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Integrating fast pyrolysis reactor with combined heat and power plant improves environmental and energy efficiency in bio-oil production

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ABSTRACT

Biomass as a renewable energy source is an alternative to fossil fuels. Due to its lower energy density compared to fossil fuels, different ways of converting biomass into an energy-dense fuel are sought after. Fast pyrolysis of biomass into pyrolysis oil represents such method, allowing wider substitution of fossil fuels. Pyrolysis is an energy-intensive process but its efficiency can be improved by integration of pyrolysis reactor into a combined heat and power plant. In this study environmental analyses are conducted on the production of 50 000 tons of pyrolysis oil from wood to substitute for heavy fuel oil. The pyrolysis oil is produced either in a stand-alone reactor or as an integrated part of a combined heat and power plant. The combined heat and power plant is wood and peat fueled, producing of 820 GWh of energy. The cradle-to-grave emissions of CO_2-eq, NO_x, SO_2, and PM are calculated by using two methods: 1) life cycle assessment and 2) the Tool for Sustainability Impact Assessment. Reductions in environmental loads of over 75% in (fossil) CO_2-eq and over 90% in NO_x, SO_2, and PM can be achieved when heavy fuel oil is replaced by pyrolysis oil. The pyrolysis is 20% more efficient if integrated with CHP production. The potential reductions vary several percent between the applied methods because of different system boundaries. Nevertheless, integrating the pyrolysis reactor into a combined heat and power plant appears as the best option irrespective of the method used. Extending the system boundaries with the life cycle inventories results in significant increases of emissions in many processes; however, combustion in plants has a dominant role in overall emissions but is not subject to the boundary extensions, and thus, the totals of emissions between the methods are nearly the same.

1. Introduction

Wood biomass will have an important role in the future of a low-fossil society by substituting for fossil resources and thus mitigating climate change over the long term (Silveira et al., 2015). However, low energy density and high moisture content in wood is a common obstacle for its substitution for fossil fuels. Naik et al. (2010) consider lignocellulosic forest biomass as environmentally and socially more sustainable than fossil fuels because of its carbon balance, food is not used for energy, and the production chain increases the number of jobs. Zinoviev et al. (2010), however, note that the practicality and environmental benefits of substituting fossil fuels with biofuels depend on the applied technology, raw material, and its availability. They also show that energy inefficient biofuel production chain can cause greater emissions than fossil fuel chains. Similarly, Gallezot (2008) emphasizes the importance to assess the production chains and methods when energy alternatives are compared.

The biofuel sector has developed rapidly during the last decades and converting biomass into biofuels such as bioethanol, biogas, char, and bio-oil allows for a wider substitution of fossil fuels (Moriana et al., 2015). Fast pyrolysis of wood (e.g. Onarheim et al., 2014) is one such a conversion method. The rapid development calls for up-to-date impact assessments and this study focuses on the changes in cradle-to-grave emissions when pyrolysis oil (PO) is displacing heavy fuel oil (HFO). The PO is produced in two ways: In

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a novel way of integrating pyrolysis reactor with a combined heat and power (CHP) plant and in a setting where the PO and CHP are as stand-alone systems. The world's first such integrated commercial scale facility was built in 2013 in Joensuu, Finland, with a capacity of 50 000 tons/a (Fortum, 2013). The company reported the fine tuning of the reactor to have taken a few years and that the production began in late 2017 (Fortum, 2017).

The aim of this paper is twofold: 1) To identify the differences in environmental loads between the alternative combinations of HFO, CHP, and PO chains; and 2) to evaluate the differences in results following the expansion of the boundaries from direct emissions (ToSIA) to include also indirect emissions (LCA).

To reach these aims, Tool for Sustainability Impact Assessment (ToSIA) (Päivinen et al., 2012; Lindner et al., 2010) is used to assess the alternatives, which is then expanded with a EcoInvent 3 life cycle inventory (LCI) (Wernet et al., 2016) to conduct a life cycle assessment (LCA) (e.g. Finkbeiner et al., 2006; Jensen et al., 1997). The results between the methods are compared. In particular, the environmental performance of displacing HFO with PO when the pyrolysis reactor is integrated into a CHP is assessed. In addition, a scenario for stand-alone CHP and PO chains is considered to identify the impacts of integrating the CHP and PO. The environmental indicators in this study are CO_2-equivalents (CO_2-eq) (including CO_2, methane (CH_4) and dinitrogen oxide (N_2O)), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM) emissions into air. These emissions were chosen because they were reported in the literature for all the processes considered within ToSIA-boundaries, thus allowing comparison between the two methods of the study.

To the authors' best knowledge there are no papers comparing the cradle to grave emissions of wood pyrolysis between PO production in integration with a CHP and in stand-alones. Also, this study is the first to make note of a potential risk of misinterpreting results when fossil and biomass are dealt with separately. In addition, the significance of the system boundaries in the context of biofuels versus fossil fuel is highlighted. With these, the paper further contributes to discussions over replacing fossil fuels with biofuels.

The hypotheses are that PO performs environmentally better than HFO due to locally supplied renewable forest biomass as raw material. Integrating the CHP plant and the pyrolysis reactor is anticipated to improve the environmental performance compared to their stand-alone versions due to higher overall energy efficiency. On the methodological side, LCA is expected to result in higher environmental loads in all chains, with the biggest increase in the HFO chain. Another assumption is that the inclusion of indirect emissions from the EcoInvent LCI data in ToSIA data brings about some significant changes in the results.

2. Materials and methods

2.1. Data collection

The information related to the CHP plant and the pyrolysis reactor are obtained from literature discussing similar plant technologies (e.g. Onarheim et al., 2014; Peters et al., 2013; Lehto et al., 2013; Steele et al., 2012) as described in sections 2.3 and 2.3. The inspiration of this study stems from the CHP-pyrolysis integrate in Joensuu, Finland. Hence, its environmental permit (ISAV, 2012) is used; however updates about the energy outputs and fuel mix are obtained by personal communications with plant personnel. For processes outside the pyrolysis and CHP plants, such as forestry and transports, databases (e.g. LIPASTO, 2015) and technical reports (e.g. Wihersaari, 1996; Laitila et al., 2012; Rieppo and Örn, 2003) and fuel classification of Statistic Finland (2017) are utilized. This information is used in ToSIA (section 2.4) for the direct emission factors which were then further expanded with data from the EcoInvent 3 database (Wernet et al., 2016) to include the indirect emissions from, for example, the production of machines and ships and their fuels, establishing a peat excavation site and oil drill infrastructure, drilling operations. Biogenic carbon emissions of wood combustion is separated from fossil carbon emissions from using diesel, HFO, and peat. Peat is categorized as a fossil fuel according to the IPCC (2006) guidelines regardless of some considering peat as a renewable fuel (International peat society 2007; Crill et al., 2000). Full lists of calculated emissions per processes are given in Appendix 1. The full list of process steps more in detail with their references is provided in the supplementary material.

2.2. Fast pyrolysis

Fast pyrolysis is one of the modern technologies for substituting fossil fuels, defined in Peters et al. (2013) as "*the thermal decomposition of a carbonaceous feedstock in a non-oxidative atmosphere that yields gases, chars and condensable vapors (tarry liquids, the bio-oil)*". While the technology has been available since the 1970s (Bridgwater and Peacocke, 2000), it has experienced a revival as interest in substituting fossil fuels has become more prominent (Radlein and Quignard, 2013). In the fast pyrolysis of forest biomass, the fine-ground feedstock is exposed to a temperature of approximately 500 °C for about 2 s (Onarheim et al., 2014). The fast pyrolysis process is optimized to maximize the PO yield; however, char and non-condensing gas fractions are unavoidable but useful side products of the process. The side products may supply the heat that is needed in the pyrolysis process itself that according to Kohl et al. (2014), consumes 15% of the feedstock energy but energy is also needed for drying and grinding the feedstock (Onarheim et al., 2014), Peters et al. (2013) add that the efficiency of pyrolysis is dependent on many factors, especially on feedstock's moisture.

The overall shares of pyrolysis oil, char, and gas depend on the parameters, such as temperature, moisture, and properties of the feedstock (Onarheim et al., 2014). Previous studies (e.g. Peters et al., 2013; Kohl et al., 2014; Onarheim et al., 2014) report yields of 10–15% gases, 10–20% char, and 60–70% PO (dry mass), but the shares are highly dependent on feedstock properties. Prior to pyrolysis, the feedstock is dried to below 10% moisture content because the water condenses into PO, which lowers the PO's energy density. Lehto et al. (2013) note that while the bio oil quality defines the emission when combusted, the quality varies even between same types of feedstocks. However, Steele et al. (2012) find that there are environmental benefits in substituting residual fuel oil by pyrolysis oil. Onarheim et al. (2014) modelled fast pyrolysis process and products when logging residues and small diameter energy wood of pine are pyrolyzed and found significant difference between these feedstocks. Further descriptions and technical details about the pyrolysis reaction and products are available, for example, in Mirkouei et al. (2017), Onarheim et al. (2014), Lehto et al. (2013) and Peters et al. (2013).

2.3. Integrating pyrolysis and CHP

Integrating a pyrolysis plant and a CHP plant is a novel way to produce bio-oil (Fortum, 2013) more efficiently than in a stand-alone system, for example, with respect to the operating hours (Kohl et al., 2013), and energy efficiency (Kohl et al., 2014). The integration allows using the heat from combusting the char and non-condensing gases in the CHP boiler to run the pyrolysis reaction, dry the pyrolysis feed and for additional efficiency in the CHP. In this study, Table 4 in Onarheim et al. (2014) is modified to