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Techno-economic assessment of biomass slow pyrolysis into different biochar and methanol concepts

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HIGHLIGHTS

- We model 3 biomass to biochar and methanol concepts to compare their profitability.
- Pyrolysis is more sensitive to biomass costs and the selling price of biochar.
- Biochar selling prices above \$220/t will yield breakeven for some pyrolysis concepts.
- The internal rates of return for all the concepts lie between 10.1% and 14.2%.

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ABSTRACT

Methanol is one of the fuels that are an alternative to petroleum-based liquid transport fuels. This paper assesses the feasibility of co-production of methanol and biochar from thermal treatment of pine in a two-stage process; pyrolysis or gasification to produce biochar and volatiles, and the processing of the volatiles to produce methanol using process data for large-scale conversions based on natural gas. Three concepts were studied: (i) slow pyrolysis at 300 °C; (ii) slow pyrolysis at 450 °C; and (iii) gasification at 800 °C, all of them followed by processing of the volatiles into syngas and the conversion of the syngas into methanol. Gasification was able to generate methanol at or below current (2012) prices of methanol produced from fossil fuel (\$422/t) from a plant size of 100 t/h upwards. Pyrolysis is not competitive without valuing the biochar as a product. Considering both biochar and methanol as marketable products improves the viability of slow pyrolysis concepts. Their profitability is sensitive to the biochar selling price between, with a break-even at a biochar price of about \$220/t for the pyrolysis at 300 °C and about \$280/t for pyrolysis at 450 °C.

1. Introduction

Renewable transportation fuels, including liquid fuels produced from biomass [1–4], are under investigation as alternatives to petroleum. Thermal pathways for conversion of biomass to liquid fuels typically also produce a solid carbon-rich residue ('char' or 'biochar' if applied to soil). The greater the quantity of biochar that is produced, the more of the heating value of the original biomass feedstock remains in this solid residue. Processes that aim to convert biomass to liquid fuel typically seek to minimize biochar production to maximize liquid fuel production. Thus, the most commonly proposed routes from biomass to liquid fuels are via gasification and fast pyrolysis [5]. However, it has been shown that biochar, if it is added to agricultural soils, has significant potential to simultaneously improve soil fertility [6], while reducing atmospheric greenhouse gas concentrations by sequestering carbon [7–9]. Co-production of biochar with bioenergy can provide a greater climate-change mitigation impact than biofuel production alone [8,10], whilst also providing the co-benefit of increased agricultural productivity on poor soils [6].

Producer gas (sometimes called pyrolysis gas), which is a mixture of mainly CH_4, light hydrocarbons, CO, H_2, H_2O, and volatile organic compounds, evolves from the pyrolysis of biomass. Conversion of producer gas into liquid fuel is a promising route that offers a high-value product [11–13]. The producer gas is typically converted into syngas (a CO- and H_2-rich mixture) as an intermediate product, and then converted to ethanol, methanol, or Fischer–Tropsch hydrocarbons, via biological or catalytic processes. Among these pathways to liquid fuels, we focus on catalytic processes as having the lowest uncertainty in production costs and methanol as having the simplest production process.

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Catalytic methanol production from syngas is a well-established process, with multiple commercial technologies developed by different companies.[1] However, the syngas for these processes is mainly produced by steam reforming of natural gas. Therefore, uncertainties remain in regard to the level of clean up of biomass-derived syngas that is needed to prevent metal catalyst poisoning. Other studies [4,14,15] have evaluated the techno-economics of biomass gasification for the synthesis of methanol and other liquid fuels. As is the case with methanol production from fossil fuels, production costs using biomass gasification show considerable economies of scale [4]. Methanol production costs have been found to decrease from \$83.70/GJ to \$30.40/GJ when plant size increases from 10 to 2000 MW (thermal), for a South African setting [4]; the larger plant's production costs are about 1.5 higher than the 2012 US prices of methanol from natural gas, with an average of \$422/t (\$18.59/GJ) [16] (taken as an average of 2010–2012 prices to account for the methanol price volatility).

Even though biochar may improve sustainability of biofuel production through its positive effects on soil health [9], a market and consequently a value of biochar has not yet been generally established [17]. Typically, the production of a biochar co-product increases the cost of biofuel production as it decreases the biofuel yield [17,18]. Brown et al. [18] have compared slow pyrolysis producing biochar and fuel gas versus fast pyrolysis producing bio-oil and biochar. They conclude that a process that primarily produces biochar is unlikely to be profitable, due to the low value of biochar assumed in their study. The magnitude of such tradeoffs for catalytic methanol production and the sensitivity to the as-yet-unknown market value of biochar has not previously been established.

2. Material and methods

2.1. Biomass conversion technologies

A simplified layout of the biomass to biochar and methanol conversion process (Fig. 1) shows the components included in modeling the energy and mass balances. Fig. 1a starts with slow pyrolysis, while Fig. 1b starts with gasification; after these initial steps the producer gases are processed through tar cracking, cleaning, compression, optional water gas shift and catalytic methanol production, all of which processes are described below.

Three different thermochemical conversion concepts were studied. (1) Py300: pyrolysis at 300 °C to maximize the biochar yield. This concept gives the highest biochar yield (80% of the biomass' carbon) and the least syngas. The resulting low syngas volume implies smaller syngas conditioning component sizes and lower equipment costs per unit of biomass feedstock (although not per unit of methanol produced). (2) Py450: pyrolysis at 450 °C, typical of slow pyrolysis units [19,20]. This concept converts about 45% of the carbon to biochar, and is within the temperature range that produces optimal biochar quality [21] and (3) Gas800: gasification at 800 °C for maximum syngas yield, for comparison with pyrolysis. This concept leaves only about 15% of the carbon in biochar by mass.

2.1.1. Syngas production

The syngas for the process is produced in two stages: pyrolysis and tar cracking. The gaseous and volatile products from pyrolysis at the temperatures considered consist of a complex mixture of volatilized tars and other condensable organic compounds, C1–C3 hydrocarbons, CO_2, H_2O, some CO, and small amounts of H_2. In contrast, the methanol synthesis stage requires a syngas that consists primarily of CO and H_2. Therefore, a tar-cracking unit was included in the process to both convert the volatile products to a syngas rich in CO and H_2. The heating conditions in these two stages determine the composition and yield of the syngas.

Syngas composition and yield for the pyrolysis scenarios (Py300 and Py450) are obtained from experimental pyrolysis data for pine from Enders [22] summarized in the Supplementary Information. The overall C, H and O composition of the combined gaseous and volatile product mixture (and thus, of the final syngas composition) is similar for pyrolysis temperatures above 350 °C, but volatiles' yield increases with temperature. Composition and yield for the gasification scenario were calculated from elemental C, H and

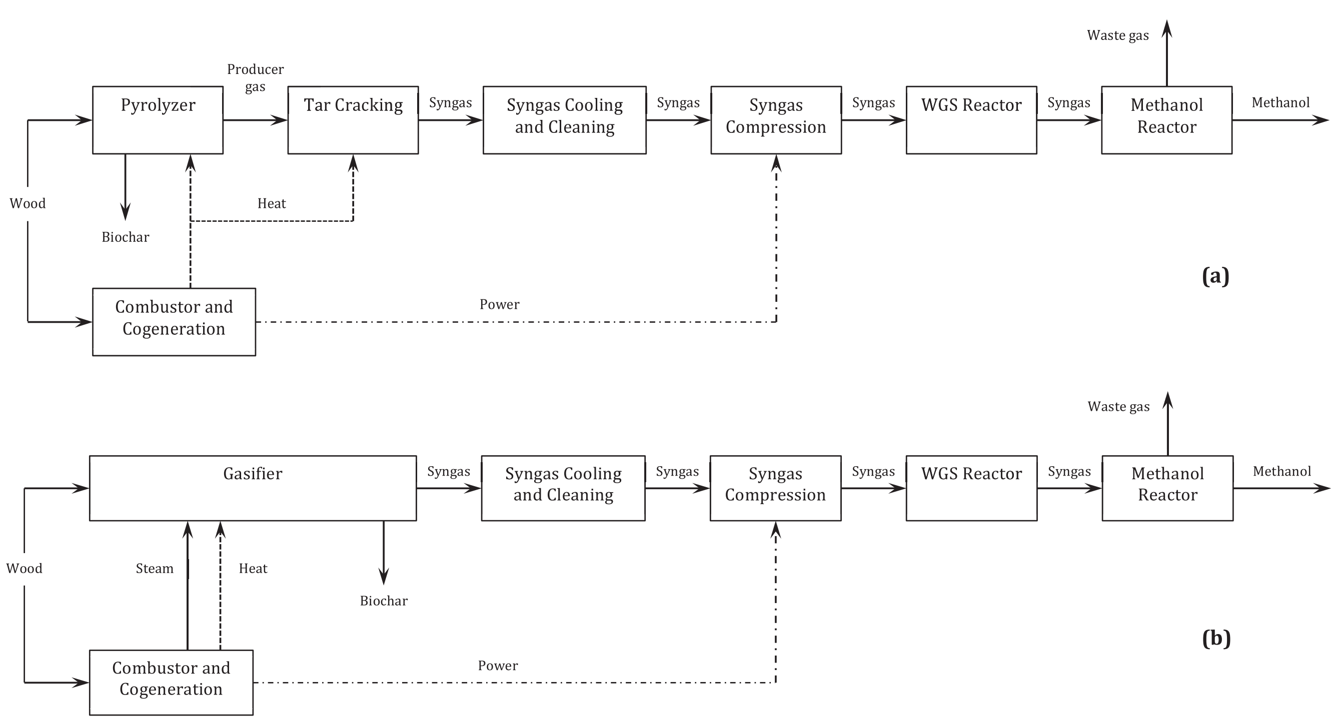

Fig. 1. Schematic layout of a biomass to methanol and biochar plant.