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Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading

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HIGHLIGHTS

- Bench-scale hydrothermal liquefaction (HTL) and hydrotreating tests were conducted.
- A techno-economic analysis was conducted for the HTL and upgrading systems.
- A state-of-technology case was evaluated based on the best available test data.
- A goal case was evaluated considering potential process improvements.
- Sensitivity analyses were conducted for alternative configuration and selected parameters.

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ABSTRACT

Techno-economic analysis (TEA) was implemented to evaluate the feasibility of developing a commercial large-scale woody biomass HTL and upgrading plant. In this system, woody biomass at 2000 dry metric ton/day was assumed to be converted to bio-oil via HTL and further upgraded to produce liquid fuel. Two cases were evaluated: a state-of-technology (SOT) case with HTL experimental testing results underpinning the major design basis and a goal case considering future improvements for a commercial plant with mature technologies. Process simulation and cost analysis were conducted. The annual production rate for the final hydrocarbon product was estimated to be 42.9 and 69.9 million gallon gasoline-equivalent (GGE) for the SOT and goal cases, respectively. The minimum fuel selling price (MFSP) was estimated to be $4.44/GGE for the SOT case and $2.52/GGE for the goal case. For advancing from the SOT to the goal case, the assumption of reducing the organics loss to the water phase led to the largest reduction in the production cost. Alternative configuration of small scale distributed HTL plants was evaluated. Sensitivity analysis identified key factors affecting the goal case and its cost uncertainties resulting from the assumed uncertainties in selected parameters.

1. Introduction

Biomass is an important domestic resource with the potential to make a significant impact on domestic fuel supplies. Biomass can be converted to liquid fuels and chemicals via a number of thermochemical approaches (e.g., gasification and liquefaction). In contrast to gasification, direct liquefaction features a simple and direct conversion of biomass to liquid fuel and relatively high liquid-fuel yields [1,2]. Typical direct liquefaction processes include fast pyrolysis and high-pressure hydrothermal liquefaction (HTL) [3,4]. The HTL bio-oil has an oxygen content of 10–20 wt%, which is much lower than that of the pyrolysis bio-oil, which is about 40 wt% [5]. The HTL bio-oil has a heating value of about 35 MJ/kg, which is also higher than the heat value of 16–19 MJ/kg for the pyrolysis bio-oil. The heating value of the HTL bio-oil is more comparable to the heating value of 40–45 MJ/kg for conventional petroleum fuels [2,5].

The concept of biomass liquefaction in hot water to produce liquid oil was originally developed in the 1920s and used alkali as a buffering agent. In the 1970s, a biomass HTL process was developed at the Pittsburgh Energy Research Center (PERC), and a pilot plant based on this process was demonstrated at the Albany Biomass Liquefaction Experimental Facility at Albany, Oregon, at a scale of 100 kg/h [1] with bio-oil recycled and a reducing gas. During the same period, the Lawrence Berkeley Laboratory (LBL) developed an HTL process, at an equivalent scale, with an acid hydroloysis pretreatment and water as the reaction media [6,7].

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In 1982, Shell Laboratory in the Netherlands began the research and development (R&D) of the HydroThermal Upgrading® (HTU) process [1,8–12]. Major technical features of these processes are provided in Table 1.

In general, HTL reactions occur at temperatures from 250 to 380 °C, at pressures between 5 and 30 MPa, and with a residence time between 5 and 60 min [13,14]. HTL of biomass under alkaline or neutral conditions has been widely investigated [15] and reactions involve dehydration, deoxygenation, and decarboxylation. Compressed hot water has enhanced solvent properties that facilitate the formation of liquid–oil products from biomass [10,11]. Biomass is dissolved and liquefied in this process, and the major products are bio-oil, gas, and water with dissolved organics. The key in biomass HTL is oxygen removal; about 85% of the oxygen in biomass can be removed as CO_2 and water [11]. The oxygen content of bio-oil can be as low as 10 wt%, and thus has a higher caloric value than the original biomass. The bio-oil produced from the HTL process can be upgraded to a conventional hydrocarbon fuel by near complete oxygen removal and molecular weight reduction via hydrotreating and hydrocracking [1,16].

Compared to biomass gasification and pyrolysis, HTL uses wet biomass as feedstock and thus avoids the energy consumption for biomass drying. In addition, hot compressed water stays in the liquid phase in HTL, eliminating the energy penalty for water vaporization present in gasification and pyrolysis. Biomass gasification and pyrolysis systems are commercially available [17,18], while biomass HTL has only been demonstrated at pilot scale. Hydrotreating to remove nitrogen and sulfur in heavy oil is a common and well established refinery process [19]. However, oxygen removal from HTL bio-oil by hydrotreating has not been demonstrated at commercial scale, and hydrocracking to remove heavy compounds in the bio-oil has not been demonstrated at experimental scale.

Since HTL technology has not been commercialized yet, extensive techno-economic analyses (TEAs) are required to provide guidance for decision making about commercial development. A number of TEAs have been conducted for gasification and fast pyrolysis-based thermochemical biomass conversion to fuels technologies [20–27]. However, only limited TEAs have been performed for biomass HTL-based system evaluation [11,28–30]. Further, little cost analysis has been conducted for HTL bio-oil upgrading processes. An important reason is lack of detailed and consistent technical information to support a systematic analysis and evaluation. Pacific Northwest National Laboratory (PNNL) under the National Advanced Biofuels Consortium (NABC) sponsorship conducted a series bench scale HTL and upgrading tests for woody biomass. The HTL process testing conducted at PNNL differs from other HTL processes developed previously: no reducing gas is used and water, versus recycled bio-oil, serves as the reaction medium. The above experimental work provided information for a techno-economic down selection process for "drop-in" biofuels pathways. The purpose is to select those strategies that showed the most promise to rapidly advance to commercialization.

In this study, TEA was implemented to evaluate the feasibility of developing a large-scale woody biomass based HTL and upgrading system. Experimental information provided a detailed and consistent design basis for this analysis. Two cases are investigated: the state-of-technology (SOT) case (based on bench scale testing results) and the goal case (based on optimal assumptions for the product yields and process design). The purpose of this study is to provide preliminary evaluation of a large-scale HTL and upgrading system, identify potential improvements effects on process economics, identify key factors affecting the cost, and estimate the uncertainty in the production cost.

2. Materials and methods

To implement TEA for a large-scale system, a detailed design basis that represents the battery limits of the system being assessed must be developed first [31]. In this study, the inside battery limits (ISBL) for a commercial scale stand-alone HTL and upgrading plant is assumed to include HTL, upgrading (hydrotreating and hydrocracking), and the hydrogen plant. In this study, the operation conditions and performance of the HTL and hydrotreating processes are mainly based on the experimental results. For other processes such as hydrocracking and hydrogen generation, their design specifications are based on literature sources. With design basis developed, process simulation can be developed. With detailed mass and energy balance information obtained from the simulation results, process economics can be estimated.

2.1. Process overview

Fig. 1 shows a simplified block diagram of the biomass HTL and upgrading system. The overall model consists of four major processes: feedstock preparation, HTL, upgrading, and the hydrogen plant. Woody biomass feedstock is ground to fine particles and

Table 1
Historical development of hydrothermal liquefaction processes on biomass. *Source:* Refs. [1,8–12].

Process	PERC	Lawrence Berkley Laboratory Process	Dutch Shell HTU
Testing and development	1970s and 1980s	1970s and 1980s	1980s–2011
Scale-tested, dry biomass	18 kg/h	~10 kg/h	~10 kg/h
Pretreatment	Drying and grinding (−500 μ) w/bio-oil	Acid pre-hydrolysis, neutralization, wet grinding (−500 μ)	Thermal softening (250 °C, several minutes)
wt% biomass in slurry	7.5%	18% (total solid) 12% (suspended solid)	10.5%
Process medium	Recycled bio-oil + water	Water/no recycle	Water/no recycle
Catalysts, wt% dry wood basis	Na_2CO_3, 10%	Na_2CO_3, 8%	None
Reducing gas	60% CO/40% H_2	60% CO/40% H_2	None
Temperature/pressure	350 °C/20 MPa	330–340 °C/20 MPa	350 °C/18 MPa
Space velocity	1–3 h^{-1}	0.15–1.3 h^{-1}	1–3 h^{-1}
Mass yield to bio-oil	53%	22–30%	38%
Mass yield to solids	1%	0.50%	n/a
Carbon yield to bio-oil	~77%	35%	~50%
Oxygen content in bio-oil	11–15%	~13%	13.5% wt%
Melting point of bio-oil	n/a	n/a	80 °C
Bio-oil viscosity	120 cSt@99 °C 72,000 cSt@52 °C	70 cSt@99 °C	n/a
Bio-oil upgrading by hydrotreating	Yes	Yes	No
Reactor and tested feedstock	Plug-flow reactor, 570 h test, Douglas Fir (TR12)	Continuous stirred-tank reactor (CSTR), 500 h test with Douglas Fir (TR7), conduct at residence time of 7 h	200 h+, at 10 kg/h (dry basis) test was conducted with onion waste in 2004