. A square collection area is assumed because of the farmland layout and existing roads.

3.2 Biomass harvesting and collection

In whole tree harvesting, operations involved are felling, skidding, and chipping. Whole trees are felled with a harvester at a fuel consumption of 0.67 L of diesel/m^3 of wood before they are skidded by grapple skidder to a roadside chipper over an assumed skidding distance of 150 m at a fuel consumption of 0.75 L of diesel/m^3 of wood (Kabir & Kumar 2011; Kumar et al. 2003). Both harvesting and skidding use ultra-low sulphur diesel (ULSD) and have an energy coefficient of 45.25 MJ/L diesel and a GHG emissions coefficient of 2727 $gCO_{2,eq}$/L (Piringer & Steinberg 2006; Environmental Protection Agency 2014). The roadside chipper chips the trees into chips that are transported to a pyrolysis plant at 3.33 L of diesel/dry tonne (Kabir & Kumar 2011). After the removal of the trees, nitrogen fertilizer is applied to the soil with an energy consumption of 50 MJ/ha to encourage sapling growth and to minimize nitrogen loss in soil (Binkley & Fisher 2012). Productivity and ULSD use in each of these sub-unit operations is calculated to obtain the amount of fossil fuel used and the corresponding GHG emissions. Table 1 shows the input quantities for each sub-unit operation based on a pyrolysis plant with a capacity of 2000 dry tonnes/day. The input quantities of fossil fuel and its corresponding emissions coefficients given in the table can be used to derive the values of GHG emissions ($gCO_{2,eq}$)/functional unit of the sub-unit operations. Similarly, using the energy coefficients, the same input quantities of sub-unit operations can be converted to their corresponding NER values.

Forest residues refer to tops and branches and are considered to be leftovers from cut-to-length logging operations. In Alberta, 80% of harvested trees are skidded to the roadside where they are delimbed and topped (Kumar et al. 2003). These residues are piled at the roadside for burning (Kumar et al. 2003). To make the discarded forest residues usable, the residues are forwarded to a roadside chipper with a fuel consumption of 0.52 L of ULSD/m^3 and chipped with a fuel consumption of 3.93 L of ULSD/dry tonne by the roadside chipper (see Table 2) (Kabir & Kumar 2011). Because forest residues differ from whole trees in terms of size and compactness, the chipping efficiency is lower for forest residues than whole trees. Like whole trees, forest residues are transported in the form of chips to the pyrolysis plant. When forest residues are removed, nitrogen is removed from the soil. As with whole tree feedstock, nitrogen fertilizer is applied to the soil with an energy consumption of 50MJ/ha to return nitrogen to the soil for sapling growth (Binkley & Fisher 2012).

The agricultural residues considered refer to the straw that is available in Alberta. Straw is often left on the fields after grain harvesting. The sub-units involved to obtain straw as biomass begin with raking the straw into windrows that can be baled, with an energy consumption of 0.47 L of ULSD/dry tonne (Kabir & Kumar 2011). The subsequent operations, using an identical grade of diesel, are baling, bale wrapping, stacking, loading, and trucking to a pyrolysis plant for bio-oil production with energy consumptions of 2.9 L diesel/dry tonne, 0.055 L diesel/bale, 0.83 L diesel/dry tonne, and 0.33 L diesel/km, respectively (Kabir & Kumar 2011). Because straw is less dense than wood chips, the truck carrying straw bales will be limited by volume rather than the weight limit of the truck. Because the agricultural residues are not returned to the soil after removal, essential nutrients are added to maintain soil fertility. These are listed in Table 3 along with other input quantities for agricultural residues harvesting.

3.3 Transportation of forest woodchips and agricultural residues to a pyrolysis plant

After whole trees are chipped, the chips are transported by trailer trucks to a pyrolysis plant where they are converted to bio-oil. The collection area for forest biomass is assumed to be circular, with the pyrolysis plant located at the center. Based on this geometry, the average transportation displacement of the biomass collection area is found to be 0.707 r by equating the area of the outer ring (from r to r_{avg}) to the area of the inner circle with the radius r_{avg}, where r is the length of the radius of the circular area and r_{avg} is the average transportation displacement. The actual hauling distance is not a straight road to the pyrolysis plant. The actual distance can be estimated using a tortuosity factor, which is defined as the ratio of the actual distance over displacement. In this assessment, a tortuosity factor of 1.27 is used to account for the non-linear transportation distance (Overend 1982), and a mean transportation distance of 19.5 km is derived. The truck capacity is 17.5 tonnes with an efficiency of 0.33 L of diesel per kilometer. For the return trip, it is assumed that the trucks are empty and therefore the efficiency improves to 0.24 L of diesel per kilometer (Mann & Spath 1997). Road construction for whole tree feedstock is required to transport wood chips to a pyrolysis plant located at an average distance of 19.5 km away. This, however, is not necessary for forest and agricultural residues feedstocks due to the existing roads available from logging and farming operations. Road infrastructure of 6 meters wide for chip transport involves primary and secondary roads; primary roads are used for trailer trucks to transport chips to a pyrolysis plant and the secondary roads are used by skidders and fellers. Secondary roads are significantly shorter than primary roads, and secondary roads do not need to be of the same quality as primary roads due to the slow-moving equipment using secondary roads; therefore, emissions and energy input associated with secondary road construction are negligible. When considering a pyrolysis plant life of 20 years, an estimated 700 km of primary roads are assumed, and these primary roads are constructed with an emission factor of 403,845 kg $CO_{2,eq}$/km and an energy factor of 1731 GJ/km (Kabir & Kumar 2011; Stripple 2001).

Forest residue chips are also transported by trailer trucks. As with whole tree chips, a transportation displacement of 0.707 r and a tortuosity factor of 1.27 is applied to calculate the transportation distance (Overend 1982). If we consider that 15-25% of the whole tree are forest residues – approximately 24.7 dry tonnes/harvested hectare – the forest residues available for collection over a 100-year period is 0.247 dry tonnes/ha (Kumar et al. 2003). A mean transportation distance of 80.3 km for trailer trucks to transport forest residues chips to a 2000 dry tonnes/day pyrolysis plant is derived. Forest residue biomass is scarcer than whole tree biomass; as a result, a longer transportation distance is required for forest residue collection than for whole trees. The truck capacity and fuel economy for the transportation of forest residue chips are identical to those for whole tree chip transportation.

It is assumed that agricultural farmlands are square and that a pyrolysis plant is located in the centre of the square. The transportation distance of agricultural residues is calculated by taking the average distance of every point within a square plot to the center of the plot and multiplying it by a tortuosity factor of 1.27 (Overend 1982). Assuming a yield of 0.517 dry tonnes/ha straw biomass for a square plot of agricultural farmland, we derived an average transportation distance of 53.2 km for bales of agricultural residues to the pyrolysis plant.

3.4 Fast pyrolysis

Fast pyrolysis, the thermal decomposition of biomass in the absence of oxygen, is used to produce bio-oil in the form of vapors, charcoal, and non-condensable gas (Bridgwater et al. 1999). To meet the short residence time of fast pyrolysis, fast pyrolysis requires efficient heat transfer during the conversion of wood biomass to bio-oil; thus, the feedstock must be <6 mm to achieve a surface-to-volume ratio sufficient for efficient heat transfer (U.S. Department of Energy 2009). For whole tree and forest residues, after wood chips are ground to 2-6 mm, they are reduced to less than 10% moisture content by a direct contact dryer using the heat energy from the hot combustion exhaust from the fast pyrolysis combustor before that exhaust is released to the atmosphere. A circulating fluidized bed reactor is then run at 500 °C and atmospheric pressure with a vapor residence time of 1 s to yield 72% bio-oil, 12% gases, and 16% char (Iribarren et al. 2012). Bio-chars are separated by a series of cyclones while the vapor is condensed to recover bio-oil before the vapor is further broken down under the catalytic effects of bio-char and ashes (Bridgwater 2012; Couhert et al. 2009; Bridgwater & Peacocke 2000). To provide heat energy for fast pyrolysis, some bio-char and all the non-condensable gases are combusted. The bio-oil separated from bio-char and gases is delivered to a hydro-processing plant for HDRD production.

Similar to whole tree and forest residues feedstocks, agricultural residue straw must be approximately 3.2 mm for fast pyrolysis; the straw is reduced with a hammer mill (Mani et al. 2004). The straw is dried with the heat from combustion exhaust until its moisture is reduced to 7%. The agricultural residues' fast pyrolysis parameters of 500 ^{o}C operating temperature, atmospheric pressure, and vapor residence time of 1 s, similar to those of whole tree and forest residues, correspond to a yield of 71.6% bio-oil (including water content), 16.4% bio-char, and 12.0% gases (Wright et al. 2010). Using the cyclone separator, bio-oil is separated from the other co-products before its delivery to a hydro-processing plant. For agricultural residues, all char and gases are combusted to provide energy for the fast pyrolysis process. Details of the energy inputs and GHG emissions for the fast pyrolysis process are shown in Table 4 through Table 6.

Process conditions affect the products produced; fast pyrolysis parameters favor the production of bio-oil, which is what we are seeking as an intermediate product (IEA Bioenergy Task 34 2007). However, due to the instability of bio-oil, phase-separation tends to occur both during the pyrolysis process, and during the aging process of bio-oil (U.S. Department of Energy 2012). Given the unstable nature of bio-oil, bio-oil has to be converted to other forms of fuel within 4 weeks to maintain the quality required for HDRD conversion (Wright et al. 2010); thus, we assume that the transportation and storage time of bio-oil is less than 4 weeks.

3.5 Transportation of bio-oil from a pyrolysis plant to an HDRD plant

Bio-oil is transported to an HDRD plant by super-B train truck with a capacity of 60 m^3 (Miller & Kumar 2013). It is assumed that the super-B train trucks are fully loaded with bio-oil when traveling to an HDRD plant and empty on the return trip and that they have a fuel consumption of 0.50 L/km when fully loaded and 0.31 L/km when empty (Miller & Kumar 2013). Due to the availability of oil and gas facilities in the Redwater, Alberta, area, we have assumed an HDRD plant location in Redwater. Based on this assumption, the distances from the pyrolysis plants to the HDRD plant are estimated to be 300 km for whole trees and forest residues and 250 km for agricultural residues.

3.6 Upgrading of bio-oil

Bio-oil is stabilized and converted to HDRD by the removal of oxygen through the hydrodeoxygenation process (U.S. Department of Energy 2009). Bio-oil is hydrotreated at 140 bar and 270 ^{o}C using Co-Mo as a catalyst in the presence of H_2 (Iribarren et al. 2012). This first step of hydrotreating maintains the stability of the bio-oil by exposing it to a mild hydrodeoxygenation process before the second step, which involves higher temperature and pressure (Elliott et al. 2009). With some of the oxygen removed in the form of water, the bio-oil then goes through a second hydrotreating at 140 bar and 350 ^{o}C using Co-Mo as a catalyst in the presence of H_2 to remove the remaining oxygen in the partially deoxygenated oil (Iribarren et al. 2012). After oxygen removal, distillation takes place to separate heavier hydrocarbons for cracking. A second round of distillation then separates gasoline and diesel as products. The hydrogen used in hydrotreating is provided by steam reforming with water as input and energy supplied from natural gas, off-gas, and electricity (Iribarren et al. 2012). All fossil fuel energy inputs for each chemical process are shown in Table 7 through Table 9. These energy inputs include electricity for equipment (i.e., for pumps and compressors) and natural gas for heating.

3.7 Transportation of HDRD

4.2 billion liters of diesel were consumed in Alberta in 2013 (Government of Canada 2014). 76.8% of Albertans reside in urban areas; hence we assume that all of the HDRD produced (approximately 243 million L/year) is below the demand from all urban areas combined (Government of Alberta 2013). Alberta's two main cities are 65 km and 380 km, respectively, from Redwater, the site of the proposed HDRD plant. The average distance to transport HDRD to the two cities is approximately 445 km (round trip). Similar to bio-oil transportation, super B-train trucks would be used for HDRD transportation.

3.8 N_2O emissions and land use change

N_2O is released from the soil after nitrogen fertilizer is applied, contributing to global warming with a global warming potential 298 times greater than CO_2 (IPCC 2013). Nitrogen fertilizer is required to ensure that the sapling growth rate in the boreal forest does not slow down following the loss of nitrogen (Mahendrappa & Salonius 1982), but the corresponding N_2O emissions will also be present from forest lands due to the nitrification and denitrification processes in the soil (IPCC 2006). Although nitrogen can be returned to the soil by atmospheric deposition, only 5% of the nitrogen from the combustion of logging residues can be returned to the forest in the form of NO_x (Borjesson 2000). Therefore, the fertilization of forest soils with nitrogen is still required. Other nutrients can be returned to the forest by returning the wood ash, which contains essential nutrients except nitrogen, thereby both returning nutrients to the soil and making ash disposal unnecessary. Furthermore, wood ash can have a neutralizing effect on the soil by reducing the natural acidity caused by tree growth (Borjesson 2000). It is assumed that forest growth remains unchanged after the removal of whole tree biomass and forest residues as long as nutrients are replaced through wood ash deposition and nitrogen fertilization (Eriksson et al. 2007). In addition, the forests in Alberta are still first generation forests, hence forest companies do not fertilize the forest (Kumar et al. 2003). As shown in Table 1, energy requirements to transport and spread nitrogen fertilizer are 6.4 kJ/kg N/km and 50 MJ/ha (Binkley & Fisher 2012).

The application of nitrogen fertilizer to a field after the field loses nitrogen through the removal of agricultural residues will result in the release of N_2O by nitrification and denitrification in the soil. Nevertheless, to ensure there is no negative impact on future crop yield, fertilization of nitrogen and other nutrients will be carried out. The decrease in crop yield ranges from 0.05-0.15 dry tonnes/ha when there is a net decrease in N content of 1.5-4.5 kg N/tonnes straw harvested (Cherubini et al. 2009). Besides nitrogen, removing agricultural residues from the field removes the carbon that would otherwise be returned to the soil, but the effects of removal are inconclusive because other influential factors affect crop yields simultaneously (Wilhelm et al. 2004; Lal 2005). In this study, we assume that there is no reduction of carbon in the soil over time (Alberta Agriculture and Rural Development 2008).

Land use change can contribute a large amount of GHG emissions. This is because soil carbon content is often high, and it is estimated that soil carbon content reduction has contributed 158 Gtonnes C since 1850 through land use change, compared to 330 Gtonnes C from combustion during the same period (Lal 2008). Therefore, slight changes to carbon concentration can lead to significant changes in GHG emissions. For forest and field, carbon is stored in three types of natural pools: vegetation, litter, and soil. With land use change, the equilibrium of the carbon stored in these pools will change and therefore the carbon concentration in the soil will change over time (Cherubini et al. 2009) with the carbon lost through the emission of CO_2 to the atmosphere (Sultana & Kumar 211). In this study, we do not consider the conversion of existing forest and agricultural land for other land uses, and thus it is assumed that the carbon content of soil does not change due to changes in land use.

4 Results and discussion

A life cycle assessment is sensitive to allocation methods, assumptions, and system boundary. In this study, allocation methods, assumptions, and system boundary are defined and the corresponding GHG emissions and NER of the LCA across three feedstocks are shown in graphs for comparison. Pyrolysis yields vary slightly in the literature depending on the pyrolysis conditions and feedstocks. For example, Peters et al. reported bio-oil yields of 68.8%, while Ringer et al. reported bio-oil yields of 73% (Peters et al. 2015; Ringer et al. 2006). To determine how bio-oil yield affects the results of the LCA, sensitivity analyses are conducted on bio-oil yield along with other factors that might have an impact on the LCA to make this study more comprehensive.

4.1 Base case scenario

The base case for whole tree feedstock, in terms of GHG emissions and energy, is 39.7 $gCO_{2,eq}$/MJ HDRD with an NER of 1.71 MJ/MJ. The corresponding base case results for forest residues are 42.3 $gCO_{2,eq}$/MJ HDRD with an NER of 1.55 MJ/MJ and 35.4 $gCO_{2,eq}$/MJ HDRD with an NER of 1.90 MJ/MJ for agricultural residues. A higher NER likely relates to lower GHG emissions, but N_2O emissions and using more electricity instead of natural gas can shift the relationship between NER and GHG emissions. This study showed that harvesting biomass feedstock from agricultural residues is more efficient than harvesting biomass feedstock from whole tree or forest residues due to the better productivity of the field equipment. The better productivity is likely related to terrain differences and the moisture content of feedstock (refer to Figure 2). Canada's forest industry carries out first cut operations in the forest. Because of the initial high concentration of nutrients in the intact forest, logging operators do not replace nutrients. If it is assumed in this study that forest lands are not fertilized after the harvesting, GHG emissions of whole tree feedstock will be 37.6 $gCO_{2,eq}$/MJ HDRD with an NER of 1.87 MJ/MJ. For forest residues, GHG emissions will be 37.3 $gCO_{2,eq}$/MJ HDRD with an NER of 1.77 MJ/MJ if nutrient return is not carried out. Cherubini et al. (2011) suggested that dynamic models with CO_2 impulse response functions can better estimate the climate impact of CO_2 emissions from the use of biomass, especially for biomass that has a long rotation period. Cherubini et al. (2011) mentioned that the carbon sequestration by biomass occurs over the entire growth period of biomass while emissions from biomass use are almost immediate on use. This global warming saving and impact difference between the biomass growing period and the emission period needs to be addressed. In Western Canada, the forestry industry uses sustainable forestry management practices to manage a continuous process of forest harvesting. The ongoing tree growth in non-harvested areas of the forest reduces the effect of biogenic carbon emissions from a harvest area, thus justifying the assumption of carbon neutrality in this study. With most of the fossil fuel consumption occurring in the hydro-processing stage followed by fast pyrolysis, the GHG emissions factor and NER do not differ much even though the percentage difference in fossil fuel demand for harvesting the three feedstocks differs significantly (refer to Figure 3). When we compare our study's GHG emissions with fossil-based diesel emissions at 90.8 $gCO_{2,eq}$/MJ diesel (Cherubini et al. 2009; Furuholt 1995), the percentage reductions in GHGs for using HDRD in its pure form are 56.3%, 53.4%, and 61.1% for whole tree, forest residues, and agricultural residues, respectively. The reason for GHG emissions savings when using HDRD is that GHG emissions from HDRD combustion are not reflected in Figure 3 as they are accounted for by the absorption of CO_2 during the growth stage of biomass.

4.2 Other scenarios - Sensitivity analysis

As indicated in Table 10, the scenarios in this study focus on how changes in the main contributors to GHG emissions and NER affect the overall results. The base case considered the return of ashes to the harvested soil to minimize nutrient loss and to reduce the need to landfill the ashes. In scenario 1, we investigated the use of trailer trucks on their return journey to send the ashes back to the forest or farm, i.e., transportation resource use was maximized and ash transportation was studied. In scenario 2, we studied the impact of sending ashes to an existing landfill if return of ashes to the soil is not welcomed by stakeholders. The energy input and GHG emissions of ash transportation to the landfill, which is assumed to be 50 km from the pyrolysis plant, are looked into for scenario 2. As with biomass transportation, trucks of the same carrying capacity and fuel economy are used for ash transportation. Because it is assumed in the study that existing landfills will be used, energy and emissions from landfill construction are not considered. The productivity of fast pyrolysis and hydroprocessing greatly affect the GHG emissions and NER. To understand the impact on the emissions and NER, scenarios 3 to 6 were set up to study a 10% increase and decrease in yield. N_2O has a GWP 298 times that of CO_2, and this high GWP can have an impact on the overall GHG emissions of HDRD production. For scenarios 7 and 8 we studied the impact of N_2O emissions factor ranges suggested by the IPCC to understand changes in emissions factor on the total emissions of HDRD production. For scenario 9, we considered forest residues and agricultural residues as by-products to facilitate comparison with studies that treat these residues as by-products or when soil fertilization is not required after residue removal. Bio-oil can replace natural gas to produce hydrogen in the steam reforming process to reduce the reliance on fossil fuel. In scenario 10, the use of bio-oil to produce hydrogen for hydrotreating instead of natural gas was considered. This scenario tested the benefits of HDRD production with reduced fossil fuel dependency by using the intermediate product generated in the production process. Transportation distance can fluctuate depending on the terrain and location of facilities. Scenarios 11 and 12 investigated how sensitive the results are toward changes in transportation distance of ±10%.

In scenario 1, ash sent back to the forest or field by return trailer trucks was investigated. The difference in the GHG emissions and NER between the base case and scenario 1 is negligible for all three feedstocks. This is mainly due to the low energy requirement for the delivery of ashes. In scenario 2, ashes were not returned, and this resulted in a lower GHG emissions and a higher NER. In this scenario, ashes were treated as waste and sent to an existing landfill. Ash spreading over the land contributes more to energy use and GHG emissions than the transportation of ashes to the field. Therefore, whole tree feedstock with a smaller harvest area than the other two feedstocks shows little change in energy use and GHG emissions between the base case, scenario 1, and scenario 2 due to minimal ash spreading over a small harvest area. On the other hand, forest residue and agricultural residue feedstocks, with larger harvest areas than whole tree feedstock, showed more significant differences in energy input and GHG emissions between scenario 2 and the base case.

For scenarios 3-6, sensitivity tests were conducted on product yields. All sub-unit operations are affected by the yields from fast pyrolysis and hydro-processing unit operations. A 10% change in bio-oil and HDRD yields was studied to see its effect on the NER and GHG emissions. Based on the understanding that efficiency is the amount of product output from a unit of input, a change in yield will be analogous to a change in the efficiency of pyrolysis and hydro-processing. All energy inputs are based on 1 MJ of HDRD produced; as a result, a drop in bio-oil output during pyrolysis or a drop in HDRD output in hydroprocessing causes more energy input and GHG emissions in the harvesting and transportation stages to obtain 1 MJ of HDRD as a final product. Scenarios 3-6 support the use of fast pyrolysis over other forms of bio-oil production methods to obtain the most bio-oil for HDRD production, for higher bio-oil yield translates to lower energy inputs and GHG emissions in the harvesting and transportation stages.

Scenarios 7-8 show the limits of N_2O emissions factors according to the IPCC-stated uncertainty range of 0.003 to 0.03 (IPCC 2006). Emissions from N_2O affect overall GHG emissions values because N_2O's GWP is 298 times that of CO_2, and nitrogen replacement is considered in all our feedstocks. With more nitrogen fertilizer used for agricultural residues than the other two feedstocks studied, agricultural residues are most sensitive to N_2O emissions, ranging from -2.7% to 7.7% followed by whole tree and forest residues, ranging from -1.9% to 5.4% and -1.8% to 5.0%, respectively. Changes in emissions factors of N_2O, however, do not have any impact on energy input or NER across all feedstocks.

In scenario 9, residues were treated as a by-product, which means that GHG emissions and energy required for fertilization are counted towards the harvesting of logs and grains but not of residues. Without the need for fertilization, the amount of GHG emissions drops significantly and falls below those of whole tree feedstock, especially those of agricultural residues. Compared to the base case, a lack of fertilization resulted in an 18.2% increase in the NER and a 14.1% reduction in GHG emissions for agricultural residues, and a 14.3% increase in the NER and an 11.7% reduction in GHG emissions for forest residues.

Scenario 10 suggested the use of bio-oil to produce hydrogen instead of using a non-renewable fuel, natural gas. Figure 4 shows that for all feedstocks, this scenario led to higher GHG emissions than the base case; on the other hand, the NER (see Figure 5) showed a mix of results, with whole tree achieving the same NER as the base case while forest residues experienced a lower NER in scenario 10 and agricultural residues' NER increasing from 1.90 to 1.94 MJ/MJ. There are several factors affecting the NER and GHG emissions in scenario 10. First, the use of bio-oil to produce hydrogen reduces the emissions and energy input from natural gas, but the amount of bio-oil available for HDRD conversion is reduced, leading to a net reduction of HDRD produced. This reduction in yield increases the GHG emissions per unit MJ of HDRD and also decreases the NER, given that NER is measured by the energy content of HDRD produced per unit of non-renewable energy input. Second, with the reduction in yield, there is an increase in electrical energy used per unit MJ of HDRD produced when natural gas is not used for the steam reformer. This increase in electrical energy use is also amplified by the high emissions associated with electricity generation in Alberta due to fossil fuel-based electricity production. The breakdown of the GHG emissions and energy input of the unit operations of the three feedstocks is shown in Table 11 and Table 12.

The difference between scenarios 11 and 12 is barely noticeable. This shows that transportation distance does not have much impact on GHG emissions and NER compared to other factors. The changes in GHG emissions are 0.8%, 1%, and 0.5% for whole tree, forest residues, and agricultural residues, respectively. For the NER, percentage changes of 0.8%, 1%, and 0.4% are observed for whole tree, forest residues, and agricultural residues, respectively. The low impact on the GHG emissions and NER is because much higher GHG emissions and fossil energy input are observed in fast pyrolysis and hydroprocessing, thus reducing the impact caused by transportation distance.

4.3 Discussion of results

The values of the base case scenario for the three feedstocks range from 35.4 to 42.3 $gCO_{2,eq}$/MJ HDRD and 1.55 to 1.90 MJ/MJ for GHG emissions and NER, respectively. Hsu (Hsu 2012) arrived at figures of 39 $gCO_{2,eq}$/MJ HDRD and 1.56 MJ/MJ NER. Hsu's NER and GHG values are very close to the values found in this study. From the use of different feedstocks, we know that different varieties of biomass feedstock will result in different sub-unit operations such as harvesting methods and transportation distance. The chemical composition of biomass can also change the yield of the pyrolysis and hydroprocessing. Any minor differences in GHG emissions between Hsu's results and the forest residues studied in this paper can be attributed to the differences in the emissions of sub-unit operations and the assumptions taken.

HDRD can be produced with other feedstocks. Miller and Kumar reported GHG emissions of 38 and 48 $gCO_{2,eq}$/MJ HDRD and NER values of 2.0 and 1.7 MJ/MJ for camelina and canola feedstocks, respectively (Miller & Kumar 2013). Comparing the NER values from their study with those from this study shows that lignocellulosic biomass requires approximately 0.03 to 0.15 MJ of fossil fuel input more than camelina and canola for every 1 MJ of HDRD produced. However, the emissions amount in the HDRD conversion pathways of camelina, canola, and lignocellulosic biomass is relatively similar. One of the reasons for differences in GHG emissions and energy input is the use of mass allocation, rather than energy allocation as used in this study. In Miller and Kumar's work, the allocation of GHG emissions and energy input to oilseed meal reduced the emissions and energy input allocated to HDRD. In addition, the oil extraction method studied by Miller and Kumar is not as energy intensive as pyrolysis, hence the difference in energy requirement. Moreover, feedstock type determines the calorific value and harvesting requirements and thus has an impact on the feasibility of producing HDRD from it. Compared to the feedstock from canola and camelina, the feedstocks chosen for this study are suitable for efficient HDRD conversion.

Some researchers have studied other types of renewable fuel such as biodiesel. Cherubini et al. reported a GHG emission range of 32.6 to 57.1 $gCO_{2,eq}$/MJ HDRD and an NER of 1.4 to 2.5 MJ/MJ for biodiesel derived from rapeseed, soy, and sunflower (Cherubini et al. 2009). The results from of lignocellulosic biomass conversion to HDRD fall into the NER range of biodiesel production, making HDRD conversion from the three feedstocks studied favorable when compared to biodiesel in terms of net energy production. GHG emissions from the lignocellulosic biomass conversion pathway to HDRD, consisting of fast pyrolysis, hydrotreating, and hydrocracking, also lie in the lower half of the range found by Cherubini and his colleagues, suggesting that the environmental sustainability of HDRD is relatively similar to biodiesel. A later discussion by Cherubini et al. (2011) suggested that a 0.08 GWP_{bio} factor needs to be accounted for with a 500-year global warming potential time horizon using the full impulse response function (FIRF) method, which considers all the carbon components and biogeochemical sinks in the ecosystem. Based on a biodiesel combustion emission factor of 68.66 kg CO2/GJ (Ministry of Environment 2014), adding a global warming bio-factor will result in a 5.5 g CO2/MJ increase in the calculated final emissions. Similarly, a 100-year GWP time horizon gives a 0.43 GWP_{bio} factor, which will lead to a 29.5 g CO2/MJ increase in final emissions.

4.4 Uncertainty analysis

Uncertainty analyses are calculated by assigning an uncertainty value for each input followed by a Monte Carlo simulation with 10 million iterations to obtain an uncertainty on the GHG emissions and NER. An uncertainty analysis was conducted for the three feedstocks considered in this study. A framework by Huijbregts et al. was adopted to classify data and assign adequate uncertainty (Huijbregts et al. 2001). The assigned uncertainty for harvesting, fertilizing, and collection is 5%, while the transportation distance, bio-oil yield, and HDRD yield are assigned an uncertainty of 10% due to the possible ranges suggested by other studies and their impact on the results (Han et al. 2013; Mohan et al. 2006; Choudhary & Phillips 2011). Without sufficient information to determine the distribution of probability of each input, a triangular distribution is assumed. The Monte Carlo simulation results are given in Figure 6 for the GHG emissions and Figure 7 for the NER.

The uncertainty analysis shows that the largest value of the 95th percentile across all feedstocks for GHG emissions is below 45 $gCO_{2,eq}$/MJ HDRD (see Table 13), indicating that it is much more environmentally friendly to use HDRD than fossil fuels. For the NER, the spread across all feedstocks is well above 1, suggesting that the biomass conversion process is viable in producing more output energy than the input energy required to produce HDRD. By taking the range from the 10th to the 90th percentiles, it is found that the percentage deviations for whole tree GHG emissions range from -3.7% to +3.9% and for forest residues and agricultural residues from -4.0% to +4.5% and -15.0% to +19.0%, respectively. For the NER, similar observations are noticed for the whole tree case – -3.7% to +3.9% – while those for forest residues and agricultural residues range from -4.5% to +4.4% and -13.8% to +14.6%, respectively. The larger variation is found for agricultural residues because they have more input variables than the other two feedstocks.

5 Conclusions

With limited environmental impact assessments on biomass to HDRD conversion to assist industry and government in future commercialization of HDRD production plants in Alberta, a life cycle assessment was conducted on the lignocellulosic biomass available in Canada for conversion to HDRD. The results show that GHG emissions can be 39-47% of those of petroleum diesel alternatives, indicating that renewable diesel can mitigate GHG emissions to a certain extent. In terms of energy production, the NER for all three feedstocks is at least 1.55 MJ/MJ, proving that HDRD is more sustainable than fossil fuel diesel.

The major energy consumers and GHG emitters from the HDRD conversion process unit operations are fast pyrolysis and hydroprocessing. The energy-intensive processes of producing hydrogen used in hydroprocessing and drying feedstock for pyrolysis contribute to the high energy consumption and GHG emissions of the entire conversion pathway from biomass to HDRD. HDRD can be made a more attractive alternative to fossil fuel dependency if hydroprocessing efficiency is improved.

When deciding which feedstock to use in order to reduce emissions and energy consumption, one should note that emissions can be reduced considerably during harvesting, and harvesting greatly depends on the availability of biomass within a unit area. Among the three feedstocks considered in this study, whole tree biomass has the advantage when it comes to biomass collection due to its shorter transportation distance. However, agricultural feedstock has a higher harvesting efficiency than whole tree harvesting, and the existing road infrastructure in farmland leads to overall lower energy use and GHG emissions for the harvesting and transporting of biomass compared to whole tree feedstock. Furthermore, if residues were considered by-products of tree-felling and grain harvesting, the fertilization of forest and fields would not be required and this would make residue biomass more favorable than whole tree biomass. Besides the direct reduction of emissions and energy consumption, indirect reduction in emissions and energy consumption can also be a determining factor in deciding which feedstock provides more environmental benefits. For example, whole tree feedstock can be made into products to substitute products derived from fossil fuel. With this substitution, an overall reduction in GHG emissions and energy consumption can be achieved.

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7 References

Agriculture Financial Services Corporation (2013) *Alberta Crop Report Oct 2013.* Lacombe: Agriculture Financial Services Corporation.

Alberta Agriculture and Rural Development (2008, August 1) *Direct seeding: Estimating the Value of Crop Residues.* Retrieved September 3, 2014, from http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex2512

Alberta Agriculture and Rural Development (2012, February 24) *Alberta Crop Production Statistics.* Retrieved May 17, 2014, from http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12061

Alberta Agriculture and Rural Development (2014) *Agriculture Statistics Yearbook 2013.* Edmonton: Alberta Agriculture and Rural Development - Information Management.

Alberta Environment and Sustainable Resource Development (2010) *Forest Industry Competitiveness - Current Facts and Statistics.* Edmonton: Environment and Sustainable Resource Development.

Alberta Environment and Sustainable Resource Development (2012) *Sustainable Forest Management - 2012 Facts and Statistics.* Edmonton: Environment and sustainable resource development.

Alberta Government (2014) *Technical Guidance for Completing Specified Gas Compliance Reports.* Edmonton: Alberta Environment and Sustainable Resource Development - Air and Climate Change Policy Branch.

Baquero G, Esteban B, Riba JR, Rius A, Puig R (2011) An evaluation of the life cycle cost of rapeseed oil as a straight vegetable oil fuel to replace petroleum diesel in agriculture. Biomass Bioenerg 35:, 3687-3697.

Binkley D, Fisher R (2012) *Ecology and management of forest soils.* Oxford: John Wiley & Sons.

Borjesson P (2000) Economic valuation of the environmental impact of logging residue recovery and nutrient compensation. Biomass Bioenerg 19: 137-152.

Bridgwater AV (2012) Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenerg 38: 68-94.

Bridgwater AV, Peacocke GV (2000) Fast pyrolysis processes for biomass. Renew Sust Energ Rev 4: 1-73.

Bridgwater A, Meier D, Radlein D (1999) An overview of fast pyrolysis of biomass. Org Geochem 30: 1479-1493.

Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S (2009) Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resour Conserv Recycling 53: 434-447.

Cherubini F., Peters GP, Berntsen T, Stromman AH, Hertwich E (2011) CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy: 413-426.

Cherubini F, Stromman AH, Ulgiati S (2011) Influence of allocation methods on the environmental performance of biorefinery products - a case study. Resour Conserv Recycling 55: 1070-1077.

Choudhary TV, Phillips CB (2011) Renewable fuels via catalytic hydrodeoxygenation. Appl Catal A-Gen, 397(1-2): 1-12.

Couhert C, Commandre JM, Salvador S (2009) Is it possible to predict gas yields of any biomass after rapid pyrolysis at high temperature from its composition in cellulose, hemicellulose and lignin? Fuel 88: 408-417.

Dang Q, Yu C, Luo Z (2014) Environmental life cycle assessment of bio-fuel production via fast pyrolysis of corn stover and hydroprocessing. Fuel 131: 36-42.

Department for Transport (2007, October 25) *The Renewable Transport Fuel Obligations Order 2007.* Retrieved July 12, 2015, from http://www.legislation.gov.uk/uksi/2007/3072/pdfs/uksi_20073072_en.pdf

Diego I, Almudena H, Maria TM, Gumersindo F (2011) Benchmarking environmental and operational parameters through co-efficiency criteria for dairy farms. Sci Total Environ 409: 1786-1798.

Diego I, Jens P, Javier D (2012) Life cycle assessment of transportation fuels from biomass pyrolysis. Fuel 97: 812-821.

Elliott DC, Hart TR, Neuenschwander GG, Rotness LJ, Zacher AH (2009) Catalytic hydroprocessing of biomass fast pyrolysis bio-oil to produce hydrocarbon products. Environ Prog 28(3): 441-449.

Environment Canada (2012) *National Inventory Report 1990-2010: Greenhouse gas sources and sinks in Canada part 3.* Ottawa: Ministry of environment.

Environment Canada (2015, July 14) *Renewable Fuels Regulations*. (Government of Canada) Retrieved July 15, 2015, from http://ec.gc.ca/energie-energy/default.asp?lang=En&n=0AA71ED2-1

Environmental Protection Agency (2014) Emission factors for greenhouse gas inventories. Washington, D.C.: United States Environmental Protection Agency.

Environmental Protection Agency (2015, May 28) *EPA Proposes Renewable Fuel Standards for 2014, 2015, and 2016, and the Biomass-Based Diesel Volume for 2017.* Retrieved July 12, 2015, from http://www.epa.gov/otaq/fuels/renewablefuels/documents/420f15028.pdf

Eriksson E, Gillespie AR, Gustavasson L, Langvall O, Olsson M, Sathre R, Stendahl J (2007) Integrated carbon analysis of forest management practices and wood substitution. Can J Forest Res 37: 671-681.

European Biomass Association (2007) *European Biomass Statistics 2007 - A statistical report on the contribution of biomass to the energy system in the EU 27.* Brussels.

Furuholt E (1995) Life cycle assessment of gasoline and diesel. Resour Conserv Recy 14: 251-263.

Government of Alberta (2008, December 11) *Renewable Fuels Standard*. (Alberta Energy Regulator) Retrieved December 7, 2013, from http://www.energy.alberta.ca/BioEnergy/1516.asp

Government of Alberta (2013) *2013 Municipal affairs population list.* Edmonton: Government of Alberta - Municipal Services Branch.

Government of Alberta (2013, November 30) *Sustainable Forest Management 2012 Facts and Statistics.* Retrieved December 9, 2013, from http://esrd.alberta.ca/lands-forests/forest-management/forest-management-facts-statistics/default.aspx

Government of Canada (2011, April 18) *Energy supply and demand, by fuel type* . (Statistics Canada) Retrieved December 9, 2013, from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/prim72-eng.htm

Government of Canada (2014, July 31) *Sales of fuel used for road motor vehicles, by province and territory.* Retrieved November 12, 2014, from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/trade37c-eng.htm

Han J, Elgowainy A, Dunn JB, Wang MQ (2013) Life cycle analysis of fuel production from fast pyrolysis of biomass. Bioresource Technol 133: 421-428.

Hansen J, Sato M, Kharecha P, Beerling D, Berner R, Masson-Delmotte V et al (2008) Target Atmospheric CO2: Where Should Humanity Aim? The Open Atmospheric Science Journal 2: 217-231.

Hartman M (2008) *Direct seeding - estimating the value of crop residues Agdex 519-25.* Edmonton: Alberta Agriculture and Rural Development.

Helin T, Sokka L, Soimakallio S, Pingoud K, Pajula T (2013) Approaches for inclusion of forest carbon cycle in life cycle assessment - a review. GCB Bioenergy: 475-486.

Hsu DD (2012) Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing. Biomass Bioenerg*,* 45: 41-47.

Huijbregts MA, Norris G, Bretz R, Ciroth A, Maurice B et al (2001) Framework for modelling data uncertainty in life cycle inventories. Int J Life Cycle Ass 6(3): 127-132.

IEA Bioenergy Task 34 (2007) *Biomass pyrolysis.* Richland: IEA Bioenergy.

International Organization for Standardization (2006) *ISO 14010:2006 Environmental management - life cycle assessment - principles and framework.* Geneva.

IPCC (2006) *N2O emissions from managed soils, and CO2 emissions from lime and urea application.* Geneva: IPCC.

IPCC (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2013) *Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* New York: Intergovernmental Panel on Climate Change 2013.

Iribarren D, Peters JF, Dufour J (2012) Life cycle assessment of transportation fuels from biomass pyrolysis. Fuel 97: 812-821.

Kabir MR., Kumar A (2011) Development of net energy ratio and emission factor for biohydrogen production pathways. Bioresource Technol 102(19): 8972-8985.

Kabir MR, Kumar A (2012) Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. Bioresource Technol 124: 394-405.

Knothe G (2010) Biodiesel and renewable diesel: a comparison. Prog Energ Combust 36: 364-373.

Kumar A, Cameron JB, Flynn PC (2003) Biomass power cost and optimum plant size in Western Canada. Biomass Bioenerg 24(6): 445-464.

Lal R (2005) World crop residues production and implications of its use as a biofuel. Environ Int 31: 575-584.

Lal R (2008) Promise and limitations of soils to minimize climate change. J Soil Water Conserv 63(4): 113A-118A.

Larson ED (2006) A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. Energy for Sustainable Development 10(2): 109-126.

Mahendrappa MK, Salonius PO (1982) Nutrient dynamics and growth response in a fertilized black spruce stand. Soil Sci Soc Am J 46(1): 127-133.

Mani S, Tabil LG, Sokhansanj S (2004) Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Biomass Bioenerg 27: 339-352.

Mann MK, Spath PL (1997) *Life cycle assessment of a biomass gasification combined-cycle system.* Golden: National renewable energy laboratory.

Miller P, Kumar A (2013) Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina. Energy 58: 426-437.

Ministry of Environment (2014) B.C. Best practices methodology for quantifying greenhouse gas emissions. Victoria, British Columbia, Canada.

Mohan D, Pittman CU, Steele PH (2006) Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review. Energ Fuel 20: 848-889.

Montana State University - Extension water quality program (2006) *A practical guide to choosing crops well-suited to limited irrigation.* Bozeman: MSU extension service.

Natural Resources Canada (2012) *Study of Hydrogenation Derived Renewable Diesel as a Renewable Fuel Option in North America.* Ottawa: Ecoressources Consultants.

Oak Ridge National Laboratory (1994) *Energy in synthetic fertilizers and pesticides: revisited.* Springfield: Environmental sciences division.

Overend RP (1982) The average haul distance and transportation work factors for biomass delivered to a central plant. Biomass 2: 75-79.

Papong S, Chom-In T, Noksa-nga S, Malakul P (2010) Life cycle energy efficiency and potentials of biodiesel production from palm oil in Thailand. Energ policy 38: 226-233.

Perez-Garcia J, Lippke B, Comnick J, Manriquez C (2005) An assessment of carbon pools, storage, and wood products market subsitution using life-cycle analysis results. Wood and Fiber Science: 140-148.

Peters JF, Iribarren D, Dufour J (2015) Simulation and life cycle assessment of biofuel production via fast pyrolysis and hydroupgrading. Fuel 139: 441-456.

Piringer G, Steinberg LJ (2006) Reevaluation of energy use in wheat production in the United States. J Ind Ecol 10(1-2): 149-167.

Raymer AK (2006) A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. Biomass Bioenerg 30: 605-617.

Ric H, Edward S, Andre F (2010) Greenhouse gas footprints of different biofuel production systems. Renew Sust Energ Rev 14: 1661-1694.

Ringer M, Putsche V, Scahill J (2006) *Large-scale pyrolysis oil production: a technology assessment and economic analysis.* Golden: National Renewable Energy Laboratory.

Stripple H (2001) *Life cycle assessment of road: a pilot study for inventory analysis.* Gothenburg: IVL Swedish environmental research institute.

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

Sultana A, Kumar A, Harfield D (2010) Development of agri-pellet production cost and optimum size. Bioresource Technol 101: 5609-5621.

U.S. Department of Energy (2009) *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case.* Oak Ridge: Pacific Northwest National Laboratory.

U.S. Department of Energy (2012) *Stabilization of Fast Pyrolysis Oil: Post Processing.* Oak Ridge: Pacific Northwest National Laboratory.

Wang M (2011) GREET 1_2011. version 1.8c. Chicago: Argonne National Laboratory.

Wilhelm WW, Johnson JM, Hatfield JL, Voorhees WB, Linden DR (2004) Crop and soil productivity response to corn residue removal: A literature review. Agron J 96: 1-17.

Wright MM, Daugaard DE, Satrio JA, Brown RC (2010) Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel 89: S2-S10.

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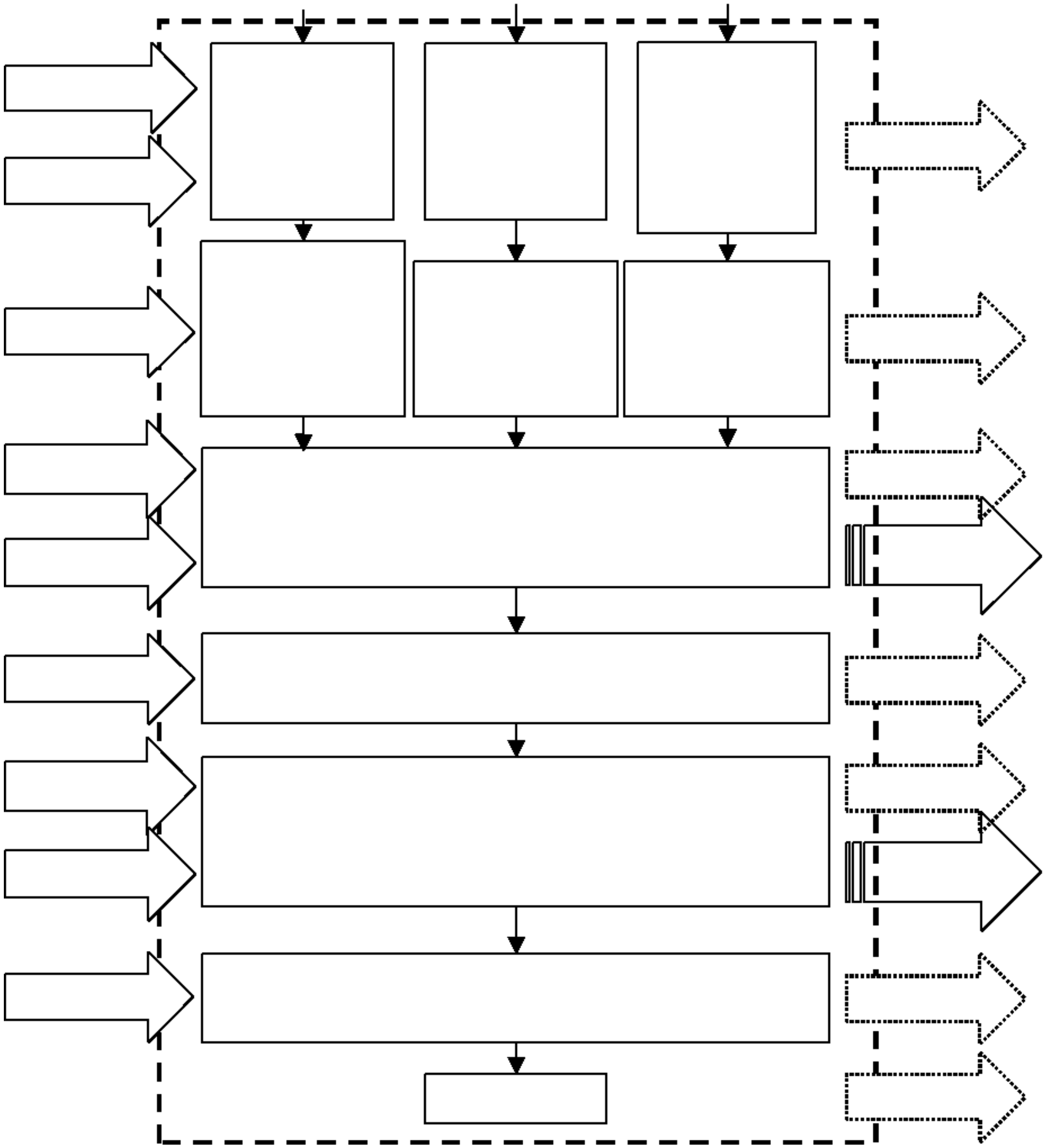

Fig 1 System boundary of LCA of HDRD production

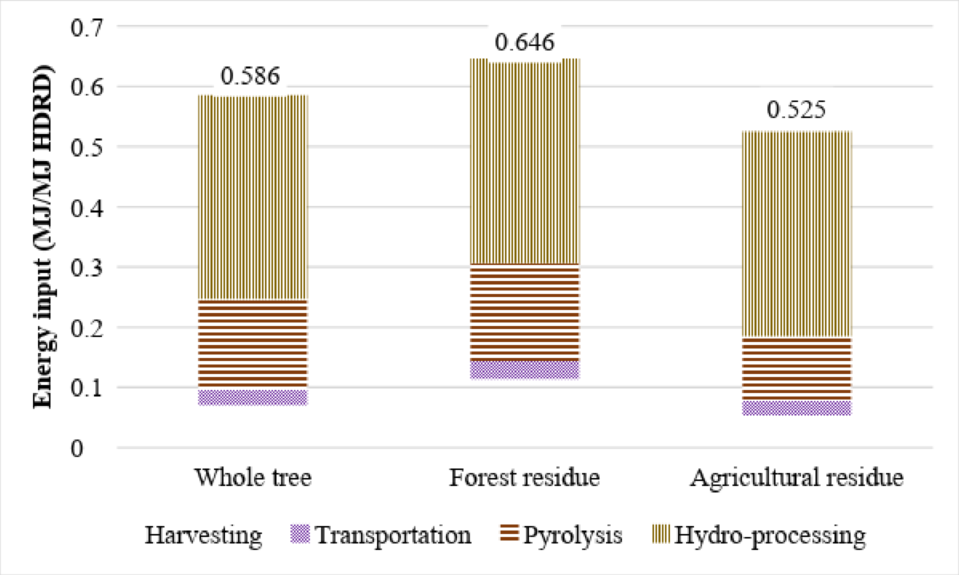

Fig 2 Base case energy input for various feedstocks

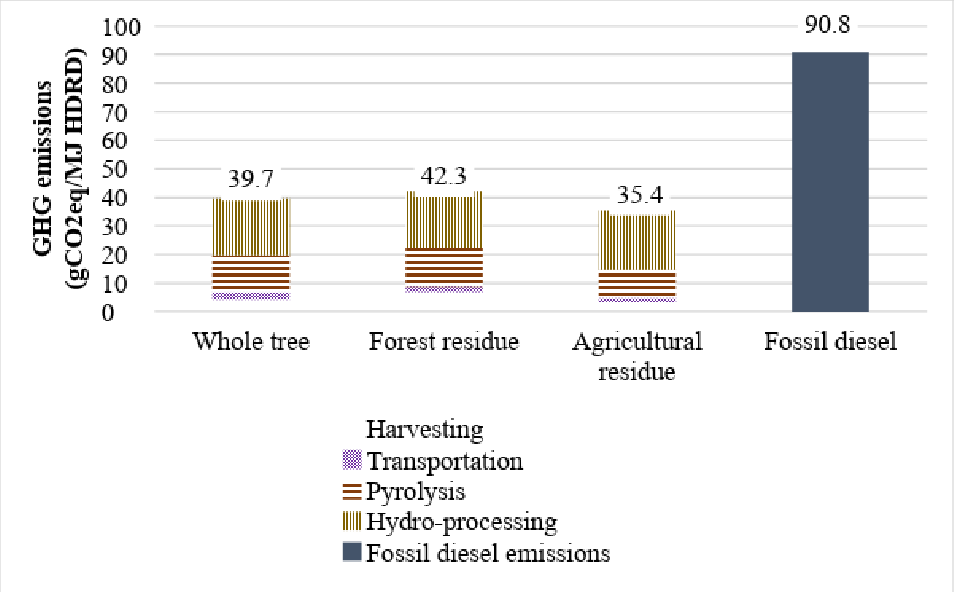

Fig 3 Base case GHG emissions for various feedstocks

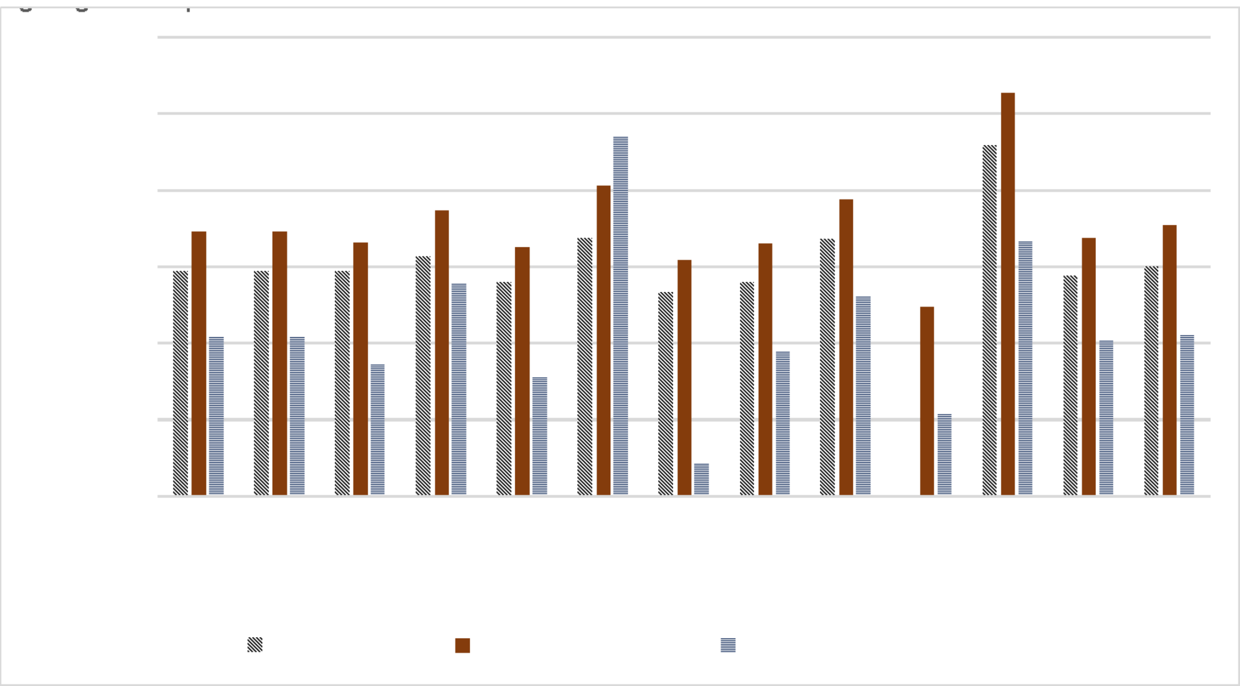

Fig 4 GHG emissions / MJ of HDRD for base case and considered scenarios

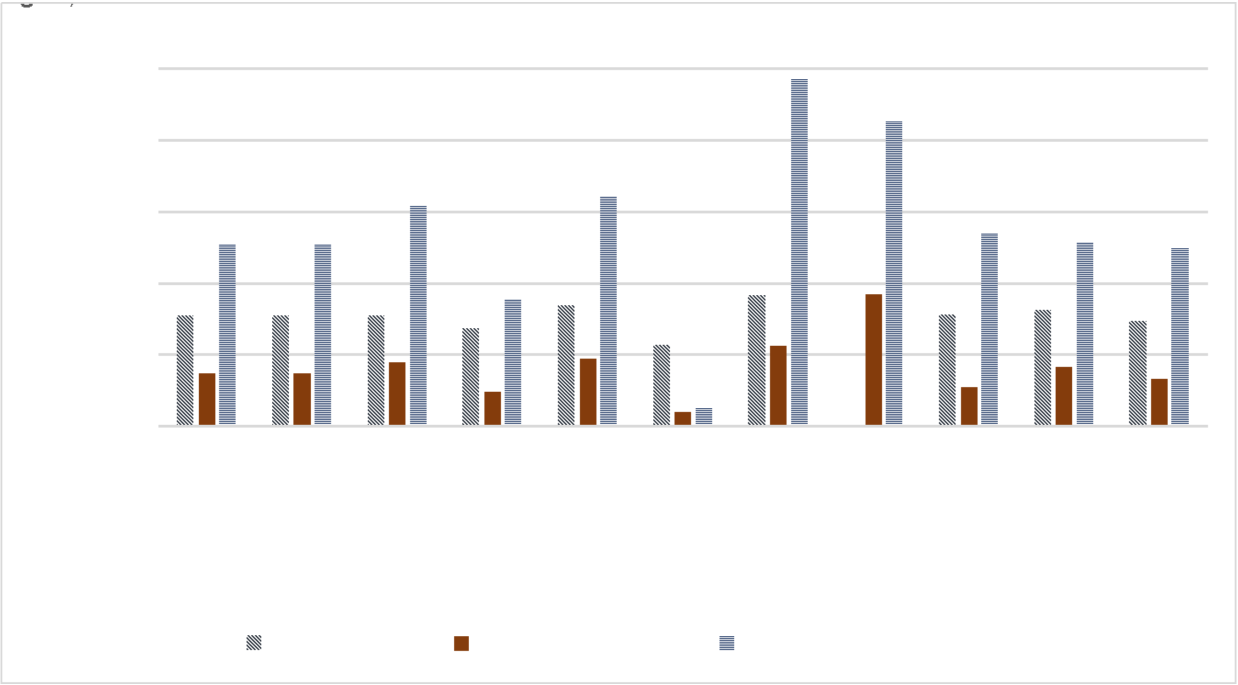

Fig 5 NER of base case and considered scenarios

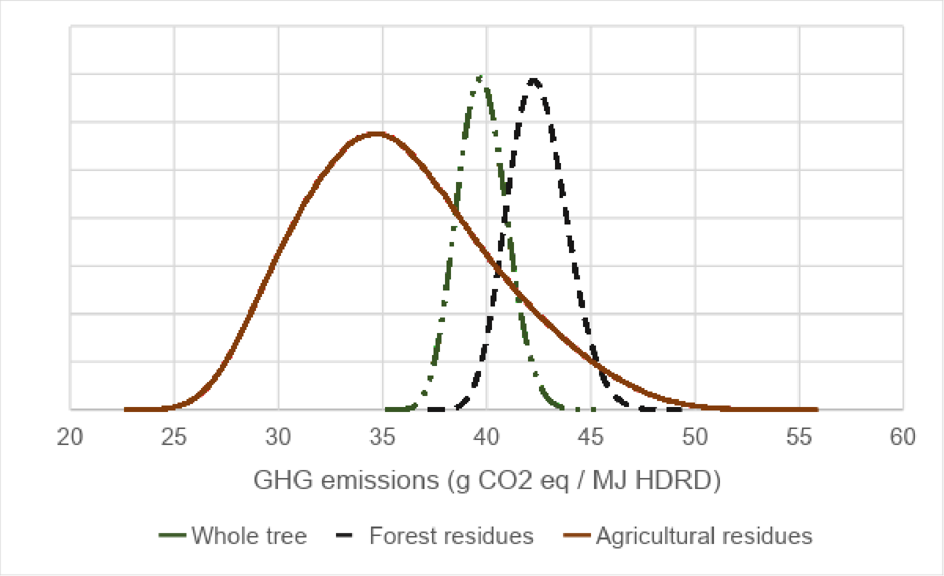

Fig 6 Uncertainty results of GHG emissions for three feedstocks using the Monte Carlo distribution

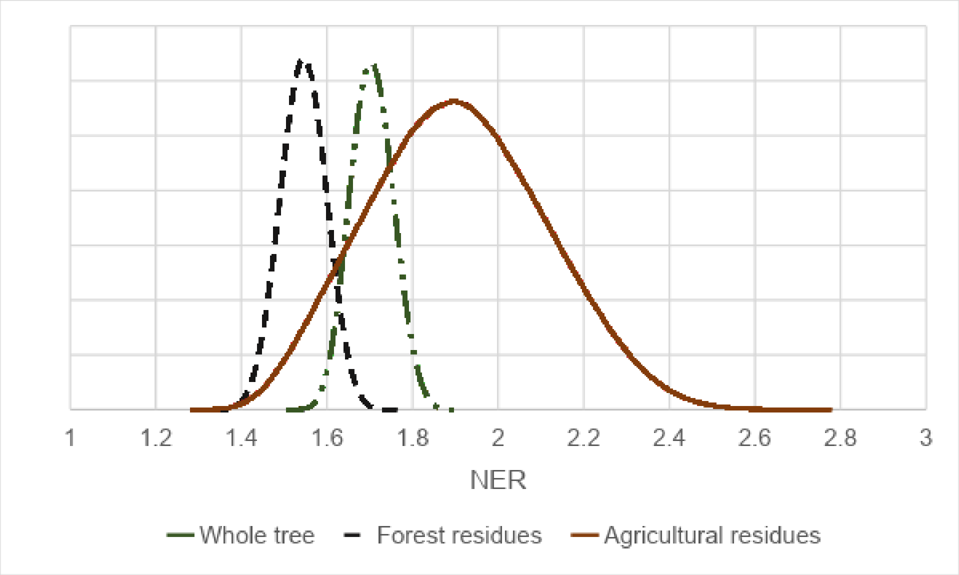

Fig 7 Uncertainty results of NER for three feedstocks using the Monte Carlo distribution

Table 1: Harvesting and transportation of whole tree chips used for feedstock (functional unit: MJ HDRD)

Whole tree											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Units	Ref	Used value	Units	Ref	Used value	Units	Ref	MJ/MJ	$gCO_{2,eq}$/MJ
Felling (diesel) [a]	0.67	L/m3	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.005	0.31
Skidding (diesel) [a]	0.75	L/m3	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.006	0.34
Chipping (diesel) [a]	3.33	L/dry tonne	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.009	0.53
Transportation of chips (diesel) [a]	0.24, 0.33	L/km	(Kabir & Kumar, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.003	0.20
Road construction [b]	700	km	(Kabir & Kumar, 2011)	1731	GJ/km	(Stripple, 2001)	403845	$kgCO_{2,eq}$/km	(Stripple, 2001)	0.006	1.34
Nitrogen replacement	0.61	wt% N	(U.S. Department of Energy, 2009)	49.45	MJ/kg	(Wang, 2011)	201.3	$gCO_{2,eq}$/kg	(Wang, 2011)	0.018	0.07
Fertilizer transport (diesel)	6.4	kJ/kg N/km	(Binkley & Fisher, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.033	1.99
Fertilizer spreading (diesel) [c]	50	MJ/ha	(Binkley & Fisher, 2012)	-	-	-	2727	$gCO_{2,eq}$ /L	(Environmental Protection Agency, 2014)	3.49E-05	0.002
N_2O emission factor	0.01	N_2O/ N	(IPCC, 2006)	-	-	-	-			-	1.07

[a] Input quantities are calculated based on the productivity and fuel economy of the equipment.

[b] Length of road constructed, energy coefficients, and emission coefficients are based on a 20-year pyrolysis plant life.

[c] A tractor is assumed to be used for the spreading of fertilizer (Binkley & Fisher, 2012).

Table 2: Harvesting and transportation of forest residues chips used for feedstock (functional unit: MJ HDRD)

Forest residues											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Units	Ref	Used value	Units	Ref	Used value	Units	Ref	MJ/MJ	gCO$_{2,eq}$/MJ
Forwarding (diesel) [a]	0.52	L/m3	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.034	2.07
Chipping (diesel) [a]	3.93	L/dry tonne	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.010	0.63
Transportation of chips (diesel) [a]	0.24, 0.33	L/km	(Kabir & Kumar, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.014	0.84
Nitrogen replacement	0.61	wt% N	(U.S. Department of Energy, 2009)	49.45	MJ/kg	(Wang, 2011)	201.3	gCO$_{2,eq}$ /kg	(Wang, 2011)	0.018	0.07
Fertilizer transport (diesel)	6.4	kJ/kg N/km	(Binkley & Fisher, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.039	2.37
Fertilizer spreading (diesel) [b]	50	MJ/ha	(Binkley & Fisher, 2012)	-	-	-	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.012	0.72
N_2O emission factor	0.01	N_2O/N	(IPCC, 2006)	-	-	-	-	-	-	-	1.07

[a] Input quantities are calculated based on productivity and fuel economy of the equipment.

[b] A tractor is assumed to be used for the spreading of fertilizer (Binkley & Fisher, 2012).

Table 3 Harvesting and transportation of agricultural residues used for feedstock (functional unit: MJ HDRD)

Agricultural residues											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Units	Ref	Used value	Units	Ref	Used value	Units	Ref	MJ/MJ	gCO$_{2,eq}$/ MJ
Raking (diesel) ^{a}	0.47	L/dry tonne	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.001	0.09
Baling (diesel) ^{a}	2.9	L/dry tonne	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.009	0.55
Bale wrapping (diesel) ^{a}	0.055	L/bale	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	3.99E-04	0.02
Bale stacking (diesel) ^{a}	0.83	L/dry tonne	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.003	0.16
Bale loading (diesel) ^{a}	0.33	L/dry tonne	(Kabir & Kumar, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.001	0.06
Transportation of bales (diesel) ^{a}	0.24, 0.33	L/km	(Kabir & Kumar, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.009	0.53
Nitrogen replacement ^{b}	6	kg N/tonne	(Hartman, 2008)	49.45	MJ/kg	(Wang, 2011)	201.3	gCO$_{2,eq}$ /kg	(Wang, 2011)	0.023	0.09
Phosphate replacement ^{b}	1.85	kg P_2O_5/tonne	(Hartman, 2008)	14.13	MJ/kg	(Wang, 2011)	439.8	gCO$_{2,eq}$ /kg	(Wang, 2011)	0.002	0.06
Potassium replacement ^{b}	15	kg K_2O/tonne	(Hartman, 2008)	8.84	MJ/kg	(Wang, 2011)	568.9	gCO$_{2,eq}$ /kg	(Wang, 2011)	0.010	0.65
Sulphur replacement ^{b}	1.4	kg S/tonne	(Hartman, 2008)	11.26	MJ/kg	(Oak Ridge National Laboratory, 1994)	17.73	gCO$_{2,eq}$ /kg	(Wang, 2011)	0.001	0.002
Fertilizer transport (diesel) ^{c}	0.24, 0.33	L/km	(Kabir & Kumar, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	gCO$_{2,eq}$ /L	(Environmental Protection Agency, 2014)	1.69 E-04	0.01
Fertilizer spreading	7	L/ha	(Baquero,	45.25	MJ/L	(Piringer &	2727	gCO$_{2,eq}$ /L	(Environmental	0.016	0.95

(diesel) [c]			Esteban, Riba, Rius, & Puig, 2011)			Steinberg, 2006)			Protection Agency, 2014)		
N_2O emission factor	0.01	N_2O/N	(IPCC, 2006)	-	-		-	-	-	-	1.37

[a] Input quantities are calculated based on productivity and fuel economy of the equipment.

[b] Nutrient replacement is estimated based on average nutrient content in straw.

[c] The truck for fertilizer transport is assumed to be the same as the truck for bale transport.

[d] A tractor is assumed to be used for the spreading of fertilizer (Baquero, Esteban, Riba, Rius, & Puig, 2011).

Table 4: Fast pyrolysis of whole tree feedstock (functional unit: MJ HDRD)

Whole tree											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Units	Ref	Used value	Units	Ref	Used value	Units	Ref	MJ/MJ	gCO$_{2,eq}$/MJ
Grinding & drying	388.8	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	gCO$_{2,eq}$/kWh	(Environment Canada, 2012)	0.083	7.082
Natural gas start up	1.58	kJ/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	-	-		56.58	gCO$_{2,eq}$/MJ	(Wang, 2011)	3.43E-5	0.002
Pyrolysis	313.5	Wh/kg	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	gCO$_{2,eq}$/kWh	(Environment Canada, 2012)	0.067	5.711
Transportation of ash to forest (diesel) [a]	0.24, 0.33	L/km	(Kabir & Kumar, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	gCO$_{2,eq}$/L	(Environmental Protection Agency, 2014)	1.94E-5	0.001
Spreading of ash (diesel) [b]	50	MJ/ha		-	-		2727	gCO$_{2,eq}$/L	(Environmental Protection Agency, 2014)	3.49E-5	0.002
Transportation of bio-oil (diesel)	0.31, 0.50	L/km	(Miller & Kumar, 2013)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	gCO$_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.008	0.479

[a] The truck for ash transportation is assumed to be the same as the truck used for transporting wood chips.

[b] The method of ash spreading for the forest land using a tractor is assumed to be the same as the method used for fertilizer spreading.

Table 5: Fast pyrolysis of forest residue feedstock (functional unit: MJ HDRD)

Forest residues											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Units	Ref	Used value	Units	Ref	Used value	Units	Ref	MJ/MJ	$gCO_{2,eq}$/MJ
Grinding & drying	388.8	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/kWh	(Environment Canada, 2012)	0.083	7.082
Natural gas start up	1.58	kJ/kg biofuel	(Iribarren, Peters, & Dufour, 2012)				56.58	$gCO_{2,eq}$/MJ	(Wang, 2011)	3.43E-5	0.002
Pyrolysis	313.5	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/kWh	(Environment Canada, 2012)	0.067	5.711
Transportation of ash to forest (diesel) [a]	0.24, 0.33	L/km	(Kabir & Kumar, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	8.01E-5	0.005
Spreading of ash (diesel) [b]	50	MJ/ha					2727	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.012	0.715
Transportation of bio-oil (diesel)	0.31, 0.50	L/km	(Miller & Kumar, 2013)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.008	0.479

[a] The truck for ash transportation is assumed to be the same as the truck used for transporting wood chips.

[b] The method of ash spreading on the forest land using a tractor is assumed to be the same as the method used for fertilizer spreading.

Table 6: Fast pyrolysis of agricultural residue feedstock (functional unit: MJ HDRD)

Agricultural residues											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Units	Ref	Used value	Units	Ref	Used value	Units	Ref	MJ/MJ	$gCO_{2,eq}$/MJ
Grinding	24.66	kWh/dry tonne	(Mani, Tabil, & Sokhansanj, 2004)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/kWh	(Environment Canada, 2012)	0.020	1.681
Drying	234.5	Wh/dry kg	(Dang, Yu, & Luo, 2014)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/ kWh	(Environment Canada, 2012)	0.160	13.589
Pyrolysis	487.3	Wh/kg bio-oil	(Dang, Yu, & Luo, 2014)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/kWh	(Environment Canada, 2012)	0.258	21.885
Combustion of char [a]										-0.372	-29.85
Transportation of ash to forest (diesel) [b]	0.24, 0.33	L/km	(Kabir & Kumar, 2012)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	2.76E-4	0.017
Spreading of ash (diesel) [c]	7	L/ha	(Baquero, Esteban, Riba, Rius, & Puig, 2011)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2727	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.042	2.547
Transportation of bio-oil (diesel)	0.31, 0.50	L/km	(Miller & Kumar, 2013)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.007	0.409

[a] Combustion of char provided credits for energy input and GHG emissions due to the allocating of GHG emissions and energy input to bio-char by energy allocation.

[b] The truck for ash transportation is assumed to be the same as the truck used for transporting wood chips.

[c] The method of ash spreading on the agricultural land using a tractor is assumed to be the same as the method used for fertilizer spreading.

Table 7: Hydro-processing of bio-oil for whole tree feedstock (functional unit: MJ HDRD)

Whole tree										Energy input	Emissions
Operation	Input quantity			Energy coefficient			Emission coefficient				
	Used value	Unit	Ref	Used value	Unit	Ref	Used value	Unit	Ref	MJ/MJ	$gCO_{2,eq}$/MJ
Hydrotreating	33.64	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/kWh	(Environment Canada, 2012)	0.008	0.650
Hydrocracking/ distillation	47.10	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/kWh	(Environment Canada, 2012)	0.011	0.910
Steam reforming	53.82	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$/kWh	(Environment Canada, 2012)	0.012	1.040
Natural gas used	256.95	g/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	52.23	MJ/kg	(Wang, 2011)	56.58	$gCO_{2,eq}$/kg	(Wang, 2011)	0.309	17.463
Transportation of bio-oil (diesel) [a]	0.31, 0.50	L/km	(Miller & Kumar, 2013)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$/L	(Environmental Protection Agency, 2014)	0.008	0.490

[a] The super B-train truck used for bio-oil transportation is assumed to be used to transport HDRD.

Table 8: Hydro-processing of bio-oil for forest residues feedstock (functional unit: MJ HDRD)

Forest residues											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Unit	Ref	Used value	Unit	Ref	Used value	Unit	Ref	MJ/MJ	$gCO_{2,eq}$/MJ
Hydrotreating	33.64	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/ kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$ /kWh	(Environment Canada, 2012)	0.008	0.650
Hydrocracking/ distillation	47.10	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/ kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$ /kWh	(Environment Canada, 2012)	0.011	0.910
Steam reforming	53.82	Wh/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	9.89	MJ/ kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$ /kWh	(Environment Canada, 2012)	0.012	1.040
Natural gas used	256.95	g/kg biofuel	(Iribarren, Peters, & Dufour, 2012)	52.23	MJ/ kg	(Wang, 2011)	56.58	$gCO_{2,eq}$ /kg	(Wang, 2011)	0.309	17.463
Transportation of bio-oil (diesel) [a]	0.31, 0.50	L/km	(Miller & Kumar, 2013)	45.25	MJ/ L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.008	0.490

[a] The super B-train truck used for bio-oil transportation is assumed to be used to transport HDRD.

Table 9: Hydro-processing of bio-oil for agricultural residue feedstock (functional unit: MJ HDRD)

Agricultural residues											
Operation	Input quantity			Energy coefficient			Emission coefficient			Energy input	Emissions
	Used value	Unit	Ref	Used value	Unit	Ref	Used value	Unit	Ref	MJ/MJ	$gCO_{2,eq}$/MJ
Hydrotreating [a]	58.2	Wh/kg HDRD	(Dang, Yu, & Luo, 2014)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$ /kWh	(Environment Canada, 2012)	0.013	1.137
Hydrocracking/ distillation [a]	81.5	Wh/kg HDRD	(Dang, Yu, & Luo, 2014)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$ /kWh	(Environment Canada, 2012)	0.019	1.592
Steam reforming [a]	93.1	Wh/kg HDRD	(Dang, Yu, & Luo, 2014)	9.89	MJ/kWh	(Piringer & Steinberg, 2006)	840	$gCO_{2,eq}$ /kWh	(Environment Canada, 2012)	0.021	1.819
Natural gas used	236	g/kg HDRD	(Dang, Yu, & Luo, 2014)	52.23	MJ/kg	(Wang, 2011)	56.58	$gCO_{2,eq}$ /kg	(Wang, 2011)	0.286	16.208
Transportation of bio-oil (diesel) [b]	0.31, 0.50	L/km	(Miller & Kumar, 2013)	45.25	MJ/L	(Piringer & Steinberg, 2006)	2722	$gCO_{2,eq}$ /L	(Environmental Protection Agency, 2014)	0.008	0.488

[a] Electrical energy consumption of hydroprocessing bio-oil derived from agricultural residues is assumed to follow the electrical energy consumption distribution of hydroprocessing bio-oil derived from whole tree and forest residues, where the electrical energy distribution is 25%, 30%, and 40% for hydrotreating, hydrocracking and distillation, and steam reforming, respectively.

[b] The super B-train truck used for bio-oil transportation is assumed to be used to transport HDRD.

Table 10: Study scenarios

Scenarios	
Base case	Ashes are returned to the soil to replace minerals
1	Ashes are sent back to the soil by return chip and bale trucks
2	Ashes are sent to a landfill for disposal
3	Decrease bio-oil yield by 10%
4	Increase bio-oil yield by 10%
5	Decrease HDRD yield by 10%
6	Increase HDRD yield by 10%
7	Decrease N_2O emissions factor to 0.003
8	Increase N_2O emissions factor to 0.03
9	Forest residues and agricultural straw are treated as by-products and there is no need for fertilization when they are removed
10	Hydrogen production from bio-oil instead of natural gas in steam reformer
11	Decrease transportation distance by 10%
12	Increase transportation distance by 10%

Table 11: GHG emissions of unit operations for each feedstock (g $CO_{2,eq}$/MJ HDRD)

Scenario 10: GHG emissions of unit operations for each feedstock (g$CO_{2,eq}$/MJ HDRD)			
Operations	Whole tree	Forest residues	Agricultural residues
Harvesting	5.67	9.11	4.33
Transportation	3.14	2.22	1.73
Pyrolysis	16.82	17.76	15.00
Hydro-processing	22.28	22.27	20.52
Total	47.91	51.36	41.58

Table 12: Non-renewable energy input of unit operations for each feedstock (MJ/MJ HDRD)

Scenario 10: Non-renewable energy input of unit operations for each feedstock (MJ/MJ HDRD)			
Operations	Whole tree	Forest residues	Agricultural residues
Harvesting	0.093	0.150	0.070
Transportation	0.030	0.037	0.029
Pyrolysis	0.198	0.213	0.171
Hydro-processing	0.262	0.262	0.245
Total	0.583	0.662	0.515

Table 13: Percentile values of uncertainty distribution plots

	NER			GHG		
Percentile	Whole tree NER value	Forest residue NER value	Agricultural residue NER value	Whole tree GHG emissions g $CO_{2,eq}$/MJ HDRD	Forest residue GHG emissions g $CO_{2,eq}$/MJ HDRD	Agricultural residue GHG emissions g $CO_{2,eq}$/MJ HDRD
5%	1.624	1.457	1.575	37.903	40.251	28.926
10%	1.641	1.476	1.638	38.288	40.691	30.108
25%	1.670	1.509	1.759	38.964	41.472	32.443
50%	1.704	1.545	1.901	39.752	42.399	35.428
75%	1.739	1.581	2.047	40.569	43.383	38.818
90%	1.771	1.613	2.179	41.321	44.306	42.166
95%	1.789	1.632	2.254	41.775	44.866	44.107