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Evaluation of value chain configurations for fast pyrolysis of lignocellulosic biomass - Integration, feedstock, and product choice

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ABSTRACT

Fast pyrolysis of lignocellulosic biomass constitutes a promising technology to reduce dependence on fossil fuels. The product, pyrolysis liquids, can either substitute heavy fuel oil directly, or be upgraded via e.g. hydroprocessing to diesel and petrol. This study presents a systematic evaluation of production costs and CO_2 mitigation potentials of different fast pyrolysis value chain configurations. The evaluation considers types of localisations, emissions from electricity and hydrogen production, biomass feedstocks, and final products.

The resulting production costs were found to be in the range of 36–60 EUR/MWh for crude pyrolysis liquids, and 61–90 EUR/MWh upgraded to diesel and petrol. Industrial integration was found to be favoured. The CO_2 mitigation potential for the pyrolysis liquids was in the range of 187–282 t-CO_2/GWh biomass. High variations were found when upgraded to diesel and petrol –best-case scenario resulted in a mitigation of 347 t-CO_2/GWh biomass, while worst-case scenarios resulted in net CO_2 emissions.

Favourable policy support, continued technology development, and/or increased fossil fuel prices are required for the technology to be adapted on an industrial scale. It was concluded that integration with existing industrial infrastructure can contribute to cost reductions and thus help enable the transformation of traditional forest industry into biorefineries.

1. Introduction

Thermochemical conversion of biomass via gasification and fast pyrolysis (FP) provides a sustainable, environmentally friendly, and energy-efficient conversion of forest feedstocks into high value-added products. These conversion technologies constitute a great potential to replace fossil products in forest rich regions. Upgrading to liquid products could be of particular interest, since it provides, compared to solids and gas, advantages in terms of transportation, storage, and possibilities for retrofitting of current industrial infrastructure [1].

Sustainable biomass is a limited resource and to maximise the economic and environmental benefits the entire value chain of the biomass usage should be evaluated considering e.g. biorefinery location and size, and feedstock and product choice [2–4]. To categorise the economic, resource, and environmental performance of different utilisation options there is thus a need for systematic evaluation of different utilisation options.

Several studies argue that the FP pathway currently offers the highest yields of liquid products and the best economic performance, compared to the gasification and biochemical pathways [5–7]. The FP process is a thermo-chemical process which produces char (solids), pyrolysis liquids[1] (PL), and non-condensable gases at moderate temperatures (around 500 °C), with PL yields up to 75 wt % [8]. The by-products, char and non-condensable gases, can be used to provide the heat needed for the FP process, and under certain conditions, generate a surplus of these products [9].

PL has properties which make it suitable for replacing heavy fuel oil in combustion applications [10], as well as useful as an intermediate product for further upgrading with physical, chemical, or catalytic processes [11]. This can be done with the PL as the sole feedstock, or the PL could be mixed with other feedstocks before

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[1] Often referred to as bio-oil or pyrolysis oil, however the product contains water and is in this study referred to as pyrolysis liquids (PL).

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upgrading e.g. black liquor to utilise the catalytic effect from the black liquor in gasification [12]. By catalytic upgrading of PL via hydroprocessing, where hydrogen is used to reduce the oxygen content in the PL, it is possible to e.g. produce diesel and petrol range fuels [13]. This is a two-step process where hydrotreating under mild conditions is followed by hydrocracking under more severe conditions [14]. The process results in both waste heat and surplus gases [15], which could be utilised to offset primary energy sources. The hydroprocessing step could significantly impact the CO_2 performance of the biofuel production from the FP process, mainly related to emissions from the H_2 production [16]. Using natural gas as feedstock for the H_2 production can result in high CO_2 impact, while using renewable electricity or biomass to produce the H_2 can result in significantly improved CO_2 performance [16,17].

For many biofuel and biomass upgrading concepts, it is advantageous to integrate the process with other industries to gain benefits related to e.g. use of industrial by-products as feedstock, cascade utilisation of excess heat and intermediate products, sharing of utilities, and use of industrial know-how, and knowledge, see e.g. Refs. [18–20]. There are several types of FP reactors, such as fluidised beds, rotating cone reactors, and ablative reactors [1], where particularly the circulating fluidised bed makes the process suitable for integration with fluidised bed boilers [21]. This has been done on a demonstration scale where a circulating fluidised bed reactor was integrated in a CHP (combined heat and power) plant in Joensuu, Finland [22].

Integrating a FP process with a CHP plant in a district heating (DH) network can provide benefits related to e.g. heat integration, logistics, utilisation of surplus char from the FP process, as well as increasing the annual operating time for the CHP plant [23,24]. This could improve the overall energy efficiency, and decrease the PL production cost. Since many DH networks may in the future face stagnating or decreasing heat loads due to more energy-efficient buildings, climate change, competition from other heating systems and market saturation [25], this could provide a benefit for CHP plant operators. However, depending on the configuration of the integration and the feedstock, the benefits from integration can vary, and may not necessarily result in a better economic performance, compared to a stand-alone FP plant [21].

Different feedstocks can be utilised for FP, and for forest-rich countries, the utilisation of residues from forestry and the forest industry can be of interest. By integrating FP production at an industrial site (e.g. forest industries) and using industrial by-products as feedstock (e.g. sawmill residues), there is a possibility to increase the overall process performance by heat integration and eliminating costs and emissions related to transport of the feedstock [26].

Integration with a pulp and paper mill has been shown to have economic advantage for the FP process [27]. A plant with high steam demand has a boiler on site that could be used for providing heat for the FP process. The boiler would also provide an offset for by-products such as char, which would reduce the need for import of new biomass to the site to satisfy the mill steam demand. Sawmills could also provide an advantageous integration option with the possibility to both use by-products on site and provide benefits for heat integration. Utilisation of sawmill by-products was investigated for a Canadian case, where an FP process using sawmill by-products was evaluated and found beneficial from a GHG performance perspective [28]. The study however considered no industrial integration other than usage of the by-product and no economic evaluation was performed.

Several parameters may have a significant impact on the overall system performance of the FP value chain; such as feedstock choice, downstream upgrading and utilisation, and facility localisation, including integration options. Regional differences can influence the economic feasibility of biofuel production, especially depending on feedstock availability [29]. Furthermore, a large number of studies have considered FP followed by hydroprocessing for the production of transportation fuels, which has shown to be promising in terms of economic and environmental performance [30,31]. It should be noted that the hydroprocessing of PL is not yet commercialised, and still needs further research. The source of H_2 has a significant impact on the GHG performance of the produced transportation fuels, where H_2 from natural gas can contribute over 50% of the net well-to-wheel GHG emissions [16].

In the literature, investigations of different FP process and supply chain configurations can be found, including integration options, from an economic and GHG performance perspective. However, a systematic study evaluating different value chain configurations regarding environmental as well as economic performance, considering different integration opportunities and end products, largely seems to be lacking. As a number of trade-offs can be identified regarding value chain configuration selections when upgrading the PL to higher value products, a systematic evaluation of different configuration options is needed in order to make those trade-offs more explicit and visible. This evaluation would also be useful regarding selection of types of industries that are of interest for further research for integration of the FP process.

The overall aim of this work is to identify FP based value chain configurations with high economic and environmental performance, measured as costs for production from well-to-gate, and CO_2 mitigation potential from well-to-use. This is done by performing a systematic analysis of the economic and CO_2 performance of biofuel[2] production from FP of lignocellulosic biomass, depending on choice of (i) localisation, and (ii) end-product. Impacts on the value chain performance resulting from on the one hand the industrial integration, and on the other hand of the upgrading of PL to diesel and petrol, will be quantified in terms of economic and CO_2 performance. The country of Sweden is used as a case study due to its well-developed forestry sector and forest industry, which provides knowledge of large-scale operation of biomass supply chains, as well as integration opportunities. While the emphasis is on Swedish conditions, the results are applicable for other similar forest rich regions.

A previous investigation of Swedish conditions estimated the economic performance of PL production via stand-alone FP, FP integrated with CHP plants in district heating systems, and FP integrated with pulp and paper mills, showing economic advantages for industrial integration [27]. However, the study lacked evaluation of integration opportunities at sawmills, which could be of interest in the Swedish context. While the study has important merits regarding the evaluation of the economic performance, evaluation is lacking of the GHG performance, as well as an analysis of the impact of the surrounding system in terms of biomass and electricity usage. Due to the newly introduced emission reduction mandate for diesel and petrol in Sweden [32], which has the aim of promoting biofuels with high GHG performance, GHG evaluation of biofuels have further increased in importance.

To evaluate the benefits of integration, a stand-alone case is in this study compared with cases integrated with CHP plants in district heating systems, pulp and paper mills, and sawmills. The value chains will be evaluated with crude PL as a product for replacement for heavy fuel oil, as well as PL upgraded to higher value products via hydroprocessing to liquid transportation fuels, as a replacement for fossil transportation fuels.

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[2] The term "biofuel" is in this study used to denote bio-based liquid fuels for use in either transportation (upgraded PL), or in stationary combustion applications (crude PL).