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Techno-economic assessment of transportation biofuels from hydrothermal liquefaction of forest residues in British Columbia

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A B S T R A C T

A techno-economic assessment was conducted to estimate the capital and operating costs of a hypothetic biofuel system based on hydrothermal liquefaction (HTL) of forest residues in British Columbia. Three scenarios were investigated to understand how supply chain designs could influence the system's economic performance. The minimum selling price (MSP) of HTL biofuels was found to be 63%–80% higher than that of petroleum fuels. Converting forest residues to bio-oil and wood pellet before being transported to the conversion facility can lower the variable operating cost but not the MSP of HTL biofuels, due to the considerable increase in capital investment. Processing parameters such as the yield of bio-oil and biofuel can significantly influence the MSP of HTL biofuels, therefore, technology advancement can make great contribution in reducing the production cost. Alternatively, a high carbon tax is needed to make the HTL biofuels competitive with petroleum fuels.

1. Introduction

British Columbia (BC) government released BC Bioenergy Strategy in 2008 and recognized bioenergy as a critical approach to help BC achieve its greenhouse gas (GHG) emission reduction goals and economic objectives [1]. By 2013, a bioenergy sector has been established within BC, including 726 MW electricity capacity from pulp and paper mills, 2400 kW biogas system, 30 community bioheat installations and 2 million tonnes capacity of wood pellets [2]. Besides, insights have been shed on developing a liquid biofuel industry in BC to help the transportation sector get rid of high reliance on fossil fuels and mitigate GHG emissions [3]. In BC, transportation consumes about 85% of refined petroleum fuels and contributes around 38% of total GHG emissions, leading all other economic sectors [4,5]. In its 2050 renewable city strategy, Vancouver proposed to replace all transportation fossil fuels with renewable hydro-electricity and renewable biofuels, demanding the development of low-carbon and renewable transportation fuels [6].

Forest residues from logging operation, consisting of branches, barks, tree tops, etc., do not have the issue of energy versus food when used as feedstock for biofuel production, and thus could be more sustainable than food crops and oil seeds. According to Industrial Forestry Service Ltd., the volume of woody biomass potentially available for bioenergy production and surplus to the demand of existing forestry industry in BC in 2016 is estimated to be around 21 million m^3, of which 15.7% is forest logging residues [7]. Forest residues make up 5%–10% of the feedstock of BC wood pellet industry, which produces about 2 million tonnes of pellets annually, representing 61% of the total capacity of Canada [2]. However, 84% of the produced pellets ends up being exported to Europe for district heating and power generation due to a lack of markets in BC [8], and the long-distance transportation also causes a high carbon foot print (295 kg CO_2-eq/tonne of pellets) [9]. Thus, the shift of abundant forest residues in BC for liquid biofuel production can be a promising strategy to meet its 2050 renewable transportation target.

Hydrothermal liquefaction (HTL) is a thermochemical conversion pathway that directly decomposes wet biomass into liquid bio-oil under moderate temperature (280–370 °C) and high pressure (10–25 MPa) [10], thus avoiding the energy-intense feedstock pre-drying step in conventional gasification and pyrolysis. Moreover, HTL can produce high quality bio-oil with lower oxygen content (5–15 wt%) [11] and higher heating value (30–37 MJ/kg) [10] compared with pyrolysis, which has the potential to be co-processed with crude oil in a refinery [12,13]. Therefore, it has

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Abbreviations

HTL	hydrothermal liquefaction
MLPY	million liters per year
ST	semi-trailer
AD	anaerobic digestion
MSP	minimum selling price
FOC	fixed operating cost
NMSP	net minimum selling price
BC	British Columbia
FDP	feedstock delivery point
LTT	liquid tanker truck
PHWW	post HTL waste water
VOC	variable operating cost
NPP	net petroleum price
LGE	liter gasoline-equivalent
Fr-CIR	Supply of forest residues to central integrated refinery scenario
Bo-DBR	Supply of bio-oil from distributed biorefineries to oil refinery scenario
Wp-CIR	Supply of wood pellet from distributed pellet plants to central integrated refinery scenario

attracted a wide interest of research, for example, Licella recently announced to collaborate with a Canadian wood product company, Canfor, in a joint venture to integrate its HTL technology with Canfor's pulp mills in Prince George, BC, to convert woody biomass to biofuels [14].

Table 1 shows the comparisons of three different thermochemical conversion pathways, including gasification, pyrolysis and HTL, based on a few technical criteria, i.e., feedstock quality requirement, reaction conditions, intermediate product yield and quality, and currently reported technology scale. We ranked the conversion pathways based on each criterion using characters "MF" (most favorable), "N" (neutral) and "LF" (least favorable) to indicate their relative favorability.

Techno-economic assessment (TEA) is one of the commonly utilized methods to evaluate the economic feasibility of a project [15], and key outcomes of TEA is the estimates of capital investment and operating cost. Several TEA studies have been reported on evaluating the economic performance of thermochemical conversion pathways, and the details are shown in Table 2. Swanson et al. [16] compared the capital investment and operating cost of corn stover to biofuels gasification plant with different technologies. The biofuel product value is found to be $1.06/L to $1.32/L, and it further concluded that the technology with a higher fuel yield could have lowered the product value, although the capital investment will be higher. Wright et al. [17] examined the product value of naphtha and diesel range fuels from fast pyrolysis of corn stover and subsequent upgrading. The assessment studied two scenarios, hydrogen from bio-oil on-site reforming versus purchased hydrogen. The results showed that in a nth plant design, the product value of purchased hydrogen scenario is $0.56/L, lower than that of on-site hydrogen production scenario $0.82/L. In the analysis for the pioneer plant, the cost considerably increases to $0.9/L and $1.73/L, respectively. Zhu et al. [18] implemented TEA to assess the economic feasibility of a commercial scale HTL biofuels plant by comparing state-of-technology case with goal case, and indicated that the potential process improvement can reduce the minimum fuel selling price to $0.74/L from the current technology status of $1.29/L.

Our previous study [19] has found that HTL biofuels from forest residues in British Columbia can achieve a significant GHG emission reduction compared with petroleum fuels, therefore, a specific TEA is timely needed to evaluate the economic feasibility of such a biofuel system in order to have a comprehensive understanding of its overall performance. The following points were addressed in this study: (1) estimation of the capital and operating costs of producing HTL biofuels in BC based on different supply chain designs and calculation of the minimum selling price (MSP); (2) comparison of the MSP of HTL biofuels produced in BC with general values reported in the open literature; (3) identification of the impact of carbon tax and technology advancement on the economic

Table 1
Technical comparisons of thermochemical conversion pathways for transportation biofuel production.

Technical criteria	Gasification	Pyrolysis	HTL
Feedstock quality requirement	N	LF	MF
Moisture content	10–20 wt% [38]	<10 wt% [39]	No requirement
Particle size	<2.0–2.5 inch [38]	<3 mm [39]	<3 mm [40]
Reaction conditions	N	MF	LF
Pressure	20–70 bar or atmospheric [41]	Atmospheric [39]	10–25 MPa [10]
Temperature	High: 600–1000 °C [42]	Moderate: 400–500 °C [39]	Moderate: 280–370 °C [10]
Intermediate product	N	LF	MF
Type	Syngas	Bio-oil	Bio-oil
Yield	1.54–2.41 m^3/kg biomass [43]	50–70 wt% [39]	30–35 wt% [22]
Oxygen content	N/A	35–40 wt% [44]	5–15 wt% [11]
HHV	N/A	16–18 MJ/kg [45]	30–37 MJ/kg [10]
Upgrading pre-treatment	Cleanup and reforming [42]	Hydrotreating to stabilize [22]	Potentially co-processed with crude oil [13]
Technology scale	LF	MF	N
Pilot	Bioliq project by Karlsruhe Institute of Technology (500 kg/h biomass) [46]	N/A	Steeper Energy (half barrel bio-oil/day) [47]
Demonstrated	Total BioTfuel project (Capacity N/A, scheduled to come on stream in 2017) [48]	BTG Bioliquids Empyro project (aiming at 20 million liters bio-oil/year) [49]	N/A
Commercial	N/A	Ensyn-UOP (3 million gallons bio-oil/year) [50]; BTG Bioliquids Malaysis plant (1.2 tonnes bio-oil/hr) [51]	Licella (Capacity N/A) [52]

Table 2
Reported TEA studies on thermochemical conversion of lignocellulosic biomass to transportation biofuels.

Conversion pathway	Region	Facility capacity	Feedstock	Focused products	Capital investment (million $)	IRR (%)	MFSP ($/L)	Reference
Gasification	US	2000 DTPD	CS	G&D	498; 606	10	1.06; 1.32	[16]
	Canada	2000 DTPD	FR	G&D	298; 552	10	0.78; 1.22	[53]
	Germany	N/A	LB	G&D	344[a]	7	1.6[a]	[54]
Pyrolysis	US	2000 DTPD	CS	N&D	(200; 287)[b]; (585; 911)[c]	10	(0.56; 0.82)[b]; (0.9; 1.73)[c]	[17]
	US	2000 DTPD	CS	G&D	429	10	0.68[d]	[55]
	US	2000 DTPD	LR&FT	G&D	358	10	0.82[d]	[22]
HTL	US	2000 DTPD	LR&FT	G&D	244	10	0.51[d]	[22]
	US	2000 DTPD	WB	G&D	(275; 301)[e]	10	(0.74; 1.29)[e]	[18]
	Finland	1500 DTPD	FR	G&D	828[g]	10	0.96[f]	[56]

IRR=Internal rate of return; MFSP = Minimum fuel selling price; DTPD = Dry tonne per day; CS=Corn stover; FR=Forest residues; LB = Lignocellulosic biomass; LR&FT = Logging residues and forest thinnings mix; WB=Woody biomass; G&D = Gasoline and diesel; N&D = Naphtha and diesel.
[a] Converted from Euro to USD using 1 € = 1.3 $.
[b] Nth plant design, capital investment 200 million $ and MFSP $0.56/L are for hydrogen purchased externally, while capital investment 287 million $ and MFSP $0.82/L are for hydrogen produced from bio-oil reforming.
[c] Pioneer plant design, capital investment 585 million $ and MFSP $0.90/L for hydrogen purchase externally, and capital investment 911 million $ and MFSP $1.73/L for hydrogen produced from bio-oil reforming.
[d] Converted from per gallon basis to per liter basis using 1 gallon = 3.78 L.
[e] Capital investment 275 million $ and MFSP $0.74/L are for goal scenario, while capital investment 301 million $ and MFSP $1.29/L are for state-of-technology scenario.
[f] Converted from €1.03/kg to $0.96/L by assuming 1 € = 1.3 $ and the gasoline density to be 0.72 kg/L.
[g] Converted from 1.7 million €/MW_{LHV} to 2.21 million $/$MW_{LHV}$ by assuming 1 € = 1.3 $ and the total feed consumption is 375.1 MW_{LHV}.

performance of HTL biofuels; and (4) sensitivity analysis on the key parameters that influence the MSP of HTL biofuels.

2. Methods

2.1. HTL biofuels system and case study scenarios

A hypothetic 100 million liters per year (MLPY) HTL biofuel system was used as the basis for the TEA case study. The potential system was assumed to be deployed in the Coast Region of BC, due to the following reasons: (1) Abundantly available forest residues as feedstock. Four feedstock delivery points (FDPs) were identified in the Coast Region for forest residues supply, i.e., Chilliwack, Squamish, Powell River and Port Alberni. The total forest residues availability is 1.1 million tonnes (wet basis), with 0.15 million tonnes from Chilliwack, 0.06 million tonnes from Squamish, 0.24 million tonnes from Powell River and 0.65 million tonnes from Port Alberni (see Supplementary material 1 for the methods used to estimate the feedstock availability). (2) Existing oil refining infrastructure for bio-oil upgrading. A Chevron oil refinery with a capacity of 8700 m^3/d [20] locates in the Coast Region. (3) Local markets for biofuel product consumption. City of Vancouver, Port of Vancouver and YVR International Airport are potential markets for HTL biofuels.

In this TEA case study, three scenarios were defined to investigate how supply chain designs could influence the system's economic performance. The main differences between these three scenarios lie in the configuration of biorefinery (integrated with Chevron oil refinery or distributed at FDPs) and the type of feedstock (bulky forest residues or forest residues derived bio-oil or wood pellets) supplied to conversion facility. For scenario 1 (denoted as Fr-CIR scenario), the collected bulky forest residues at FDPs are directly transported to the central integrated refinery for conversion (Fig. 1(a)). For scenario 2 (denoted as Bo-DBR scenario), the forest residues are first converted to bio-oil in distributed HTL plants at FDPs and then transported to the central oil refinery for upgrading (Fig. 1(b)). For scenario 3 (denoted as Wp-CIR scenario), forest residues are first densified to wood pellets in distributed pellet plants at FDPs and then transported to the central integrated refinery for conversion (Fig. 1(c)).

2.2. Description of processes

Although the process models vary with different scenarios, the proposed HTL biofuel system generally includes the following stages: forest residues collection, transportation and biomass to biofuels conversion. It should be noted that the biofuel distribution and end use were not considered in this study. The detailed processes associated with each stage will be described in the following subsections.

2.2.1. Forest residues collection

Table 3 shows the supply of forest residues at each FDP for different scenarios to meet the 100 MLPY biofuel production target. The density (dry basis), moisture content (wet basis) and higher heating value (HHV) (dry basis) of forest residues used in this study are 420 kg/m^3, 49%, and 20.24 MJ/kg, respectively. The detailed methods for calculating the forest residues requirement at each FDP can be found in Supplementary material 1.

The collection of forest residues was modeled in two steps. First, the piled forest residues on distributed forest stands around FDPs are gathered by loaders, chipped to smaller size and loaded to dump trucks, and then the chipped residues are shuttled to the nearby FDPs. Due to the unavailability of the specific location and production of each forest stand, we simply assumed that the forest residues were uniformly distributed around the FDP and 12.5 km was used as the average distance for shuttling forest residues to FDP.

2.2.2. Transportation

The transportation of biomass feedstock varies with each scenario. For Fr-CIR scenario, forest residues arriving at FDPs are directly reloaded to semi-trailers and transported to the central integrated refinery for conversion. Whereas for Bo-DBR and Wp-CIR scenarios, the arriving forest residues are first converted to bio-oil and wood pellet, respectively, and the intermediate products are loaded to semi-trailers (STs) or liquid tanker trucks (LTTs) and transported to the further conversion facility. It should be noted that transportation from Powell River and Port Alberni to Chevron oil refinery will undergo marine routes, STs or LTTs were thus assumed to be carried by ferries run by British Columbia Ferry Services Inc [21]. The distance from Chilliwack, Squamish, Powell

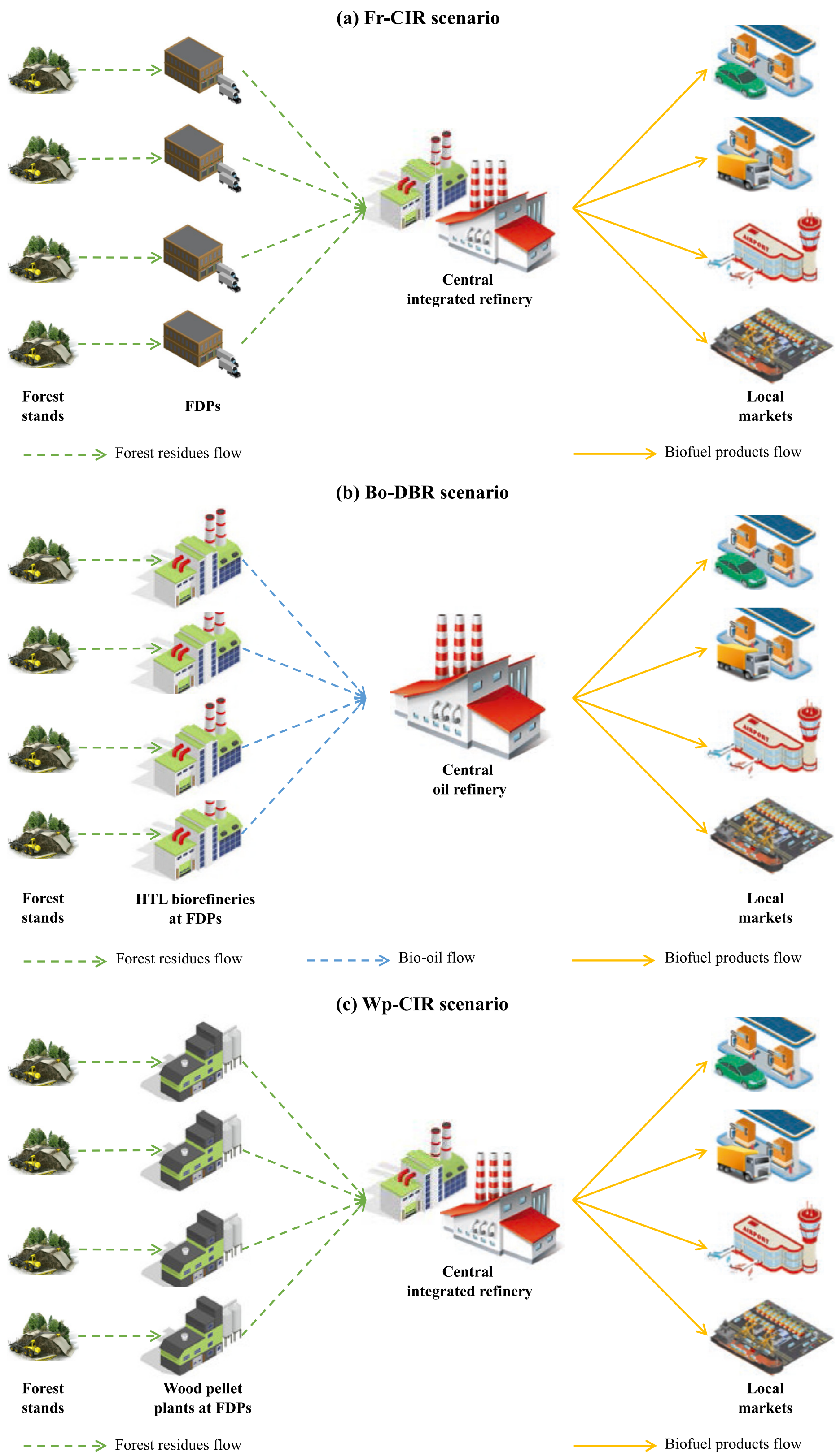

Fig. 1. Supply chain designs of HTL biofuel system for each scenario (the dash line arrows stand for the flow of feedstock or intermediate products and the solid line arrows stand for the flow of final biofuel products).

Table 3
Forest residues supply at each FDP for different scenarios.

	Forest residues supply (dry tonne)		
	Fr-CIR	Bo-DBR	Wp-CIR
Chilliwack	7.64E+04	7.64E+04	7.64E+04
Squamish	3.14E+04	3.14E+04	3.14E+04
Powell River	1.21E+05	1.21E+05	1.21E+05
Port Alberni	7.12E+04	7.12E+04	1.07E+05
Total	3.00E+05	3.00E+05	3.36E+05

River and Port Alberni to Chevron oil refinery are 102 km, 74 km, 179 km (including 37 km marine transportation), and 170 km (including 57 km marine transportation), respectively.

2.2.3. Biomass to biofuels conversion

Biomass to biofuels conversion stage covers two parts, i.e., thermochemical conversion of biomass feedstock in biorefinery to produce bio-oil and bio-oil upgrading in the oil refinery. The wood pellet plant operation process in Wp-CIR scenario is also incorporated into this stage. The process design of biorefinery thermochemical conversion and oil refinery upgrading are based on the study by Tews et al. [22]. For wood pellet plant operation process, the modeling parameters used to determine the mass and energy balances were extracted from Pa et al. [9,23]. Biorefinery conversion includes the following processes: biomass feedstock pre-processing, HTL and anaerobic digestion (AD), while oil refinery upgrading includes bio-oil hydrotreating and hydrogen production. Fig. 2 shows the process flows of the conversion stage for integrated and distributed systems. The major parameters used to model the processes of conversion stage are summarized in Table 4 and the mass and energy balances are detailed in Supplementary materials 2.

In biorefinery, the incoming forest residues or wood pellets will first go through the pre-processing step, where the biomass feedstock is unloaded, cleaned and sent to a grinder for further size reduction, and then mixed with hot water recycled from HTL to form biomass-water slurry with 8 wt% solids content [22]. Next, the produced slurry is pressurized and sent to the HTL reactor. Sodium carbonate (Na_2CO_3) is used as buffer agent for HTL reaction and the required amount was assumed to be 1 wt% of biomass slurry [18]. HTL decomposes biomass slurry at 20.3 MPa and 355 °C [22], and produces oil, gaseous, solid and aqueous phase products, i.e., bio-oil, off-gases, biochar and post HTL waste water (PHWW), respectively. Bio-oil was assumed to be sent to the Chevron oil refinery to be co-upgraded with crude oil based on the potential evaluation study [12,13], although the co-processing technology has not been commercialized. Off-gases contain the incondensable volatile compounds, mostly CO_2, a moderate fraction of light hydrocarbons (C_1~C_4) and a small portion of H_2. Depending on the scenario, off-gases can be reused in the conversion processes differently. For Fr-CIR and Wp-CIR scenarios, these gases are used as fuel in hydrogen plant, and the remaining is consumed in anaerobic digester for heating. For Bo-DBR scenario, these gases are only consumed in the biorefinery due to the inaccessibility to hydrogen plant, and the energy requirement of hydrogen plant is thus met by the purchased natural gas (NG). The solid phase product biochar as a by-product was assumed to be sold for profit. According to Yu et al. [24], up to 40% of the carbon and up to 80% of the nutrients from the feedstock are released into PHWW, which has largely lowered the energy efficiency of HTL. Therefore, we assumed that the majority of PHWW was recycled for biomass slurry formation and the balance was conditioned and sent to an anaerobic digester for energy recovery. In the anaerobic digester, the PHWW is converted into biogas, solid and liquid digestate. All biogas is sent to the HTL heater and used as heating fuel. The solid and liquid digestates are sent to waste treatment plant for disposal. Due to the lack of reported data for AD of PHWW, a large-scale anaerobic digester using liquid swine manure as feedstock was used as an approximation to quantify the heat and electricity requirement of

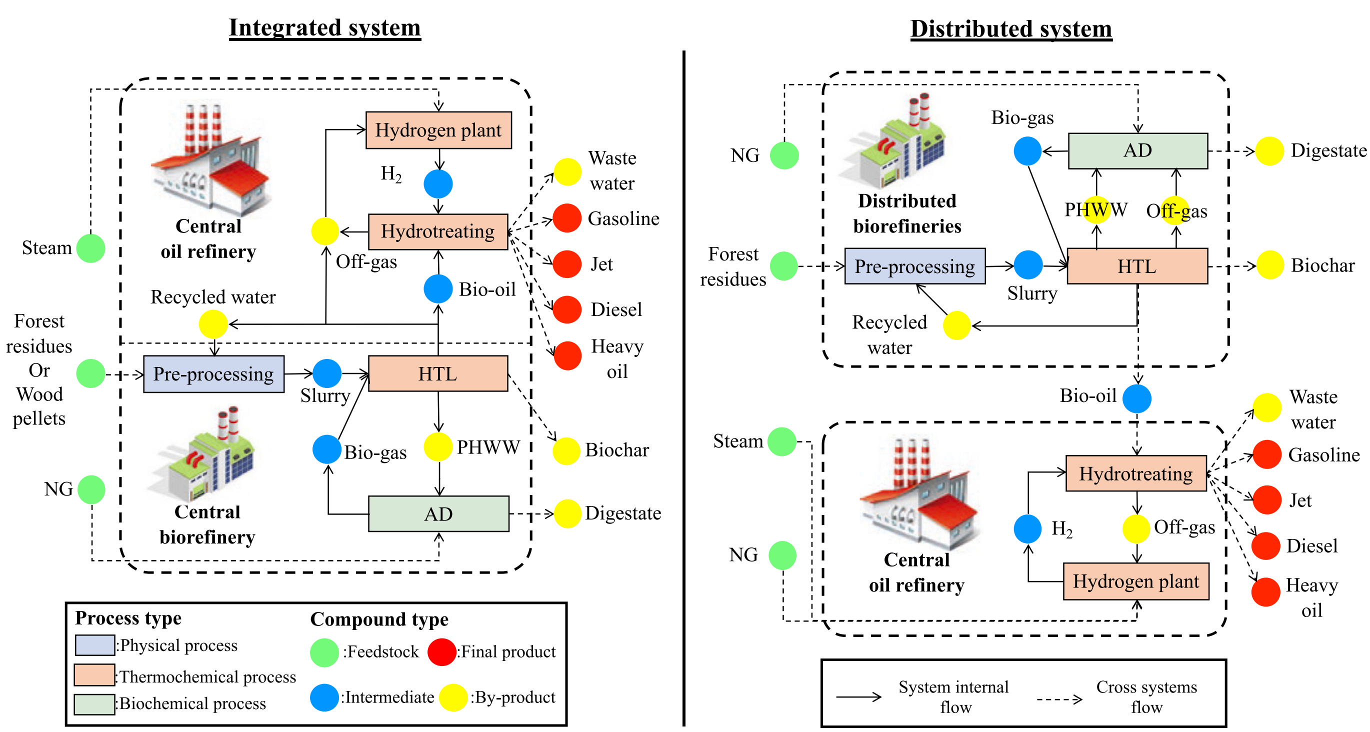

Fig. 2. Process flow diagram of biomass to biofuels conversion stage for integrated and distributed system (Fr-CIR and Wp-CIR scenarios belong to integrated system, while Bo-DBR scenario belongs to distributed system).

Table 4
Major modeling parameters for biomass to biofuels conversion stage.

Parameters	Value	Reference
Biorefinery		
Hydrothermal liquefaction		
Material and energy input		
Buffer (Na_2CO_3) content, wt% of slurry	1	[18]
Electricity/Heat, MW	4.03/50.42	Scale from Ref. [22]
Yields, kg/100 kg dry feedstock[a]		
Bio-oil/Off-gas/PHWW/Biochar	36.7/17.3/40.4/5.6	[22]
Anaerobic digestion		
Material and energy input, MJ/GJ biogas produced		
Electricity/Heat	102.32/140.89	Average of [25,26]
Yields, kg/kg wastewater		
Biogas/Solid digestate/Liquid digestate	0.23/0.01/0.76	Scale from Ref. [22]
Oil refinery		
Hydrotreating		
LHSV, h^{-1}	0.22	[22]
Material and energy input		
H_2, g H_2/g dry bio-oil	0.033	[18]
Catalyst[b] load, kg catalyst/tonne bio-oil	0.41	Calculated based on LHSV
Electricity, MW	1.12	Scale from Ref. [22]
Product distribution, wt%		
Deoxygenated oil/Water/Off-gas	75/18/7	[22]
Hydrogen Plant		
GHSV, h^{-1}	4000	[57]
Material and energy input		
NG (feed)/NG (fuel)[c], kg/m^3 H_2 produced	0.24/0.03	Scale from Ref. [29]
Steam, kg/m^3 H_2 produced	0.76	Scale from Ref. [29]
Catalyst load[d], kg catalyst/tonne H_2 produced	0.12	Calculated based on GHSV
Electricity, MW	0.15	Scale from Ref. [29]
Wood pellet plant		
Material and energy input, MJ/tonne wood pellet		
Diesel/Propane/Wood wastes[e]/Electricity	23.5/6.16/1059/490	[9]
Yield, tonne pellets/dry tonne forest residues	0.89	[23]
Wood pellet moisture content, %wt (wet basis)	5.6	[23]

[a] Feedstock stands for either forest residues or wood pellets, and wood pellets were assumed to have the same conversion rate as forest residues on the dry-basis.
[b] Life time was assumed to be 1 year.
[c] For Fr-CIR and Wp-CIR scenarios, the NG requirement is met by the off-gases from HTL and hydrotreating. For Bo-DBR scenario, the NG is purchased externally.
[d] Life time was assumed to be 3 years.
[e] The requirement of wood wastes was assumed to be met by the input forest residues.

AD process [25,26] based on the amount of PHWW input into the AD unit.

Bio-oil from HTL is sent to the hydrotreating unit in the oil refinery, where the oxygenated compounds in bio-oil are exposed to hydrogen under elevated pressure and high temperature [27]. The catalyst utilized in hydrotreating process was assumed to be conventional NiMo/Al_2O_3 catalyst which is commonly used in crude oil hydroprocessing. The required volume of NiMo/Al_2O_3 catalyst was assumed to be the same as the reactor volume, which was calculated based on the design liquid hourly space velocity (LHSV) of hydrotreater from Tews et al. [22]. The effluent of hydrotreating reactors is separated into deoxygenated oil, off-gases and wastewater. The deoxygenated oil is further distilled into gasoline, jet, diesel and heavy oil as final products, making up 21 wt%, 25 wt%, 35 wt% and 19 wt%, respectively, based on the experimental study results by Elliott et al. [28]. The off-gases containing mainly light hydrocarbons are sent to the hydrogen plant as feedstock for steam reforming. The modeling of hydrogen production via steam reforming process is based on the model proposed by Spath and Mann [29]. The reformer is fueled mainly by the off-gases of hydrogen production and the remaining 4.4 wt% [29] was assumed to be supplied by off-gases from hydrotreating as well as HTL depending on the scenarios. The catalyst used for hydrogen production is also NiMo/Al_2O_3.

2.3. Economic analysis

The following context describes the method for estimating the capital investment and operating cost of the three different HTL biofuel production scenarios, as well as the method for calculating the minimum selling price (MSP) of the biofuel products. The economic analysis was carried out based on each stage as described in the previous section and the details can be found in Supplementary material 1.

2.3.1. Capital investment

The capital investment was estimated using the factor method summarized in Table 5. The method begins with the total purchased equipment cost (TPEC) of major process equipment or operation unit based on literature [22,30] and scales to the specific capacity using the following cost-capacity relationship:

$$C_{new} = C_{base} \times \left(\frac{S_{new}}{S_{base}}\right)^x \quad (1)$$

where C_{base} is the base cost of equipment of base capacity S_{base}, C_{new} is the new cost of equipment of new capacity S_{new} and x is the scaling factor, which was assumed as 0.7 [31]. Other capital investment elements were estimated based on TPEC. The reference costs of the specific process equipment or operation unit can be

Table 5
Methods for estimating the capital investment of the studied HTL biofuel system.

Parameters	Methods	Reference
Capital investment	Biorefinery/Wood pellet plant	
Depreciable cost (DepC)	TIC + IC	
Total installed cost (TIC)	2.47[a]/X[b]*TPEC	
TPEC	100%	
Indirect cost (IC)	1.2/1.23*TPEC	
Engineering	32%/33%	[33]
Construction	34%/39%	[33]
Contractor fees	18%/17%	[33]
Contingency	36%/34%	[33]
Non-depreciable cost (NDepC)	3.99%/4.35% of DepC	
Land cost	1.5% of DepC	[33]
Site development	2.49%/2.85% of DepC	[33]
Fixed capital investment (FCI)	DepC + NDepC	
Start-up cost (SC)	9% of FCI	[58]
Working capital (WC)	20% of FCI	[31]
Total capital investment (TCI)	FCI + SC + WC	

[a] From Ref. [59]. The installation factor 2.47 was used for all operating units in HTL biorefinery. This factor covers the costs including equipment installation, instrumentation and controls, piping, electrical systems, building and yard improvement.
[b] From Ref. [31]. X is the individual factor varied with specific process equipment modules and the details are presented in Supplementary material 1.

found in Supplementary material 1.

It should be noted that in this study we assumed that bio-oil was upgraded in an existing Chevron oil refinery, hence, we didn't consider the capital investment associated with building the upgrading infrastructure in view of the transition of fossil fuels to renewable biofuels in the future. Specifically, the capital investment of Chevron refinery was not considered in neither integrated refinery scenarios, i.e., Fr-CIR and Wp-CIR scenarios, nor distributed biorefineries scenario, i.e., Bo-DBR scenario.

2.3.2. Operating cost

The major assumptions for estimating the operating cost are summarized in Table 6. The operating cost includes variable part and fixed part. The variable operating cost consists of the costs associated with purchasing feedstock, catalyst and chemicals, utilities and the treatment of wastes. The cost of feedstock is essentially the delivered cost of feedstock from forest stands to plant, which is divided into raw material cost, machinery cost, transportation cost in this analysis. The detailed economic model for feedstock delivered cost estimation is presented in Supplementary material 1. The fixed cost covers the costs of labor, maintenance and supplies, property tax and insurance, and plant overhead. Besides, the credit from selling the by-product biochar was also considered. Three types of labor are involved, i.e., operating labor, maintenance labor and supervisory labor. The operating and maintenance labor requirement was estimated by the following equation from US EPA [32]:

$$L_{new} = L_{base} \times \left(\frac{V_{new}}{V_{base}}\right)^{y} \quad (2)$$

where L_{base} is the base-case labor requirement of base-case plant of capacity V_{base}, L_{new} is the new labor requirement of new plant of capacity V_{new} and y is the scaling factor, which was assumed to be 0.25 in this study. The base-case plant capacity and labor requirement for biorefinery and wood pellet plant were referenced from study by Tews et al. [22] and Hoque et al. [30], respectively. The supervisory labor cost was assumed to be 20% of the operating labor cost [31]. The maintenance cost, including materials and operating supplies, and the property tax and insurance, were estimated as 2.55% and 3% of FCI, respectively [33]. The plant overhead was assumed to be 72% of the total labor cost [33].

2.3.3. MSP calculation

The MSP of HTL biofuels was calculated using discounted cash flow rate of return (DCFROR) analysis, which manipulates the fuel selling price to find the breakeven point where the project net present value (NPV) equals zero. The calculation was performed by iteration in Excel using self-developed Excel VBA code and the detailed spreadsheet can be found in Supplementary material 1. Table 7 presents the major assumptions used in DCFROR analysis. It should be noted that the MSP of HTL biofuels was calculated as the

Table 6
Methods for estimating the operating cost of the studied HTL biofuel system.

Parameter	Methods	Reference
Variable operating cost (VOC)		
Feedstock delivered cost	see Supplementary material 1	
Catalyst and chemicals		
Na_2CO_3 price (HTL), \$/tonne	275	[60]
$Ni/Mo/Al_2O_3$ price, \$/kg	34	[61]
Waste disposal		
Waste disposal cost, \$/tonne	0.73	[22]
Utilities		
Electricity price, \$/kWh	0.057	[62]
Diesel, \$/L	0.97	[63]
Natural gas, \$/GJ	2.84	[64]
Propane, \$/L	0.54	[65]
Wood wastes, \$/dry tonne	3[a]	[66]
Fixed operating cost (FOC)		
Labor cost		
Operating labor rate, \$/hr	24	[67]
Maintenance labor rate, \$/hr	28	[67]
Supervisory labor cost	20% of operating labor cost	[31]
Maintenance and supplies	2.55% of FCI	[33]
Property tax and insurance	3% of FCI	[31]
Plant overhead	72% of total labor cost	[33]
Total operating cost	VOC + FOC	
By-product (biochar) price, \$/tonne	385[b]	[68]

[a] The wood wastes used in the pellet plant operation was assumed to be part of the forest residues input.
[b] Took the average of high-end price \$500/ton (\$550/tonne) and low-end price \$200/ton (\$220/tonne).

Table 7
Major assumptions for DCFROR analysis.

Parameter	Assumption
Internal rate of return (IRR)	10%
Plant life time	20 years
Plant annual operating time	8000 h/yr
Plant financing by equity/debt	40%/60% of total capital investment
Interest rate for debt financing	6.5% annually
Term for debt financing	10 years
Salvage value	0
Depreciation schedule	7-year MACRS[a] schedule
Income tax rate	26%
Construction period (spending schedule)	3 years (year 1: 30%, year 2: 50%, year 3: 20%)
Start-up time	3 months
Revenue and costs during start-up	Revenue = 50% of normal Variable operating cost = 75% of normal Fixed operating cost = 100% of normal

[a] Modified Accelerated Cost Recovery System.

price of biofuel product mix, including gasoline, jet, diesel and heavy oil in a unit of \$/L. In addition, to account for the difference in heating value, the liter gasoline-equivalent (LGE) price at \$/LGE for the biofuel product mix was calculated using Equation (3) for a consistent comparison with the price of petroleum gasoline. The HHV of biofuel product mix was calculated to be 37.9 MJ/L based on the products distribution and HHVs of individual component (34.7, 37.4, 38.6 and 41.4 MJ/L for bio-based gasoline, jet, diesel and heavy oil, respectively), while the HHV of petroleum gasoline was assumed to be 34.7 MJ/L.

$$\text{MSP}\ (\$/\text{LGE}) = \frac{\text{MSP of final product} \times \text{Gasoline HHV}}{\text{Final product HHV}} \tag{3}$$

Table 8
Estimated costs for the HTL biofuel system.

	Scenarios		
	Fr-CIR	Bo-DBR	Wp-CIR
Capital investment, million \$			
Total installed cost (TIC)	120.4	178.8	138.0
Indirect cost (IC)	58.5	86.9	68.1
Non-depreciable cost	7.1	10.6	8.3
Fixed capital investment (FCI)	186.0	276.2	214.4
Star-up cost (SC)	16.7	24.9	19.3
Working capital (WC)	37.2	55.2	42.9
Total capital investment (TCI)	240	356.3	276.6
Annual operating cost, million \$/year			
Variable operating cost	50.7	34.7	46.6
Fixed operating cost	16.0	26.4	24.6
Total annual operating cost	66.7	61.2	71.2
Annual sales, million \$/year			
Main products – biofuels	89.2	97.4	98.1
By-product – biochar	6.5	6.5	6.5
Total annual sales	95.7	103.8	104.6
Minimum selling price (MSP), \$/L	0.89	0.97	0.98
Minimum selling price (MSP), \$/LGE	0.82	0.89	0.90

3. Results and discussion

3.1. Cost estimation

Table 8 summarizes the major costs of the 100 MLPY HTL biofuel system for the investigated scenarios. The TCI is dominated by the installed equipment cost, which accounts for about 50% for all scenarios. As expected, Fr-CIR scenario has the lowest capital investment. Other two scenarios have a higher capital investment as a result of the economy of scale, i.e., several small distributed plants need more capital investment than a large centralized plant of the same total capacity, as well as additional infrastructure construction, i.e., wood pellet plants. The detailed installed equipment cost of three studied scenarios is shown in Fig. 3 (a). The results indicate that the HTL reactor system requires the most capital expense, making up about 70% of the TIC on average for three scenarios. Therefore, the cost reduction of the HTL reactor system is significant for lowering the TCI. Fig. 3 (b) demonstrates the detailed operating cost. Bo-DBR scenario has the lowest operating cost, followed by Fr-CIR scenario and lastly Wp-CIR scenario. The fixed operating costs of Bo-DBR and Wp-CIR scenarios are both higher than the Fr-CIR scenario, because most of the elements in fixed operating cost, such as plant overhead and the property tax and insurance were estimated based on the FCI (Table 5). In contrast, the variable operating costs of these two scenarios are 32% and 8% lower than the Fr-CIR scenario. The main reason is the reduction in feedstock cost. As the pie chart of Fig. 3 (b) shows, the feedstock cost of Fr-CIR scenario is dominated by the transportation cost, which makes up about 73%, indicating that the long-distance transportation of low energy density bulky forest residues is not a cost-effective option. Bo-DBR and Wp-CIR scenarios try to address this issue by converting the bulky forest residues into high energy density intermediate products, bio-oil and wood pellet. This strategy shows a reduction of the feedstock cost by 48% and 20% for Bo-DBR and Wp-CIR scenarios, respectively. Bo-DBR scenario successfully reduces the total operating cost by lowering the feedstock cost, however, Wp-CIR scenario fails to do so as the increase of fixed operating cost and other variable operating costs outweigh the decrease of feedstock cost.

For comparing the overall economic feasibility, MSPs of different studied scenarios were calculated based on an assumed minimum acceptable IRR of 10% and the results are shown in Table 8. Fr-CIR scenario achieves the lowest MSP of HTL biofuels at \$0.89/L, followed by Bo-DBR scenario at \$0.97/L and Wp-CIR scenario at \$0.98/L. When compared with the 2016 gasoline wholesale price in Vancouver at \$0.50/L [34], the MSPs of HTL biofuels (\$/LGE) are 63%–80% higher, which means under current circumstance, the HTL biofuels are not economically competitive with petroleum fuels. To promote the HTL biofuels, government incentives would be needed, or technology should be advanced to bring down the production cost of HTL biofuels.

3.2. Results comparison with peer-reviewed literature

In order to check whether the MSP of HTL biofuels from this study agree with those from peer-reviewed literature, we compared our results with the literature data presented in Table 2. For a specific conversion pathway, the median value of the results from all studies was used instead of the mean, because the mean can be easily influenced as the results varied from study to study. Fig. 4 compares the MSPs of biofuels from different thermochemical conversion pathways. The literature results show that pyrolysis has the best economic performance (\$0.82 ± 0.38/L), followed by HTL (\$0.85 ± 0.29/L) and lastly gasification (\$1.22 ± 0.27/L). The result from our study (\$0.97 ± 0.04/L) is about 12% higher than the

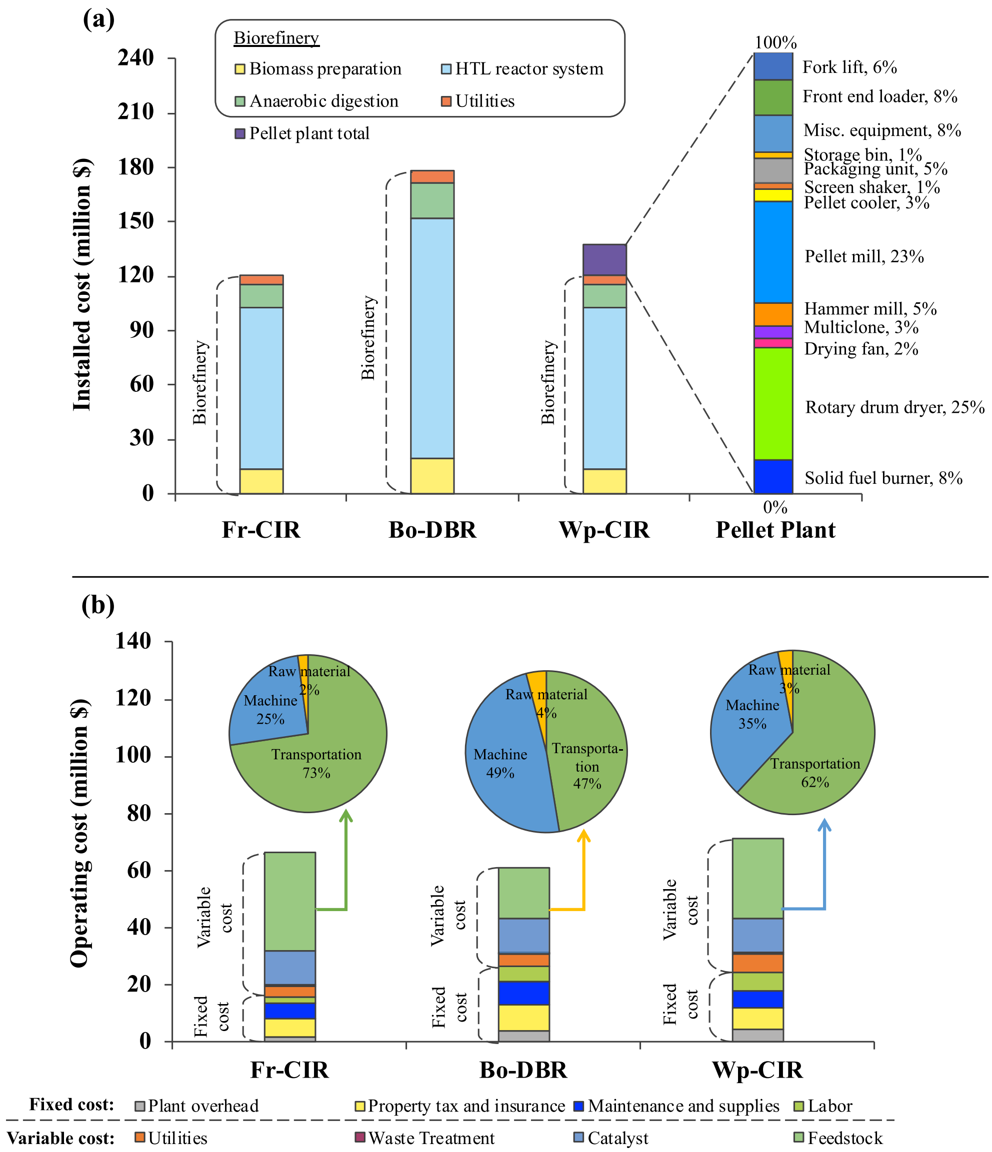

Fig. 3. Detailed installed equipment cost and operating cost of studied HTL biofuel scenarios (the pie chart in part (b) represents the distribution of the feedstock cost).

median value of literature results for HTL biofuels. This is due to the variance in the system configuration, factors and parameters used for process modeling, estimating the capital investment and operating cost as well as calculating the MSP. Since this study aims at a preliminary assessment of the economic feasibility of HTL biofuels in BC, the factors used in the cost estimation tended to be conservative.

3.3. *Impact of carbon tax and technology advancement on the economics of HTL biofuels*

To help mitigate the global warming impact, BC government has implemented a carbon tax since 2008 [35], which is levied based on the life cycle GHG emissions of a fuel. The initial carbon tax is 10 Canadian dollar (CAD) per tonne of CO_2-eq, and it increased to 30 CAD/tonne CO_2-eq in 2012. In 2016, BC government implemented a Climate Leadership Plan to further enhance GHG emission mitigation and help BC move towards 2050 emission reduction target of 80% below 2007 level [3]. The Climate Leadership Team had called for a 10 CAD increase in carbon tax beginning in 2018 [36].

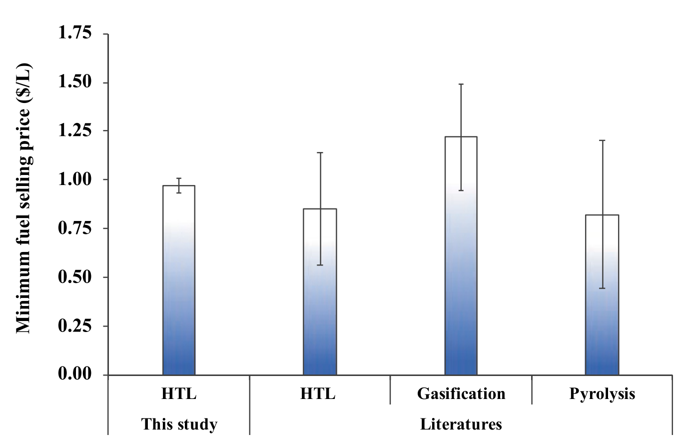

Fig. 4. MSP of HTL biofuels from this study and literature.

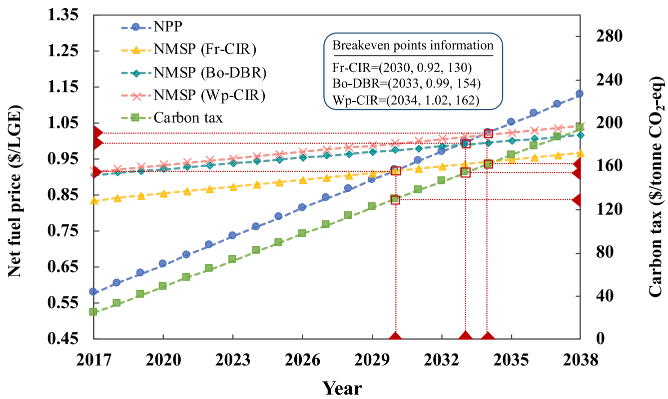

Fig. 5. Impact of carbon tax on petroleum fuel and HTL biofuels price (carbon tax was converted from Canadian dollars to US dollars using exchange rate of 1 CAD = $ 0.81; NPP: net petroleum price; NMSP: net minimum selling price).

Fig. 5 shows the trend of BC carbon tax with a 10 CAD increase per year starting from 2018, the net petroleum price (NPP) and the net minimum selling price (NMSP) of HTL biofuels under the impact of increasing carbon tax. The initial MSPs of HTL biofuels are based on the MSPs of HTL biofuels from three studied scenarios, i.e., $0.82/LGE, $0.89/LGE and $0.90/LGE for Fr-CIR scenario, Bo-DBR scenario and Wp-CIR scenario, respectively. The initial petroleum price was assumed to be $0.50/L [34]. The life cycle GHG emission of petroleum fuel is based on 2005 gasoline baseline 93 g CO_2-eq/MJ (3226 g CO_2-eq/L) [37], while the life cycle GHG emissions of HTL biofuels are 20.5 g CO_2-eq/MJ (778 g CO_2-eq/L), 17.0 g CO_2-eq/MJ (646 g CO_2-eq/L) and 19.5 g CO_2-eq/MJ (739 g CO_2-eq/L) for Fr-CIR scenario, Bo-DBR scenario and Wp-CIR scenario, respectively, based on the results from our previous work [19].

With the impact of carbon tax, the price gap between HTL biofuel and petroleum fuel shrinks year by year. The breakeven points are achieved when the carbon tax reaches $130/tonne CO_2-eq in 2030 for Fr-CIR scenario, $154/tonne CO_2-eq in 2033 for Bo-DBR scenario and $162/tonne CO_2-eq in 2034 for Wp-CIR scenario, corresponding to the NMSP of HTL biofuels at $0.92/LGE, $0.99/LGE and $1.02/LGE, respectively. This analysis has been conservative without the impact of technology advancement being accounted for. Even if a 1% cost reduction per year is assumed to be achieved by the advancement of HTL technology, the breakeven points are achieved in 2026, 2028 and 2029 with the NMSP of HTL biofuels at

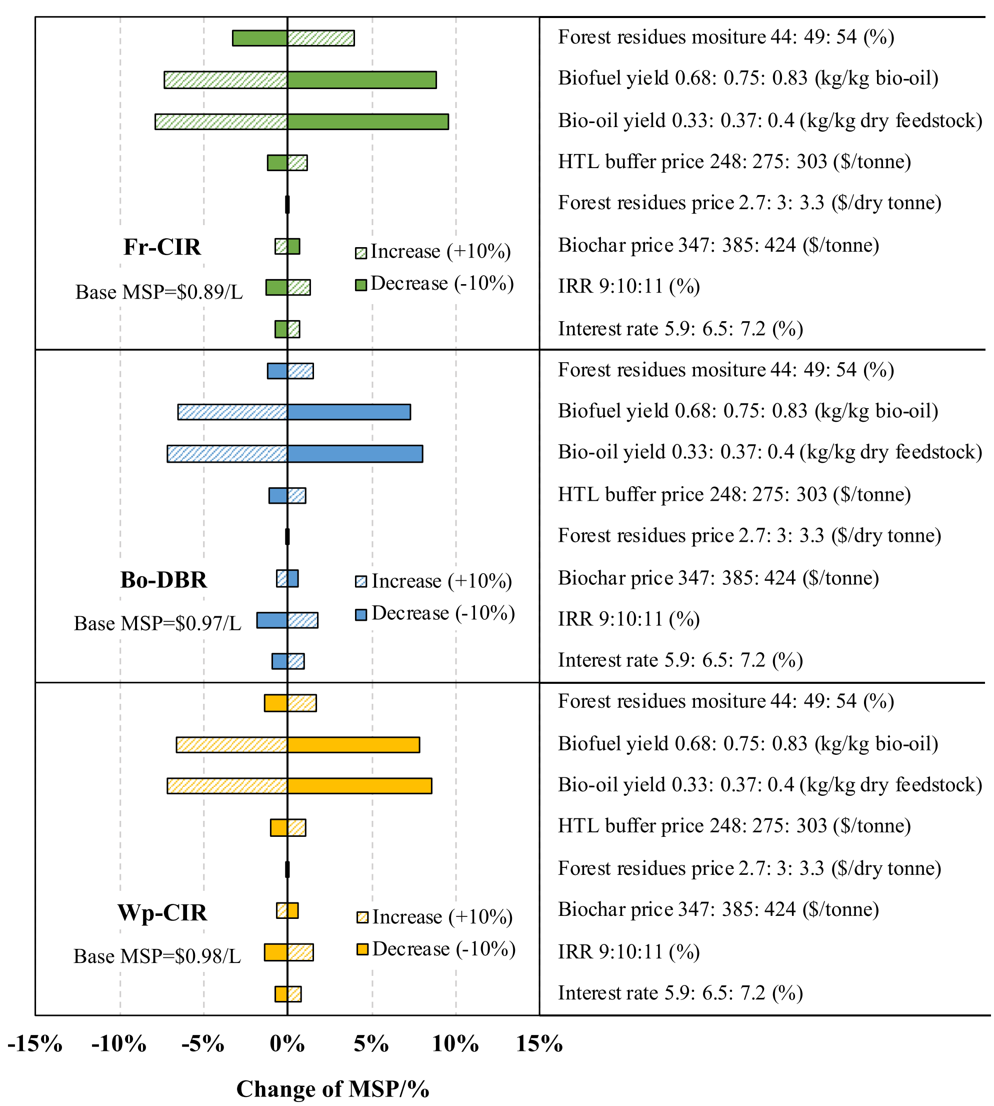

Fig. 6. Sensitivity analysis of the MSP of HTL biofuels for different scenarios.

$0.81/LGE, $0.86/LGE and $0.88/LGE for Fr-CIR, Bo-DBR and Wp-CIR scenario, respectively. Hence, with the current technology, carbon tax should be counted as a key strategy to promote the HTL biofuels, while from a long-term point of view, the technology should be advanced to bring down the cost of HTL biofuels.

3.4. Sensitivity analysis

Large scale commercial HTL plants have not been reported. The uncertainty exists in the process design and cost estimation of the proposed HTL biofuel system due to the reliance on literature data. To investigate key factors influencing the MSP of HTL biofuels, a sensitivity analysis was conducted by adjusting the nominal values of uncertain parameters by ± -10%.

As shown in Fig. 6, although each scenario presented different results, in general, the most influencing parameters are associated with conversion processes, i.e., bio-oil and biofuel yield. The yield of intermediate and final products can significantly influence the input and output of other materials, as well as the energy consumption associated with the entire supply chain of HTL biofuels. It further implies that the technology advancement to improve the conversion and energy efficiency of HTL will make key contributions in reducing the costs of HTL biofuels. The property of raw material, i.e., the moisture content of forest residues, also matters, but shows different effect on each scenario. Fr-CIR scenario is the most sensitive, because the moisture content of forest residues can largely determine the cost of feedstock transportation, which has a significant contribution to the total operating cost of Fr-CIR scenario as discussed in the previous section (Fig. 3 (b)). In contrast, the moisture content has less impact on the other two scenarios since the raw bulky forest residues are first converted to high energy density intermediate products before transportation. The cost estimation factors, such as debt interest rate and IRR, have a moderate impact on the MSP of HTL biofuels. Besides, the price of raw material, HTL buffer and by-product show little influence, i.e., the change rates of MSP are within ±1.2% based on a ±10% change of the nominal values.

4. Conclusions

This study estimated the capital investment and operating cost of a hypothetic 100 MLPY HTL biofuel production system in BC based on three different supply chain designs. The MSP of HTL biofuels was estimated to be $0.82/LGE-$0.90/LGE, which is about 63%–80% higher than that of petroleum fuel. Converting forest residues to bio-oil and wood pellet before being transported to the conversion facility can considerably reduce the variable operating cost, but the MSPs of HTL biofuels were found to be 9%–10% higher, respectively. With the increasing carbon tax and technology advancement, HTL biofuels will become competitive with petroleum fuels. A sensitivity analysis indicates the importance of technology advancement, such as the increased yield of bio-oil and biofuel, to the economic performance of HTL biofuels.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2018.04.057.

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