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Techno-economic comparisons of hydrogen and synthetic fuel production using forest residue feedstock

Duncan Brown[*], *Andrew Rowe*, *Peter Wild*

Institute for Integrated Energy Systems, Department of Mechanical Engineering, University of Victoria, PO Box 3055 STN CSC, Victoria, BC V8W 3P6, Canada

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ABSTRACT

Mobile distributed pyrolysis facilities have been proposed for delivery of a forest residue resource to bio-fuel facilities. This study examines the costs of producing hydrogen or synthetic petrol (gasoline) and diesel from feedstock produced by mobile facilities (bio-oil, bio-slurry, torrefied wood). Results show that using these feedstock can provide fuels at costs competitive to conventional bio-fuel production methods using gasification of a woodchip feedstock. Using a bio-oil feedstock in combination with bio-oil steam reforming or bio-oil upgrading can produce hydrogen or petrol and diesel at costs of 3.25 $ kg^{-1} or 0.86 $ $litre^{-1}$, respectively, for optimally sized bio-fuel facilities. When compared on an energy basis ($ GJ^{-1}), hydrogen production costs tend to be lower than those for synthetic petrol or diesel production across a variety of bio-fuel production pathways.

Introduction

Climate change concerns and government policies aimed at reducing greenhouse gas emissions from fossil fuels continue to contribute to an increasing demand for fuels from biomass sources ('bio-fuels'). The extent to which bio-fuels mitigate climate change by reducing greenhouse gas emissions compared against fossil fuels is a subject of debate, particularly when land use changes are considered in lifecycle analyses [1–5]. However, bio-fuels produced from waste wood, such as forest or mill residues, can reduce net carbon emissions whilst avoiding controversy related to land use change as they are a by-product of the forest industry [6].

Forest residues, in particular, have potential for increased utilisation for bio-fuel production – at present, most are burned on-site at the end of commercial forestry operations. However, forest residues suffer from low spatial and energy densities, which hinder their use as a biomass resource. Typically, forest residues are spread-out over wide areas of land, thus large distances are travelled for collection and delivery to bio-fuel production facilities. If forest residues are transported in their raw form or as woodchips, truck capacity is limited by volume rather than weight and, as a result, more delivery trips are required than if the truck were transporting a more energy dense substance at full weight capacity [7]. The combination of low spatial and energy densities of biomass results in high transport costs which, in turn, elevate the final bio-fuel production cost.

* *Corresponding author*. Tel.: +1 (250) 721 8885.
E-mail addresses: drbrown@uvic.ca (D. Brown), arowe@uvic.ca (A. Rowe), pwild@uvic.ca (P. Wild).
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One proposed method of reducing the cost of delivering a forest residue resource is to implement a distributed network of mobile biomass conversion facilities ('mobile facilities') near the location of forest residues [8,9]. These mobile facilities convert raw biomass to a more energy dense substance, which is then transported longer distances to a centralised bio-fuel production facility. Mobile facilities can be moved from a depleted region and relocated to a region with abundant forest residues. Relocating mobile facilities reduces transport distances of raw biomass material.

Two processes that are suited for mobile facilities are fast pyrolysis and torrefaction [10–12]. These are both forms of pyrolysis, which is the thermal decomposition of materials in the absence of oxygen. Fast pyrolysis involves high heating rates and short reaction times, and produces three main products: bio-oil, bio-char and syngas [13]. Transportable products from fast pyrolysis reactions are bio-oil or bio-slurry (a mixture of bio-oil and bio-char). Torrefaction occurs at lower temperatures than fast pyrolysis and the principal product suitable for transport is a solid char-like substance known as torrefied wood [14,15]. The energy and mass densities of the liquid and solid products are typically higher than those of forest residues or woodchips.

Upon delivery to a bio-fuel facility, the product of mobile facilities (bio-oil, bio-slurry or torrefied wood) can be used directly as feedstock for bio-fuel production. All products are suited for gasification [13,16], which produces syngas. This can be used to yield additional hydrogen via water gas shift reactions or to synthesise petrol (gasoline) and diesel via Fischer–Tropsch reactions. Alternatively, the bio-oil product of fast pyrolysis can undergo steam reforming to produce hydrogen or be upgraded to produce petrol and diesel. Therefore, implementing mobile facilities introduces new pathways for bio-fuel production using a forest residue resource.

Previous work by Brown et al. (2013) [9] studies forest residue feedstock delivery costs when using distributed mobile facilities. Results show that mobile torrefaction facilities can reduce the levelised delivered cost of feedstock ($\$ \ GJ^{-1}$) compared to conventional woodchip delivery when transport distances are large (over 300 km) or when annual feedstock requirements are high (over 2.5 million m^3 per year). Bio-slurry product from mobile fast pyrolysis facilities can provide lower delivered feedstock costs than woodchips, but is more expensive than torrefied wood. Bio-oil product is the most expensive method of delivering a forest residue resource and is not cheaper than woodchip delivery for transport distances up to 500 km.

This study extends the work by Brown et al. (2013) [9] to examine the levelised cost of producing hydrogen or synthetic petrol and diesel in conjunction with a network of mobile facilities to harvest a forest residue resource. Previous studies have provided techno-economic evaluations of centralised and distributed bio-fuel facilities utilising forest residue resources and pyrolysis products e.g. Refs. [17–21], however no studies have been identified in the literature that consider the use of mobile facilities as a method of delivering a forest residue resource for similar analyses. An overview of the fuel production routes analysed in this study are shown in Fig. 1.

Gasification

Gasification is the conversion of carbon-based feedstock into large quantities of gaseous product and small amounts of char and ash [22]. It requires high temperatures between 500 and 1400 °C, and may be performed at pressures of 0.1–3.3 MPa [23]. The produced gas is cleaned to remove particulates, tars, alkali compounds, sulphur compounds, nitrogen compounds and other contaminants to yield a clean syngas consisting of carbon monoxide, hydrogen, carbon dioxide, water, and methane [24].

Syngas is a 'platform chemical' that can be used for many different purposes, including hydrogen production via the water gas shift and Fischer–Tropsch synthesis of petrol and diesel fuels [25]. Principal reactions that occur during gasification to produce syngas are outlined in Equations (1–7) (using methane as an example) [26]:

Reforming:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{1}$$

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \tag{2}$$

Combustion:

$$2CH_4 + O_2 \rightarrow 2CO + 4H_2 \tag{3}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4}$$

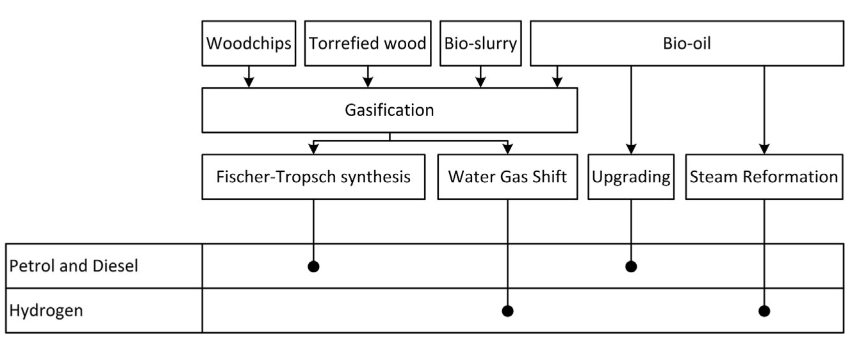

Fig. 1 – Bio-fuel production routes considered in this study using products of mobile facilities.