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Large-scale biohydrogen production from bio-oil

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ABSTRACT

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).

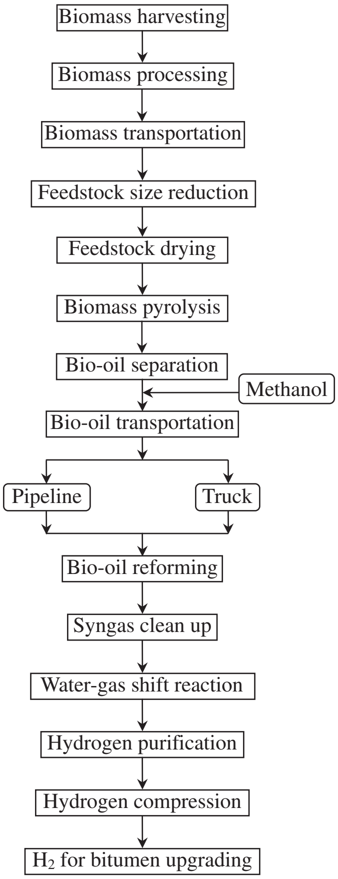

Fig. 1. Flow diagram of biohydrogen production from biomass fast pyrolysis process.

The cost of producing H_2 from biomass via bio-oil production has been estimated for various plant sizes. Data on the costs and characteristics of upstream and downstream processes have been collected from the review of the literature and discussion with experts and manufacturers. Data on bio-oil production have been estimated from simulation models developed using Aspen Plus and from the data on operating plants (Mullaney et al., 2002; Ringer et al., 2006). The process of bio-oil reforming is modeled using Aspen Plus simulation tool (Aspen Plus, 2010) representing a large-scale biohydrogen plant for which bio-oil is the feedstock. This modeling is conducted in order to determine the equipment size, plant operating parameters, and biohydrogen yield. Variable operating costs are estimated from the data generated from the simulation, and the fixed operating cost is estimated by analyzing earlier studies on producing hydrogen from natural gas (Curtis et al., 2003; Longanbach et al., 2002). Finally, the cost of delivered biohydrogen is estimated for this pathway. Note that all the costs presented in this study are in 2008 US dollars, unless specified otherwise and are estimated at an internal rate of return of 10% in the base case. Other additional assumptions are described in this paper in subsequent sections.

4. Biomass pyrolysis for biohydrogen production

The process of producing biohydrogen by the fast pyrolysis of biomass can be separated into three phases: bio-oil production from biomass (i.e. from forest and agricultural biomass), transportation of bio-oil by truck, and bio-oil reforming to produce biohydrogen. The following sections explain the production of biohydrogen from bio-oil using the fast pyrolysis of biomass.

4.1. Production of bio-oil from biomass

Biomass feedstock is collected from the field using existing harvesting technologies and then is transported to a bio-oil production plant. Forest biomass is transported in the form of chips by B-train chip trucks, and agricultural residue is transported in the form of bales by flat-bed trailer trucks. The key operating parameters for bio-oil production by fast pyrolysis include small feedstock size (2–3 mm), low feedstock moisture content (<10%), high heat transfer rate to the feedstock (50 W/cm^2), operating temperature in the range of 425–500 °C, short pyrolysis vapor residence time (around 2 s) in the reactor, and rapid cooling of the pyrolysis vapor (Bridgwater, 2003, 2004; Mohan et al., 2006). Ground feedstock is dried using flue gas generated from the bio-oil quenching process, while non-condensable pyrolysis vapor is recycled to increase the feedstock temperature to enhance the decomposition of the biomass and its fluidization (Mohan et al., 2006). With a very short vapor residence time, pyrolysis vapor leaves the reactor at around 500 °C and is cooled in the heat recovery steam generation (HRSG) process to a temperature of 20 °C, forming bio-oil. This bio-oil is stored in the anti-corrosive tanks that could be made of stainless steel, cobalt, brass, plastic, or fiberglass because of low pH (around 2.5) of bio-oil (Darmstadt et al., 2004; Pootakham and Kumar, 2010a). Note that methanol is added to the bio-oil in the bio-oil production plant, and this bio-oil/methanol blend (10 wt% methanol) is transported to a bitumen upgrading plant where it is used as a feedstock for producing H_2 fuel.

The production of bio-oil from biomass feedstocks has been discussed in earlier studies, and the production technology for bio-oil is commercially available. It can be concluded from the earlier studies that yield of bio-oil depends on the feedstock properties, operating conditions, and type of pyrolysis reactor. In this study, the yields of bio-oil from fast pyrolysis are assumed to be 70.7 wt% (includes 10.8 wt% water) for whole-tree (Ringer et al., 2006), 50.53 wt% for forest residues (includes 20.57 wt% water) (Hassan et al., 2009), and 42 wt% (includes 19.07 wt% water) for straw-based feedstocks (Liu et al., 2010; Tsai et al., 2007).

The yield of bio-oil from whole-tree is higher than that of biomass residues, and there are several explanations for low yields of bio-oil from residues. First of all, from proximate analysis of biomass feedstocks, both forest residues and straw have high ash content and fixed carbon compared to whole-tree biomass that will generate higher char and ash buildup (Hassan et al., 2009). Second, high lignin content in biomass may produce high amount of char resulting in lower yield of bio-oil (Mohan et al., 2006). Third, high volatile matters in whole-tree may result in high bio-oil yield compared to forest residues and straw (Hassan et al., 2009).

Char, which is also produced from biomass during fast pyrolysis process, has a heating value similar to coal. This char can be burnt to generate heat for the pyrolysis process and for the production of steam (Lu et al., 2008). In the long run, fast pyrolysis results in reduced fossil fuel consumption for bio-oil production.

Pyrolysis vapor can be quenched by spraying cold bio-oil (Lu et al., 2008); however, in this study, the quenching process is assumed to be carried out through the steam generation and air preheating processes. Finally, bio-oil is stored in the bio-oil production plant by adding methanol before transporting it to the bitumen upgrading plant.

4.2. Production of biohydrogen from bio-oil

4.2.1. Feedstock preparation for bio-oil reforming

The bio-oil produced from the fast pyrolysis of biomass consists of mainly large amount of organic acids, aldehydes, ketones, alcohol, and water (Hassan et al., 2009; Jung et al., 2008; Oasmaa and Peacocke, 2001; Tsai et al., 2007). Some of the properties of bio-oil which are different compared to conventional liquid fuels are: high water content, low energy density, high viscosity, high density, high oxygen content, high alkali metals, and high ash/solid contents (Chiaramonti et al., 2007). On the other hand, some of the benefits for producing bio-oil are: low GHGs emissions and renewable.

The properties of bio-oil vary significantly with the change in temperature and over time. Viscosity is the most important property which is altered. Mixing solvent (10 wt% methanol) reduces viscosity and density and stabilizes water-insoluble fraction of bio-oil for long-term storage and makes it suitable for transportation without phase separation (Bridgwater, 2003; Oasmaa et al., 2004). Most of the previous studies have experimentally studied the addition of 5%, 10%, and 15% methanol with bio-oil, and it is concluded that 10% methanol is sufficient to maintain the properties of bio-oil for at least 5 days (Domine et al., 2008; Lu et al., 2008; Oasmaa et al., 2004; Oasmaa and Peacocke, 2001; Yu et al., 2007). However, better properties of bio-oil are observed with increasing percentage of methanol. On the other hand, sulfur content is also an important issue for the reforming catalysts of any feedstock. Biomass as well as bio-oil has a low sulfur content that depends on the type of biomass feedstock used for bio-oil production (Oasmaa and Peacocke, 2001; Wang et al., 1997); hence, desulfurization of the feedstock is not considered before bio-oil reforming.

4.2.2. Bio-oil reforming

Bio-oil reforming is an endothermic process that leads toward the small amount of fossil fuel combustion for generating heat for the reforming process. The bio-oil/methanol mixture is transported to the bitumen upgrading plant by truck and then heated using flue gas generated from the combustion of natural gas. The bio-oil reforming process which produces syngas (mixture of mainly H_2 and CO) is carried out in a fluidized-bed reactor where steam acts as the fluidizing medium. The different components of bio-oil which were used during modeling in Aspen Plus are shown in Table A.1 in Appendix. Note that, during the simulation in Aspen Plus, only the high energy portion of bio-oil is steam reformed excluding the water content from bio-oil.

Steam reforming of bio-oil is carried out in the presence of a noble metal catalyst, rhodium (Rh) which resists coke formation during reforming reactions (Domine et al., 2008; Vagia and Lemonidou, 2008b). Bio-oil is a complex liquid fuel consisting of a large number of long-chain chemical compounds; the reforming process generates carbon on catalyst surface requiring a catalyst regeneration process (Davidian et al., 2008b). Noble metal catalysts, such as Pt and Ru, control better carbon formation on the catalyst surface and reactor wall making these catalysts suitable for large-scale H_2 production by biomass fast pyrolysis (Domine et al., 2008). There have been other studies reporting experimental work on using noble metal catalysts for bio-oil reforming (Basagiannis and Verykios, 2007; Iojoiu et al., 2007; Rioche et al., 2005). Some works have been completed on bio-oil reforming in the presence of low cost Ni-based catalyst, and research is still going onto improve the performance of Ni catalyst during the bio-oil reforming process (Bimbela et al., 2007; Davidian et al., 2008a; Magrini-Bair et al., 2002). Finally, autothermal steam reforming of bio-oil (at 850 °C, oxygen/carbon ratio of 0.7, and steam/carbon ratio of 3) produces mainly CO_2, CO, H_2, H_2O, and CH_4 which are cooled and compressed after removing solid particles (i.e. char and ash) from the product gas (Czernik et al., 2007; Evans et al., 2008). Although a significant number of studies have been published on H_2 production from bio-oil by catalytic reforming process, continuous H_2 fuel production from bio-oil reforming has not been successfully demonstrated yet.

4.2.3. Reformed gas clean up and compression

Upon being separated from char during fast pyrolysis of whole-tree, bio-oil contains about 0.2 wt% solid content (i.e. ash/char that vary with feedstock) which, in passing through the reforming process, results in coke formation on the surface of the catalyst (Bridgwater, 2004). Some catalysts are removed with the reformed gases and from them catalysts must be separated before the compression process. This is carried out by cyclone and baghouse filter. Gases produced by the reforming process are at a low pressure (0.17 MPa) and high temperature (850 °C); they require a rise in pressure for the water–gas shift reaction, if the rate at which hydrogen is produced is to be increased. Three stages of cooling (by HRSG) decrease the temperature of syngas (to 50 °C) in preparation for the compression process. A reciprocating compressor with 5-stage integrated with intercoolers increases the pressure of the gas (about 2.27 MPa). Compression of the gas further increases temperature, which is decreased by an air-cooled intercooler that causes water condensation. The water formed in the syngas mixture during the cooling process is removed before the next stage of compression by using knockout vessels. In short, reciprocating compressor with 5-stage is used in conjunction with 5 intercoolers and 5 knockout vessels to increase the gas pressure. The power required to run the compressor shaft is supplied by the electric motor (23.52 MW_e).

4.2.4. Water–gas shift reaction

The water–gas shift reaction, an exothermic reaction, increases the concentration of hydrogen gas in the product gas through the conversion of CO into CO_2 by steam. Heat is generated during the shift reaction; and hence, high temperature decreases the rate of hydrogen production (Chen et al., 2008). For that reason, catalysts are used in the beds of the shift reactors during the conversion process to produce more hydrogen without excessive temperature rise. Generally, two shift reactors – a high temperature shift (HTS) reactor and a low temperature shift (LTS) reactor – are used for producing hydrogen; iron oxide and chromium oxide are the two catalysts commonly used in the former reactor, and copper oxide and zinc oxide are the two catalysts commonly used in the latter reactor (Chen et al., 2008). The CO conversion rates in both HTS and LTS reactors rely on several factors, being influenced mainly by the residence time, catalyst bed size, temperature, and CO/steam ratio (Chen et al., 2008). One of the most important design parameters for the water–gas shift reaction is the steam requirement for the process. If the reformed gas has enough steam to accelerate the water–gas shift reaction in the presence of catalysts, no further steam is required for the process. Additionally, the steam requirement is governed by the CO/steam ratio in the reactors. The gas leaving the reactor is cooled for the biohydrogen purification process.

4.2.5. Biohydrogen purification

During the syngas cooling process after the water–gas shift reaction, a small percentage of steam in the reformed gas is condensed and then removed to prevent catalyst poisoning in the pressure swing adsorption (PSA) unit. The PSA unit is a gas separation/purification unit where H_2 gas at a high pressure and low temperature is separated from a blend of gases by adsorption solvents such as activated carbon, silica gel, and zeolite (Sircar and Golden, 2000). The PSA unit has several columns where successive pressurization and depressurization in the columns separate the hydrogen from other gases with a separation efficiency of 80–90% (Sircar and Golden, 2000). In this study, the recovery rate of biohydrogen from a PSA unit is assumed to be 80 wt% based on the values reported by Sircar and Golden (2000).

4.2.6. Steam production

Steam is one of the most important design parameters of the bio-oil reforming process, and its flow rate has a large impact on the production of biohydrogen. Steam is basically required to create the fluidizing medium, to transfer heat into the reforming reactor, and to be the feed gas in the water–gas shift reactors; it assists in the conversion of CO into CO_2 and the production of hydrogen. In this study, the steam required for the reforming process and the water–gas shift reaction is produced from the HRSG process. The electricity required for the equipment is purchased from the grid, although there is great opportunity of using electricity generated from a cogeneration process at the bitumen upgrading plant (this has not been investigated in this study). Bio-oil reforming is an endothermic process which produces reformed gases at a high temperature; heat is recovered from the reformed gases for steam production. The steam required for the reforming process could also be produced from external sources such as the combustion of natural gas or charcoal.

5. Estimation of biohydrogen production cost

The cost of producing biohydrogen from bio-oil, which in turn is produced from the fast pyrolysis of biomass, has three key cost components: the cost of producing bio-oil from biomass, the cost of transporting bio-oil, and the cost of reforming bio-oil for biohydrogen production. Details on the cost parameters for biohydrogen production are given in the subsequent sections. Once all the cost parameters are determined, techno-economic models are developed to estimate the cost of bio-oil and biohydrogen.

5.1. Cost of producing bio-oil

5.1.1. Capital cost

The capital cost of the biomass fast pyrolysis process for bio-oil production includes: the cost of biomass harvesting, transportation, and pretreatment, the cost of converting biomass to bio-oil, the cost of storing bio-oil and recycling non-condensable gas, and the cost of producing steam and electricity. "As received" biomass from the forest has a high moisture content and a large feedstock size after the chipping process which requires the drying and grinding processes. In this study, a plant capacity of 500 dry tonnes/day is assumed in the base case which has been derived from earlier studies (Curtis et al., 2003; Phillips et al., 2007). The cost of the feedstock drying and handling equipment contributes about 32% of the total equipment cost for the base case plant size. The second largest cost contributor (17% of the total equipment cost) is the pyrolysis unit which includes a bubbling fluidized-bed reactor and a char combustor. Rest 41% of the capital cost consists of the components listed in Table 1. Scale factors and maximum equipment size for the biomass fast pyrolysis process are derived from different studies and explained in Table 1. Finally, the estimated overall scale factor for a bio-oil production plant is 0.78, that is calculated using the capital costs at various production plant sizes. This scale factor is specific to whole-tree-based plants. Details on the components of the capital cost of a base case bio-oil production plant including scale factors are summarized in Table 1.

One of the most important plant design parameters is the size of the pyrolysis reactor which is designated here by dry tonnes of biomass/day. Bio-oil production plant with large pyrolysis reactor can process large amount of biomass feedstock in a single reactor that will provide higher economy of scale benefits. The maximum capacity of the bubbling fluidized-bed (BFB) reactor is assumed to be 1000 dry tonnes/day based on an earlier study conducted in National Renewable Energy Laboratory, US (Spath et al., 2005). In this study, this size is assumed to be the maximum size of the pyrolysis reactor, and multiple reactors are used for plants processing more than 1000 dry tonnes/day.

Table 1
Capital cost of whole-tree-based bio-oil production plant (500 dry tonnes/day).

Factors	Base case cost ($1000)	Scale factor[k]
Feedstock drying and handling[a]	8053	0.70
Pyrolysis unit[b]	4335	0.65
Quenching unit[c]	2145	0.65
Heat recovery unit[d]	1261	0.70
Bio-oil recovery and storage unit[e]	885	0.60
Recycle pyrolysis vapor unit[f]	1526	0.70
Steam and power generation unit[g]	3495	0.70
Cooling tower unit and other utilities[h]	3462	0.78
Equipment contingency (% of equipment cost)	35	
Total equipment cost	33,970	
Warehouse (% of total equipment cost)	1.5	
Site development[i]	1195	
Total installed cost (TIC)	35,674	
Indirect cost[j] (% of TIC)	48	
Total capital investment (TCI)	52,797	
Startup cost (% of TCI)	10	
Total project investment	58,077	

[a] Maximum size of the feedstock drying and handling system is 2640 wet tonnes/day (Hamelinck and Faaij, 2002), and multiple numbers of feedstock handling systems are used when plant size exceeds the maximum size. Cost of the feedstock pretreatment is estimated from Phillips et al. (2007) by comparing cost values with other studies (Jones et al., 2009; Spath et al., 2005), and most of the costs are contributed by biomass dryer and boilers. From these studies, mentioned here, the scaling factor of rotary biomass dryer is 0.75 and steam generator is 0.60–0.65.

[b] The pyrolysis reactor is a bubbling fluidized-bed reactor, which is currently used commercially for bio-oil production (Jones et al., 2009); its estimated cost is based on the cost of the fluidized-bed boiler (Ringer et al., 2006). The scaling factor of fluidized-bed reactors are 0.65–0.70 (Hamelinck and Faaij, 2002; Jones et al., 2009; Phillips et al., 2007; Spath et al., 2005).

[c] Pyrolysis vapor is cooled and condensed by water and air, and steam is produced from the HRSG process (Ringer et al., 2006). Scaling factors for the heat exchangers are reported in between 0.60 and 0.70 (Hamelinck and Faaij, 2002; Kreutz et al., 2005; Spath et al., 2005).

[d] Char is burnt to generate heat that will be used to produce steam and to preheat ground biomass. Scale factor of heat recovery section is in the range of 0.60–0.70, which is actually the scale factor of heat exchanger and boiler (Spath et al., 2005). However, Larson et al. (2005) have used scale factor 1 (i.e. no economy of benefit for increasing plant size) for boiler and heat exchangers.

[e] Bio-oil recovery unit mainly consists of pump, cooler, mixer, and storage tank (Ringer et al., 2006), and high economy of scale is plausible with increasing equipment size when bio-oil is quenched by spraying cold bio-oil. In contrast, scaling factors will be high for cooling bio-oil by water and air.

[f] Non-condensable pyrolysis vapor is recycled back to the pyrolysis reactor to transfer heat and to fluidize feedstock, and major components for recycling pyrolysis vapor are pumps, compressor, condenser, and flash drum (Ringer et al., 2006). Therefore, scaling factor for gas-compressor is 0.60–0.80, while scaling factor for pump is 0.33–0.79 (Kreutz et al., 2005; Spath et al., 2005).

[g] Cost represents the purchase price of an economizer, a boiler, and a steam turbine capable of generating 4.9 MW_e of electricity (Ringer et al., 2006). This is similar to the values reported by other studies, while scaling factor of HRSG is 0.67–1 and of steam turbine is around 0.67 (Hamelinck and Faaij, 2002; Kreutz et al., 2005; Larson et al., 2005).

[h] Major units are the cooling tower and mixing chambers (Ringer et al., 2006), and the scaling factor for the cooling tower is around 0.78 (Phillips et al., 2007; Spath et al., 2005), which is used here.

[i] Represents 9% of the major equipment cost for a biomass pyrolysis plant (Ringer et al., 2006).

[j] Indirect costs are for engineering, construction, project contingency, and contractor fee; these costs are about 44–51% of TIC, based on the figures from different biomass-based studies (NRC, 2004; Spath et al., 2005).

[k] Scale factors are estimated from earlier studies which use similar processes (Hamelinck and Faaij, 2002; Larson et al., 2005; Spath et al., 2005).

Note that separate cases have been developed for biohydrogen production from bio-oil for three different feedstocks: whole-tree, forest residues, and straw. The capital costs of the bio-oil production plants for three feedstocks differ due to the differences in the drying requirements of the feedstock; hence, capital costs are modified accordingly. A 10% capital cost penalty is attributed to the plant processing whole-tree and forest residues due to their remote location from the urban area.

5.1.2. Operating cost

The operating cost of a bio-oil production plant includes the cost of electricity for the feedstock grinder, compressor motors, pumps, and other plant equipment. No air/oxygen is supplied to the pyrolysis reactor; this is carried out to impede complete combustion of the feedstock. The heat required for the drying process is provided from the combustion of char. Even at a char combustion efficiency of 34 wt%, there is excess char (about 0.1% of the biomass dry basis capacity) in the biomass fast pyrolysis process (Mullaney et al., 2002). In this study, the yield of char is assumed to be 15.3 wt% of dry whole-tree, all of which is burnt for heat and steam production; therefore, there will be some excess electricity produced during bio-oil production which could be transmitted to the grid. Fixed values are assumed for the costs of electricity and chemical consumption for waste-water treatment. The estimated plant yearly operating cost, excluding the cost of feedstock, is about 1.2% of its capital cost (Ringer et al., 2006; Spath et al., 2005). The ash in biomass is collected from char in the cyclones as fly ash. In this study we have assumed that this ash is distributed in the field/forest within an average radius of 50 km. The cost of transporting and spreading ash is considered in this study at $0.18/dry tonne/km and $25.22/dry tonne/ha of ash for the base case plant size, respectively. These costs are derived from earlier studies (Kumar et al., 2003; Sarkar and Kumar, 2009; Zundel et al., 1996).

In this study, the delivered costs of chips from whole-tree and forest residue from the forest to the bio-oil production plant are $35 and $28/dry tonnes, respectively and are derived earlier by the authors (Kumar et al., 2003; Sarkar and Kumar, 2009, 2010). Similarly, straw bales from the field to the bio-oil plant are delivered at a cost of $67/dry tonne and derived from an earlier study for Western Canada (Sultana et al., 2010). These costs are estimated for a plant size of 500 dry tonnes of biomass/day, and estimated yields are 84 dry tonnes/ha, 0.247 dry tonnes/ha, and 2.25 dry tonnes/ha for whole-tree, forest residues, and straw from wheat and barley crops, respectively (Kumar et al., 2003; Sultana et al., 2010).

This study includes the grinding cost and storage cost of the biomass. Purchase price of grinder is included in the capital cost, and operating cost of the grinder is shown in Table 2. The shredding cost of straw is $1.48/dry tonne and is incurred at the plant. These costs are derived from earlier studies (Polagye et al., 2007; Sokhansanj et al., 2006). Three months of biomass storage cost at the plant is included in this study. This cost is $4.06/dry tonne that consists of loading and unloading costs (Hamelinck et al., 2005).

Fixed operating costs, i.e. administrative ($64/h) and labor ($40/h) costs are assumed to be comparable with the fixed operating cost of a biomass gasification plant, as explained in Sarkar and Kumar (2009). It is assumed that there will not be any significant difference in the fixed operating cost of biomass gasification and fast pyrolysis plants, although in reality, fixed operating cost of biomass pyrolysis plant will be lower than that of biomass gasification plant. All of the variable operating costs of a bio-oil production plant are listed in Table 2. The maintenance cost of a biomass fast pyrolysis plant is assumed to be 2% of the plant investment cost based on different studies on the biomass processing (Kumar, 2009; Spath et al., 2005).

5.1.3. Bio-oil production cost

Whole-tree, forest residues, and straw are used for bio-oil production. Different cost components of bio-oil production for a plant capacity of 500 dry tonnes/day (base case) are listed in Table 3. In the base case, whole-tree biomass feedstock has the lowest production cost of bio-oil ($0.20/kg), where 38% and 29% of the total production cost are contributed by capital cost and feedstock delivery cost, respectively. As plant size increases, the contribution of the feedstock delivery cost increases for all of the feedstocks because of increasing transportation distance of biomass. This bio-oil production cost is on the lower end side as compared to the values reported in the literature because of the large scale of the production plant. The benefit from the economy of scale in capital cost is more than the increase in the transportation cost due to larger size. The bio-oil production costs from forest residues and straw from a 500 dry tonnes/day plant are $0.35 and $0.61/kg, respectively. There is scarcity of data on the bio-oil production cost from forest residues and straw in the literature.

Fig. 2 gives a summary of the variation in bio-oil production cost at different capacities for plants processing whole-tree, forest residues, and straw. The whole-tree-based plant has the lowest bio-oil production cost; however, the costs of bio-oil from whole-tree and forest residues follow the similar trends. The cost of bio-oil drops rapidly when the plant size increases from 500 to 2000 dry tonnes/day, while costs of bio-oil are almost flat after a plant size of 2000 dry tonnes/day for these feedstocks (until 10,000 dry tonnes/day). In contrary, cost of bio-oil from straw increases after a plant size of 2000 dry tonnes/day with a rapid drop

Table 2
Variable operating costs for a bio-oil production plant.

Factors	Value	Comments/sources
Gross electricity production from HRSG (kW h/dry tonne)	235	Electricity is produced from a heat recovery steam generation process (Ringer et al., 2006)
Non-condensable recycle gas compression (kW h/dry tonne)	125	Non-condensable gases are recycled back to the pyrolysis reactor (Ringer et al., 2006)
Feedstock grinding process (kW h/dry tonne)	67	Overall energy consumption for feedstock grinding (about 3 mm) process (Ringer et al., 2006)
Purchase price of methanol ($/l)	0.25	Spot price of methanol (Haas et al., 2006)
Electricity selling price ($/kW h)	0.07	The excess electricity, which is produced from the HRSG process, could be sold to the grid

Table 3
Base case production cost of bio-oil from biomass fast pyrolysis (500 dry tonnes/day).

Cost components	Whole-tree (% of total cost)	Forest residues (% of total cost)	Straw (% of total cost)
Capital	38	36	25
Operating	4	4	4
Maintenance	6	6	4
Administrative	22	25	16
Harvesting	9	11	15
Transportation	7	12	12
Feedstock storage	1	1	2
Road and infrastructure	7	0	0
Silviculture	2	0	0
Nutrient replacement	0	0	18
Royalty cost/premium	4	4	3
Ash disposal	0	1	1
Total production cost ($/kg of bio-oil)	0.20	0.35	0.61

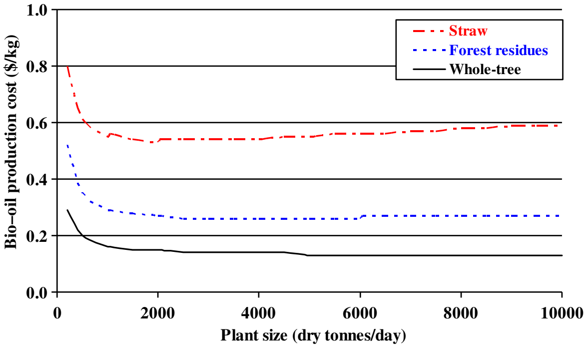

Fig. 2. Variation of bio-oil production cost with plant size for whole-tree, forest residues, and straw.

in production cost for plant size of 500–2000 dry tonnes/day. These trends in production costs for straw-based bio-oil are different than forest biomass due to high feedstock delivery cost of straw compared to forest biomass and low bio-oil yield from straw.

The cost of producing bio-oil decreases rapidly for whole-tree feedstock until the plant capacity reaches 1500 dry tonnes/day ($0.15/kg of bio-oil). Additionally, the cost of producing bio-oil drops rapidly to $0.27/kg for forest residues and $0.53/kg of bio-oil for straw at a plant capacity of 2000 dry tonnes/day. Beyond these plant capacities, costs are almost constant for whole-tree and forest residues, whereas, for straw, bio-oil production cost increases after a plant capacity of 2000 dry tonnes/day. As a result, there is no technical optimum plant size (i.e. the size at which the cost of production is minimum) for bio-oil production based on whole-tree within the plant capacity shown in Fig. 2, but it is possible to build a size at which the cost of production is lowest. Optimum size of different biomass-based facilities has been discussed earlier in various studies (Cameron et al., 2006; Kumar, 2009; Kumar et al., 2003; Sarkar and Kumar, 2009, 2010).

From the above discussion, it is reasonable to assume that bio-oil will be produced in a plant processing 2000 dry tonnes of whole-tree/day. This is the assumed size in the base case for bio-oil reforming process. Bio-oil produced by this plant is transported to a biohydrogen production plant. The size of the biohydrogen production plant relies on the type of biomass feedstock (i.e. whole-tree, forest residues, or straw) is the used for bio-oil production. This is because the bio-oil yields are different for the selected biomass feedstocks which will result in different optimum bio-oil production plants.

5.2. Cost of transporting bio-oil

Once bio-oil is produced, it is stored in a large tank, and methanol is added to keep the properties of bio-oil stable, as explained earlier. The bio-oil/methanol blend is transported to a biohydrogen production plant by truck, and that same truck will transport methanol to the bio-oil production plant on the way back to bio-oil production plant. The transportation of bio-oil is carried out by super B-train trucks with a transportation capacity of about 60 m^3 (about 72 tonnes of bio-oil) each. This truck has a distance-fixed cost (i.e. this mostly includes loading and unloading cost) and a distance-variable cost (i.e. this includes cost of labor, fuel, maintenance) of \$1.193/m^3 and \$0.048D/m^3 of bio-oil, respectively (Transport Canada, 2005). Here, D is the transportation distance between the bio-oil production plant and the bitumen upgrading plant. In this study, this is assumed to be 500 km. The transportation of bio-oil by B-train truck costs $0.041/kg of bio-oil for each 500 km trip.

Although current transportation method of bio-oil is truck, pipeline could be another attractive transportation method for large scale and long transportation distance. Pipeline transportation of bio-oil has been extensively studied earlier (Pootakham, 2009; Pootakham and Kumar, 2010a,b).

5.3. Cost of reforming bio-oil

5.3.1. Capital cost

Fast pyrolysis of whole-tree yields 59.9 wt% bio-oil. Based on this yield, 1198 tonnes of bio-oil is produced from the fast pyrolysis of 2000 dry tonnes of whole-tree. Thus a plant processing 2000 dry tonnes of whole-tree/day would supply feedstock to a bio-oil reforming plant that has a capacity of processing 1198 tonnes bio-oil/day. The bio-oil reforming plant produces biohydrogen. The capital cost of the biohydrogen production plant (or bio-oil reforming plant) is $155 million with a scale factor of 0.70 for a plant capacity of 1198 tonnes of bio-oil/day (illustrated in Fig. 3). Basically, different equipment sizes of bio-oil reforming plant are estimated from the Aspen Plus simulation tool. Once the size is known, different literatures have been used to estimate the cost of the equipment. Note that, capital costs and scale factors of bio-oil production and bio-oil reforming are estimated from different studies which uses similar types of equipment (Corradetti and Desideri, 2007; Hamelinck and Faaij, 2002; Kreutz et al., 2005; Larson et al., 2005; Spath et al., 2005).

The total amount of bio-oil/methanol blend transported in a day is 1331 tonnes; this requires 18 truck trips/day (including the transportation of 10 wt% of methanol). The operating parameters of bio-oil reforming plant have been estimated from literatures (Cicconardi et al., 2006; Hao et al., 2008; Vagia and Lemonidou, 2008a), which have studied similar processes or equipment and the Aspen Plus model. The capital cost of steam reforming of bio-oil for producing biohydrogen includes the cost of each unit of feedstock (bio-oil and methanol) storage, feedstock reforming, product gas clean up, product gas compression, water–gas shift reaction, hydrogen purification (i.e. PSA), and steam production. The Aspen Plus simulation tool is used to calculate equipment size and other operating parameters (e.g. stream flow rate, hydrogen yield from bio-oil). Meanwhile, the capacity of the heat transfer equipment (i.e. boiler, superheater, and heater) is calculated from the heat duty, and the capacities of the pump and compressor are calculated from the power required to drive the motor. Once all the cost components and operating parameters are estimated, a techno-economic model of bio-oil production from biomass and of biohydrogen production from bio-oil is developed to estimate the cost of production of biohydrogen.

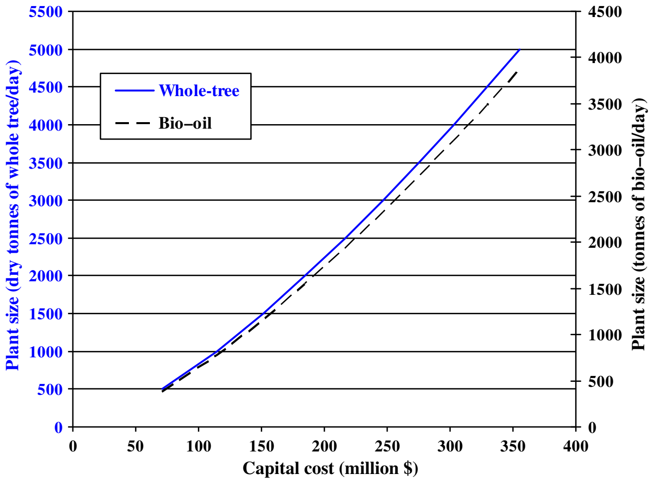

Fig. 3. Capital cost of a bio-oil reforming plant for biohydrogen production.

Table 4
Variable operating cost for base case bio-oil reforming (1198 tonnes bio-oil/day).

Factors	Value	Comments/sources
Power requirement (MW_e)	39.16	Gas compression and air separation units consume most of the power
Price of electricity ($/kW h)	0.07	A fixed value is assumed for electricity price in Alberta
Natural gas consumption (million GJ)	4.04	Natural gas is used to produce steam for the reforming reaction and water–gas shift reaction
Cost of natural gas ($/GJ)	5	A fixed value is assumed for natural gas price in Alberta
Amount of reforming catalyst (kg)	1890	The amount of catalyst is calculated from a stand-alone hydrogen production plant with a capacity of 1500 kg/day (Evans and Steward, 2007)
Life of catalyst (in years)	5	Catalyst is lost from the reactor because solids are removed with the syngas (Evans and Steward, 2007)
Cost of reforming catalyst ($/kg)	13,540	Rhodium (Rh) is the catalyst which is used in the bio-oil reforming process (Evans and Steward, 2007)
Water consumption (m^3/kg of H_2)	0.02	The steam to carbon ratio is assumed to be 3
Cost of water treatment ($/$m^3$)	0.78	Cost of waste-water treatment (Phillips et al., 2007; Spath et al., 2005)

5.3.2. Operating cost

The variable operating cost of a bio-oil reforming process includes the cost of electricity, natural gas, reforming catalyst, boiler chemicals, waste-water treatment, and reactor catalysts. In this study, natural gas is burnt to produce only the process steam. The electricity required to operate the auxiliary equipment of the plant is purchased from the grid. However, a large bitumen upgrading facility typically will have a cogeneration facility for steam and electricity production using natural gas as its feedstock with an efficiency of about 75% (NEB, 2004). It could be assumed that the cogeneration process will produce sufficient electricity to meet the electricity demand of the bitumen upgrading and bio-oil reforming processes. Although this has not been analyzed in this study. The variable operating costs for bio-oil reforming are shown in Table 4.

6. Results and discussion

6.1. Delivered biohydrogen cost

The cost of whole-tree-based H_2 from a 2000 dry tonnes/day plant (one that produces 1198 tonnes of bio-oil/day) is $2.40/kg ($20/GJ). For a plant with a capacity of 2000 dry tonnes of whole-tree/day, the cost of bio-oil production is $0.15/kg, and bio-oil production cost contributes 34% of the total cost of biohydrogen production. The overall yield of biohydrogen from the fast pyrolysis process is 9.8 wt% of the dry whole-tree biomass feed in the bio-oil production plant, or 14.7 wt% of the blend of bio-oil and 10 wt% methanol in a biohydrogen production plant. The theoretical maximum yield of biohydrogen from bio-oil could be 17.2 wt% (Milne et al., 2002), while yield of H_2 from catalytic reforming of bio-oil is 12.6 wt% of dry biomass (Wang et al., 1997). If methanol amount is increased to 15 wt% instead of 10 wt%, the yield of biohydrogen drops to 9.71% of dry whole-tree feed resulting in biohydrogen production cost of $2.42/kg ($20.17/GJ). Therefore, lower methanol use in the reforming process results in higher yield, but the amount should be high enough to keep the properties of bio-oil stable during storage and transportation. In this study, it is assumed that 10 wt% methanol is added with bio-oil-based on the different literatures on bio-oil properties and from the simulation results on biohydrogen yield which is explained earlier.

Note that the properties of bio-oil from these three biomass feedstocks are different that will result in different yields of hydrogen fuel from bio-oil; however, only the whole-tree-based bio-oil is simulated in this study to estimate the biohydrogen production cost. Bio-oil produced from whole-tree and forest residues will have similar properties which will result in similar yields of H_2 from whole-tree and forest residues. Basically, straw has high ash content and different composition compared to whole-tree or forest residues that will result in lower yield of H_2. However, straw-based bio-oil has not been simulated in this study, and cost of H_2 is estimated assuming similar properties of bio-oil derived from the selected three biomass feedstocks. The basic differences in bio-oil from different biomass feedstocks would be in water content, pH values, viscosity, and heating values (Hassan et al., 2009; Liu et al., 2010; Lu et al., 2008). Table 5 lists the cost associated with producing biohydrogen from steam reforming of bio-oil produced by the fast pyrolysis of whole-tree.

The largest contributor to the cost of producing biohydrogen from bio-oil is the feedstock delivery cost (53%, includes cost associated with bio-oil and methanol production and transportation) followed by plant operating and maintenance cost (35%). Consumption of natural gas constitutes about 42% of the variable operating cost; other variable operating costs are the cost of electricity for compressors, pumps, air separation unit, and electric motors (45%), cost of the reforming catalyst (11%), and cost of water treatment (2%).

Fig. 4 shows the costs of producing biohydrogen from the fast pyrolysis of biomass and the steam reforming of bio-oil from different biomass feedstocks. The cost of producing biohydrogen decreases rapidly up to a plant capacity of about 2000 dry tonnes/day. There is no technical optimum size for biohydrogen production using pyrolysis of biomass below a plant capacity of 10,000 dry tonnes/day. The costs of producing biohydrogen from whole-tree and forest residues follow the similar trends. The cost of producing straw-based biohydrogen is higher than whole-tree-based and forest residues-based biohydrogen, and the optimum size of straw-based biohydrogen plant is 4000 dry tonnes/day ($4.49/kg of H_2). This is because of low yield of bio-oil from straw resulting in high cost of bio-oil production from straw and high straw transportation cost.

Whole-tree has the lowest biohydrogen production cost, followed by forest residues. At a bio-oil production cost of $0.27 and $0.53/kg from 2000 dry tonnes of biomass/day, the costs of producing biohydrogen are $3.00 and $4.55/kg of H_2 from forest residues and agricultural residues, respectively. Hence, whole-tree has the greatest potential for biohydrogen production through the fast pyrolysis when there is a constraint in the availability of biomass feedstock. In contrary, the production cost of H_2 from natural

Table 5
Delivered H_2 production cost from fast pyrolysis of whole-tree (2000 dry tonnes/day) with bio-oil reforming.

Cost factors	Value ($/kg of H_2)	% of total cost
Capital	0.28	12
Operating	0.74	31
Maintenance	0.03	2
Administrative	0.06	2
Bio-oil production	0.83	34
Methanol purchase	0.20	8
Bio-oil transportation	0.26	11
Total cost	2.40	100

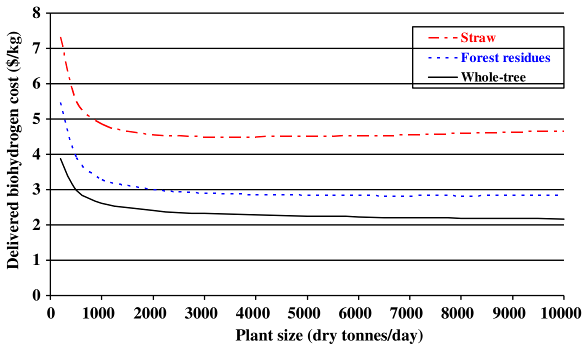

Fig. 4. Cost of delivered biohydrogen from bio-oil produced by fast pyrolysis of biomass.

gas is about \$0.96–3.5/kg (Balat, 2008; Chen and Elnashaie, 2006; Sarkar and Kumar, 2009), which varies with the plant size, natural gas price, and other variables. This cost is lower than the cost of biohydrogen. Currently, H_2 for bitumen upgrading process is exclusively produced from natural gas in Alberta (Dunbar, 2007), while around 50% of world H_2 fuel is produced from natural gas followed by oil and coal (Balat, 2009).

6.2. Sensitivities

6.2.1. Carbon credits required for biohydrogen

Biohydrogen production using fast pyrolysis of biomass involves bio-oil production from biomass and steam reforming of bio-oil. Hence, life cycle emission for producing biohydrogen from biomass fast pyrolysis could be separated in three sections: emissions from producing bio-oil, emissions from transporting bio-oil/methanol blend, and emissions from reforming of bio-oil. The

Table 6
Life cycle emissions (kg CO_2 equivalent/kg of H_2) from biohydrogen production from fast pyrolysis of biomass (2000 dry tonnes/day).

Factors	Whole-tree	Forest residues	Straw
Biomass production[a]	0.327	0.882	0.476
Biomass transportation[b]	0.073	0.616	0.346
Construction and decommissioning of bio-oil production plant[c]	0.185	0.369	0.482
Bio-oil transportation[d]	0.502	0.502	0.502
Energy conversion	0	0	0
Construction and decommissioning of bio-oil reforming plant[e]	0.068	0.034	0.026
Total emissions	1.15	2.40	1.83

[a] With a bio-oil yields of 59.9 wt%, 29.97 wt%, and 22.93 wt% from whole-tree, forest residues, and straw, and with a biohydrogen yield of 14.72 wt% from the bio-oil/methanol blend, the amount of feedstock required for 1 kg of H_2 production is 10.2 kg of dry whole-tree, 20.39 kg of dry forest residues, and 26.66 kg of dry straw, respectively. Emissions for whole-tree biomass production include emissions during felling, skidding, chipping, and transportation of chips to the bio-oil production plant. Emissions for forest and agricultural residues are explained earlier by the authors (Sarkar and Kumar, 2010).

[b] Biomass is transported from the forest by truck to a bio-oil production plant capable of processing 2000 dry tonnes/day; the average transportation distance is 18 km, 76 km, and 89 km for whole-tree, forest residues, and straw, respectively.

[c] Emission from plant construction and decommissioning is calculated based on the amount of biomass required to produce 1 kg of biohydrogen, and the calculated value is 18.1 g CO_2/kg of dry biomass (Kumar et al., 2003).

[d] The bio-oil/methanol blend is transported 500 km by truck having a capacity of 60 m^3.

[e] Estimated emission from the construction and decommissioning of the bio-oil reforming plant is calculated from the comparison of hydrogen production from natural gas reforming plant (Spath and Mann, 2001).

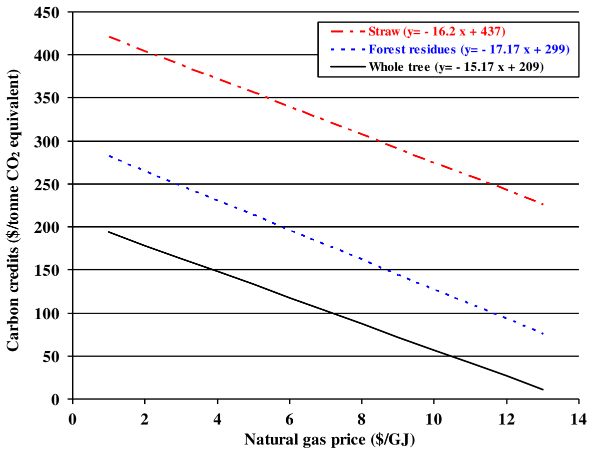

Fig. 5. Carbon abatement cost for biohydrogen where bio-oil replaces natural gas-based hydrogen.

Table 7
Key sensitivities of producing H_2 from the fast pyrolysis of biomass.

Factors	Price (\$/kg)	Price impact (%)
Base case, cost of producing bio-oil from whole-tree	0.15	
Capital cost of bio-oil plant		
10% higher	0.15	0
10% lower	0.14	−6.7
Operating cost of bio-oil plant		
10% higher	0.15	0
10% lower	0.14	−6.7
Yield of bio-oil		
10% higher	0.13	−13.3
10% lower	0.16	+6.7
Utilization of bio-oil plant		
95% in 3rd year and onward	0.14	−6.7
80% in 3rd year and onward	0.15	0
Base case, cost of producing biohydrogen from the fast pyrolysis of whole-tree	2.40	
Capital cost of biohydrogen plant		
10% higher	2.44	+1.7
10% lower	2.37	−1.2
Operating cost of biohydrogen plant		
10% higher	2.48	+3.3
10% lower	2.32	−3.3
Cost of bio-oil		
10% higher	2.49	+3.8
10% lower	2.32	−3.3
Yield of biohydrogen		
10% higher	2.19	−8.8
10% lower	2.67	+11.3
Cost of bio-oil transportation		
10% higher	2.43	+1.3
10% lower	2.38	−0.8
Cost of natural gas		
10% higher	2.44	+1.3
10% lower	2.37	−1.7
Cost of electricity		
10% higher	2.44	+1.7
10% lower	2.37	−1.2
Bio-oil reforming with a cogeneration plant with no purchased electricity	2.07	−13.8
Utilization of biohydrogen plant		
95% in 3rd year and onward	2.37	−1.2
80% in 3rd year and onward	2.42	+0.8
Pretax return on capital cost is 12% rather than 10%	2.51	+4.6

emissions are calculated based on the total amount of biomass required to produce 1 kg of biohydrogen (i.e. functional unit). During the storage and transportation of bio-oil, 10 wt% of methanol is added to the bio-oil, the emissions from producing methanol are disregarded as it is assumed that this will come from a renewable resource; and hence, there would be negligible emissions compared to the total emissions from the process of producing bio-oil. On the other hand, emissions during the transportation of methanol are included in the total emissions for bio-oil transportation. Table 6 gives the life cycle emissions for producing biohydrogen from the pyrolysis of biomass.

Using the data in Table 6, the cost of carbon mitigation is estimated for biohydrogen production from bio-oil which is produced from whole-tree, forest residues, and straw. Fig. 5 depicts the comparison of the carbon credits required for biohydrogen to be competitive with natural gas-based hydrogen. At a natural gas price of \$5/GJ, carbon credits of \$133, \$214, and \$356/tonne of CO_2 equivalent are required for making the biohydrogen from the fast pyrolysis of whole-tree, forest residues, and straw, respectively to be competitive with natural gas-based hydrogen.

6.2.2. Other sensitivities

Sensitivity analyses of bio-oil production from whole-tree, forest residues, and agricultural residues show similar characteristics. The impact of different cost components is approximately same for these three biomass feedstocks. The yield of bio-oil has the greatest impact on the cost of bio-oil production, followed by the capital cost for a forest biomass-based bio-oil plant. The size of a bio-oil reforming plant is estimated based on the rate at which its bio-oil production plant processes biomass. Various sensitivity analyses show that biohydrogen yield has the greatest impact on biohydrogen cost, although other parameters have a slight impact on that cost. Table 7 provides a sensitivity analysis of biohydrogen production from the fast pyrolysis of whole-tree. Because whole-tree biomass provides the cheapest biohydrogen, the various in costs are shown for this case.

7. Conclusions

Biohydrogen can be produced from the fast pyrolysis of whole-tree, forest residues, and straw at a cost of \$2.40 (\$20/GJ of H_2), \$3.00 (\$25/GJ of H_2), and, \$4.55/kg of H_2 (\$38/GJ of H_2), respectively. The cost of biohydrogen production is lowest for whole-tree, where cost of bio-oil production is \$0.83/kg and cost of bio-oil transportation is \$0.26/kg. There is no technical optimum size for bio-oil production plants processing whole-tree and forest residues below a size of 10000 dry tonnes/day; however, maximum economy of scale benefits in capital cost for fast pyrolysis of whole-tree is observed at 2000 dry tonnes/day. Cost at this size is \$0.15/kg of bio-oil for whole-tree-based biomass feedstock. For plants larger than this size, there is a very slight decrease in the cost of bio-oil as the plant size increases. A 2000 dry tonnes/day whole-tree-based fast pyrolysis plant produces 1198 tonnes of bio-oil/day. That will produce 167 tonnes of H_2/day at a cost of \$2.40/kg of H_2. The optimum size of straw-based biohydrogen plant is 2000 dry tonnes/day, and costs of bio-oil and biohydrogen from straw are higher than that of forest biomass. As the cost of biohydrogen is higher than the cost of natural-gas-based H_2, carbon credit (\$133/tonne of CO_2 equivalent at a natural gas price of \$5/GJ) is required for it to be competitive with natural-gas-based H_2.

Appendix A

See Table A.1.

Table A.1
Simulated composition of bio-oil derived from whole-tree.

Selected compound	Simulated composition[a] (wt%)	Compound type
Acetic acid ($C_2H_4O_2$)	9.9	Carboxylic acid
Propionic acid ($C_3H_6O_2$)	12.2	Carboxylic acid
Formic acid (CH_2O_2)	5.69	Carboxylic acid
3,5-Dimethoxy-4-hydroxy benzoic acid ($C_{10}H_{12}O_2$)	27.31	Carboxylic acid
Guaiacol ($C_7H_8O_2$)	1.02	Phenol
Phenol (C_6H_6O)	0.77	Phenol
Toluene (C_7H_8)	3.79	Aromatic hydrocarbon
Benzene (C_6H_6)	1.29	Aromatic hydrocarbon
Methyl acetate ($C_8H_{10}O_3$)	6.34	Esters
Furfural ($C_5H_4O_2$)	31.69	Aromatic aldehyde

[a] Chemical composition of bio-oil is taken from the bio-oil produced from wood and used in Aspen Plus during modeling of biohydrogen production from bio-oil (Ringer et al., 2006).

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