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Large-scale biohydrogen production from bio-oil

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A B S T R A C T

Large amount of hydrogen is consumed during the upgrading of bitumen into synthetic crude oil (SCO), and this hydrogen is exclusively produced from natural gas in Western Canada. Because of large amount of emission from natural gas, alternative sources for hydrogen fuel especially renewable feedstocks could significantly reduce CO_2 emissions. In this study, biomass is converted to bio-oil by fast pyrolysis. This bio-oil is steam reformed near bitumen upgrading plant for producing hydrogen fuel. A techno-economic model is developed to estimate the cost of hydrogen from biomass through the pathway of fast pyrolysis. Three different feedstocks including whole-tree biomass, forest residues (i.e. limbs, branches, and tops of tree produced during logging operations), and straw (mostly from wheat and barley crops) are considered for biohydrogen production. Delivered cost of biohydrogen from whole-tree-based biomass ($2.40/kg of H_2) is lower than that of forest residues ($3.00/kg of H_2) and agricultural residues ($4.55/kg of H_2) at a plant capacity of 2000 dry tonnes/day. In this study, bio-oil is produced in the field/forest and transported to a distance of 500 km from the centralized remote bio-oil production plant to bitumen upgrading plant. Feedstock delivery cost and capital cost are the largest cost contributors to the bio-oil production cost, while more than 50% of the cost of biohydrogen production is contributed by bio-oil production and transportation. Carbon credits of $133, $214, and $356/tonne of CO_2 equivalent could make whole-tree, forest residues, and straw-based biohydrogen production competitive with natural gas-based H_2 for a natural gas price of $5/GJ, respectively.

1. Introduction

Mitigating greenhouse gases (GHGs) is one of the biggest challenges in the 21st century and requires long-term planning as well as social awareness. Renewable sources of energy can contribute significantly to the effort of mitigating GHGs. Among different renewable energy technologies, biomass-based energy technologies have high potential and are at various stages of development, demonstration, and commercialization.

Western Canada is one of the largest hydrocarbon bases in the North America. The production of synthetic crude oil (SCO) from crude bitumen – a product of the oil sands in Alberta – requires hydrogen. This hydrogen comes almost exclusively from natural gas, and it is predicted that as SCO production increases, more hydrogen will be required for bitumen upgrading and that will further increase the demand for natural gas (Dunbar, 2007). Due to high volatility in the price of natural gas and GHG emissions associated with its extraction and consumption, alternative sources of energy such as biomass could be considered for producing hydrogen for the oil sands in Alberta. Use of biomass-based H_2 for production of synthetic crude will help in reduction of overall GHG emissions from the process and hence could reduce the carbon footprint of the process.

Biomass feedstock has two key characteristics. First, biomass feedstocks are highly dispersed, i.e. the amount of biomass which can be obtained per unit of area is low (dry tonnes of biomass/ha). As a result, the distance biomass must be transported to a bioenergy facility is longer compared to the distance fossil fuels must be transported to a facility with the same capacity. Due to remote location of biomass resources, the transportation cost of biomass feedstock is high compared to natural gas or crude oils. Second, biomass has low energy density (MJ/m^3) compared to fossil fuels (Kumar et al., 2003; McKendry, 2002a; Pootakham and Kumar, 2010a). These two characteristics of biomass make its delivery-cost high. In contrast, biomass-based fuels have lower emissions over their life cycle compared to fossil fuels. This makes biomass an alternative fuel which could reduce GHGs by replacing fossil fuels.

Conversion of biomass to a dark viscous liquid called bio-oil can help by increasing energy density (Bridgwater, 2004; Kumar et al., 2003); if transported in liquid form, biomass can be transported at a reduced cost. Bio-oil has the properties similar to grade #2 fuel oil. It can be produced by fast pyrolysis of biomass along with char and non-condensable gas (Bridgwater, 2004). Bio-oil could be combusted in a boiler, diesel engine, and combustion turbine for producing electricity or heat, or it could be upgraded to petroleum

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products or steam reformed for producing hydrogen fuel (Chiaramonti et al., 2007; Kumar, 2009).

This part of the work provides a techno-economic assessment of producing biohydrogen by reforming bio-oil that is produced from the fast pyrolysis of biomass. Hence, the main objective of this study is to estimate the cost of biohydrogen (\$/kg of H_2) from three different biomass feedstocks using fast pyrolysis process. These feedstocks include whole-tree biomass, forest residues (i.e. limbs, branches, and tops of tree which are produced during logging operations), and agricultural residues (mostly wheat and barley straw). This study also estimates the cost of producing bio-oil (\$/kg), optimum sizes of the bio-oil and biohydrogen production plants (dry tonnes/day), and cost of carbon abatement (\$/tonne of CO_2 equivalent) for these three selected biomass feedstocks. The costs are estimated by modeling all the conversion processes with Aspen Plus Simulation tools (Aspen Plus, 2010).

2. Background on H_2 production from bio-oil

DynaMotive Energy Systems Corporation (www.dynamotive.com/technology), Ensyn Group Inc. (www.ensyn.com), and BTG Biomass Technology Group (www.btgworld.com) are the three major bio-oil producers with a plant capacity of 200, 100, and 2–6 dry tonnes/day of biomass feedstock, respectively (Svoboda et al., 2009). Currently, most of the bio-oil is consumed as fuel in the engines or co-fired with fossil fuels (Bridgwater, 2004; Czernik and Bridgwater, 2004). Additionally, most of the studies have only considered wood-based feedstock for bio-oil production with a bio-oil yield (including water) in the range of 60–83 wt% (Bridgwater, 2003, 2004; Briens et al., 2008; Czernik and Bridgwater, 2004; Darmstadt et al., 2004), while some studies have analyzed production of bio-oil from other biomass residues such as straws, olive waste, olive husk, rice husk with a bio-oil yield (including water) in the range of 40–68 wt% (Demirbaş, 2008; Demirbas, 2006; Ji-lu, 2007; Jung et al., 2008; Liu et al., 2010; Lu et al., 2008; Mahinpey et al., 2009; Tsai et al., 2007).

A significant number of experimental studies have been conducted to produce syngas from bio-oil but not exclusively for hydrogen (Basagiannis and Verykios, 2007; Bimbela et al., 2007; Davidian et al., 2008a,b; Domine et al., 2008; Iojoiu et al., 2007; Magrini-Bair et al., 2002; Rioche et al., 2005; Vagia and Lemonidou, 2008b). There is a scarcity of data on the detailed hydrogen production cost from bio-oil and the optimum size of the of production plants. Some studies have reported only the cost of H_2 production from biomass at small scale, and these costs are in the range of \$1.42–\$2.47/kg of H_2 (DOE, 2003; McHugh, 2005; Spath et al., 2003). None of these earlier studies conduct a detailed mass and energy balance modeling of the production process for estimation of hydrogen production cost from bio-oil. This research is an effort to fill this gap.

The harvesting processes of biomass have been studied earlier, and costs of harvesting and transportation have also been estimated by different studies (Campbell et al., 2002; Jenkins et al., 2000; Kumar, 2009; Kumar et al., 2003, 2008). Several authors have extensively studied reactor design, scaling, heat transfer characteristics, and bio-oil production (Bridgwater, 2004; McHugh, 2005; McKendry, 2002b; Mohan et al., 2006). Most of these studies have estimated production cost of bio-oil from wood-based biomass using bubbling fluidized-bed pyrolysis reactor. Ringer et al. (2006) have estimated production cost of bio-oil (\$0.15/kg) from a plant utilizing 500 dry tonnes of wood chips/day using Aspen Plus simulation tool. The delivered wood chip cost was assumed \$36.57/dry tonne, and cost was calculated for 10% internal rate of return (IRR) with 100% equity. On the other hand, Mullaney et al. (2002) have estimated production cost of bio-oil for different commercial plants, and costs of bio-oil production from plant capacities of 60, 120, and 240 dry tonnes/day are \$0.20–\$0.30/kg, \$0.21–\$0.25/kg, and \$0.19–\$0.22/kg of bio-oil, respectively. However, none of these studies have estimated the cost of producing hydrogen from bio-oil. There is scarcity of study on detailed simulation and modeling of the process of production of hydrogen from bio-oil. There is a need to fill this gap.

The conversion of biomass to bio-oil helps in increasing the energy density, and bio-oil can act as an energy carrier. The cost of production of H_2 from bio-oil includes mainly cost of biomass harvesting, processing, transporting, and storing to a bio-oil production plant, capital and operating costs of bio-oil production from biomass, transportation of bio-oil to a biohydrogen production plant, and capital and operating cost of H_2 production from bio-oil. This work is focused on the conversion of biomass to bio-oil in the forest/field, transportation of bio-oil from the forest/field to the H_2 production plant which is located near the consumer (i.e. bitumen upgrader), and then production of H_2 from bio-oil in the bitumen upgrading plant. This approach would help in transporting biomass energy in a concentrated form with high volumetric energy density and would help in reducing transportation cost.

3. Scope and assumptions

The overall scope of this work includes production of bio-oil in the field/forest and transportation of bio-oil by truck to a bitumen upgrading plant where it can be used for the production of biohydrogen. Biomass is transported to the bio-oil production plant from field/forest, and then the fast pyrolysis of biomass is carried out in the field/forest. This helps in shortening transportation distance of biomass that has low energy density, thereby lowering transportation cost of biomass. The bio-oil, produced in the field/forest, has very high volumetric energy density compared to raw biomass feedstock. Bio-oil is transported to the bitumen upgrading plants over longer distances. Whole-tree, forest residues, and agricultural residues are the selected feedstocks for bio-oil production. The bio-oil produced from these feedstocks is used for biohydrogen production.

Alcohol (e.g. methanol) is added to bio-oil to keep its properties (i.e. density, viscosity) stable (Lu et al., 2008). This study assumes that methanol is transported to the bio-oil production plant by the same truck that will transport bio-oil to the bitumen upgrading plant. According to Methanol Institute (2009), there are different distribution and storage terminals in US and Canada. Methanol is used in different chemical plants across Western Canada. Hence, infrastructure is there for methanol to be transported by truck to the bio-oil production plant in the field/forest. Once received at the biohydrogen production plant, the bio-oil and methanol blend goes through an autothermal steam reforming process and finally becomes biohydrogen (Czernik et al., 2007). Fig. 1 shows the flow diagram of biohydrogen production from biomass using fast pyrolysis process. Note that, in this study, transportation of bio-oil is carried out by truck.

In this study, the whole-tree biomass is cut in the stands and skidded to the roadside. On the roadside, the whole-tree biomass is chipped, and these chips are transported to the bio-oil production plants by B-train chip vans. In case of forest residues, the residues are forwarded and piled on the roadside before chipping. The chips are transported to the bio-oil production plants by B-train chip vans. Straw is collected from the field in the second pass and baled. These bales are tarped and transported to the bio-oil production plant by trucks. The details on the process of collection of forest and agriculture biomass are given in earlier studies by the authors (Kumar, 2009; Kumar et al., 2003; Sarkar and Kumar, 2009, 2010; Sultana et al., 2010).