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Biohydrogen production from forest and agricultural residues for upgrading of bitumen from oil sands

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ABSTRACT

In this study, forest residues (limbs, tops, and branches) and straw (from wheat and barley) are considered for producing biohydrogen in Western Canada for upgrading of bitumen from oil sands. Two types of gasifiers, namely, the Battelle Columbus Laboratory (BCL) gasifier and the Gas Technology Institute (GTI) gasifier are considered for biohydrogen production. Production costs of biohydrogen from forest and agricultural residues from a BCL gasification plant with a capacity of 2000 dry tonnes/day are \$1.17 and \$1.29/kg of H_2, respectively. For large-scale biohydrogen plant, GTI gasification is the optimum technology. The delivered-biohydrogen costs are \$2.19 and \$2.31/kg of H_2 at a plant capacity of 2000 dry tonnes/day from forest and agricultural residues, respectively. Optimum capacity for biohydrogen plant is 3000 dry tonnes/day for both residues in a BCL gasifier. In a GTI gasifier, although the theoretical optimum sizes are higher than 3000 dry tonnes/day for both feedstocks, the cost of production of biohydrogen is flat above a plant size of 3000 dry tonnes/day. Hence, a plant at the size of 3000 dry tonnes/day could be built to minimize risk. Carbon credits of \$119 and \$124/tonne of CO_2 equivalent are required for biohydrogen from forest and agricultural residues, respectively.

1. Introduction

In Western Canada, large amounts of forest and agricultural residues are left in the forest/field which could be harvested for energy production. Forest residues are the limbs and tops of the trees which are left on the roadside after logging operation by pulp and lumber companies. These residues are left to rot and release GHGs to the atmosphere. Agricultural residues include straw from wheat and barley crops. Utilization of forest and agricultural residues for biohydrogen production could reduce emission of GHGs and dependence on fossil fuels. Biohydrogen from biomass resources could be used in bitumen upgrading for synthetic crude oil (SCO) production in Western Canada. On average, there are about 3.29 million dry tonnes/year of forest residues and 3.19 million dry tonnes/year of agricultural residues available in Alberta which could be used for biohydrogen production [1–3].

Most of the whole-forest biomass (i.e. use of whole-tree as feedstock) in the Province of Alberta is allocated to pulp and timber production companies. As a result of this, whole-forest biomass is not available at present for biohydrogen production, although a large amount of forest residues could be sustainably removed for biohydrogen production. At present, the only residue collected in Alberta is the forest residue on the roadside, which is burnt to prevent forest fires [4]. Similarly, there is some use of the agricultural residues but most of it is left to rot in the field, although it could be removed from the field for biohydrogen production.

Generally, natural gas and coal are used for producing hydrogen that is consumed in chemical and oil sands industries in Canada. In 2005, Western Canada had a production capacity of about 3 million tonnes of hydrogen and 31% of this was used for upgrading 527 thousand barrel of bitumen/day. The capacity of upgrading bitumen is expected to be about 2045 thousand barrel of bitumen/day in 2020 [5,6]. So, it is quite apparent that the demand for hydrogen fuel for bitumen upgrading will increase.

Consumption of hydrogen fuel during bitumen upgrading varies with primary upgrading technology (i.e. coking or hydro-conversion) and quality of synthetic crude oil (SCO) [7]; typical value is 1000 standard cubic feet (scf) of hydrogen/barrel of bitumen (i.e. about 2.41 kg of H_2/barrel of bitumen) upgraded [8]. Additionally, about 2.86 kg of natural gas is consumed as fuel and feed, emitting 11.88 kg of CO_2 equivalent for producing 1 kg of H_2 by steam methane reforming (SMR) process [9]; however, this rate may vary with plant size and efficiency. Utilization of biomass for producing hydrogen will reduce the intensity of CO_2 emission from oil sands industries.

Demonstrations at various scale have been carried out for gasification of biomass for producing electricity and heat by co-

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firing with fossil fuels [10,11]; although, none of these plants have produced hydrogen from gasification of biomass. A number of studies have dealt with techno-economic assessment of hydrogen fuel production from gasification of biomass especially from wood [12–19]. Besides, most of these studies have considered a fixed-value for delivered-biomass cost (approximately $30–$60/dry tonne), and estimated production cost of H_2 is in the range of $1–$2/kg of H_2 for plants processing 360–5000 dry tonnes biomass/day. Although some studies have estimated production cost of $2–$5/kg of H_2 [17,20].

In an earlier study by the authors [21], the cost of producing biohydrogen from whole-forest was estimated along with the cost of transporting it to an upgrader in Western Canada. The carbon credits required to make it competitive with natural gas-based hydrogen were also estimated. This paper deals with using forest and agricultural residues for producing biohydrogen for bitumen upgrading. Two types of gasification technology are considered for biohydrogen production. This paper also compares biohydrogen production from agricultural and forest residues with the whole-forest case.

This part of the work focused on the collecting and harvesting of forest residues and straw by conventional harvesting methods, and their transportation by truck to a biohydrogen production plant using the existing road networks. Once the biohydrogen is produced in a plant, it is transported to an upgrader. After collecting all the data and making some assumptions, techno-economic models were developed to calculate the cost of producing biohydrogen from forest residues and straw. Note that all the costs presented in this study are in 2008 US dollars, unless specified otherwise. Other additional assumptions are described in this paper as required.

2. Gasification technologies

The general methodology for gasifying forest residues and straw is similar to the whole-tree gasification process which is given in detail in an earlier study by the authors [21]. The gasification of biomass can be carried out in an atmospheric pressure gasifier [12] or a pressurized gasifier [18]. The former gasifier is the Battelle Columbus Laboratory (BCL) gasifier which was developed by the National Renewable Energy Laboratory (NREL) (Fig. 1 shows the schematic of a BCL gasifier). The latter gasifier is the Gas Technology Institute (GTI) gasifier which was named for its developer (Fig. 2 shows the schematic of a GTI gasifier). The key difference between these two gasifiers is in their operating pressure. BCL gasification is an atmospheric pressure (~0.16 MPa) and involves feedstock drying with flue gases from char combustion, a wet gas cleaning process, a water-gas shift reaction, and a purification process [12]. GTI gasification operates at high pressure (~3.45 MPa) and involves a high temperature syngas (~982 °C) cleaning process, a shift reaction, and a purification process [14,22–24]. In fact, pure oxygen is obtained from an oxygen production plant for the process in the GTI gasifier. This adds to the capital cost of the GTI process. The oxygen flow rate for GTI gasification process is 0.3 kg/kg of dry biomass, while 0.4 kg and 0.3 kg steam are supplied for each kg of dry biomass feed rate in BCL and GTI gasifiers, respectively [12,22,24]. Further details on this are given in subsequent sections.

Figs. 1 and 2 depict the gasification of biomass in a BCL and in a GTI gasifier, respectively. Syngas clean up, compression, water-gas shift reaction, and pressure swing adsorption (PSA) are the remaining steps in the BCL gasification process; hot gas clean up, water-gas shift reaction, and PSA are the remaining steps in the GTI gasification process [12,18,25]. The temperature and pressure of the syngas vary with the types of gasification process (i.e. BCL or GTI processes), and detail of the syngas clean up to remove particulates and sulfur, tar reforming, compression, and cooling are explained in different studies [18,25–31].

The basic operating principle of fluidized bed reactors is the same for gasification, combustion, or pyrolysis of biomass or coal. A number of studies have considered fluidized bed gasifiers for the biomass gasification process [23,31–37]. Biomass is fed into a bubbling fluidized bed (BFB) reactor, while oxidant and steam flow at the bottom of the reactor to create the fluidized medium, and product gases leave at the top of the reactor [18]. Ash is separated by solid-particle-removal units such as the cyclone, baghouse filter, and/or electrostatic precipitator. The circulating fluidized bed (CFB) gasifier (i.e. the BCL gasifier) has similar operating characteristics, except that heat is transferred to the reactor by hot sand which leaves through the top of the reactor along with product gases and char [34]. A large number of studies have been published on biomass gasification process that produces syngas, and the syngas is used either in: electricity production by burning syngas in turbines/boilers; or liquid fuel production processes by liquefying in a synthesis reactor [24,30,31,38–41].

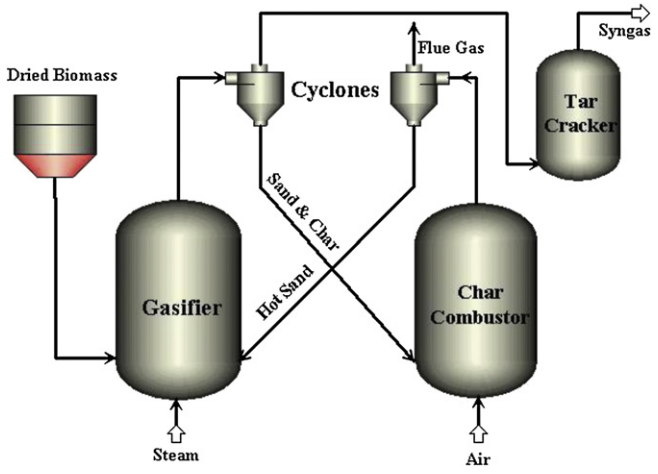

Fig. 1. Schematic diagram of a BCL gasifier for biohydrogen production (derived from Spath et al. [12]).

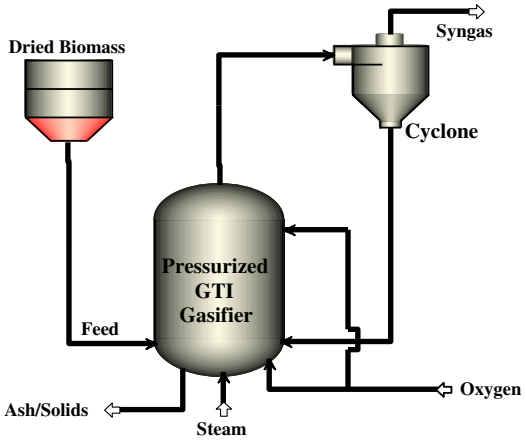

Fig. 2. Schematic diagram of a GTI gasifier for biohydrogen production (derived from Larson et al. [18]).