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Direct liquefaction of ligno-cellulosic residues for liquid fuel production

Samir Bensaid, Romualdo Conti, Debora Fino *

Department of Materials Science and Chemical Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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ABSTRACT

This study focuses on the valorization of biomass wastes in the Piedmont Region, in Italy, with the aim of producing synthetic liquid fuels. On the basis of a territorial survey, the selected fractions from the separate collection of municipal solid wastes (organic fraction, pruning residues and wood refuses) and, to a lesser extent, the residues of the agro-industry, were considered potentially important, due to their abundance and availability throughout the year. Dedicated arborous cultivations, evaluated on the basis of the land that is currently cultivated, also showed a great potential. The sum of the potential recoverable energy from these three categories reaches 35.99×10^6 GJ/year, i.e. 6.79% of the total final energy consumption of the Piedmont Region.

The target of this valorization is here the conversion of these low energy density biomasses into valuable liquid fuels. The direct liquefaction technology was chosen due to its flexibility towards the feed and the possibility of working with wet substrates, these being typical constraints which are difficult to be overcome in the other thermo-chemical processes. In the direct liquefaction process, a pulp of organic material, with a water content ranging from 50% to 90%, is fed to a reactor at around 330 °C and 180 bar, with a residence time of 4–10 min, according to the biomass pulp composition. The resulting bio-oil can be fed to the upgrading section of a refinery, in order to reach standard fuel-grade specifications, which allows it to be blended with currently sold transportation fuels, or it could be used as a source of valuable chemicals in an alternative scenario. A 50 ktons/year plant (based on the dry biomass content) was considered, and the balance of plant was sized in order to estimate the energy requirements of the plant and the bio-oil yield. A very convenient configuration was designed, and a bio-oil net production of 37.1 wt% was reached (referring to the dry matter of the biomass), which takes into account all the fuel needs of the plant. The specific power consumption was equal to 0.258 kWh/kg_{Oil}, which corresponds to a ratio between the output and input energy of 35.8 (excluding the biomass lower calorific value). Finally, it should be mentioned that this target was obtained using simple and economic equipment, thus responding to the need to devise a process which could be profitable, even at a medium scale, for local applications.

1. Introduction

In order to achieve the ambitious target set by the EU Commission of reaching a 10% consumption of transportation fuels from renewable sources by 2020, of which at least 40% from "non-food and feed-competing" biofuels, a great effort must be made. At the same time, the recycling of wastes from human activities has become mandatory for mature societies that have to face resource rationalization, to be more and more efficient and thus competitive at a global scale. In this context, this work is focused on the valorization of organic wastes through the production of liquid fuels for transportation. The intention is to exploit the enormous potential of these low value biomasses, to which a cost for disposal is often associated, and to convert them into a valuable and necessary commodity of our society: liquid fuels.

Several processes have already been devised to carry out this conversion, but many of them require a rather strict control of the feed parameters (size, humidity, etc.), which makes these processes advantageous for some selected biomasses [1], but unsuitable for others because of the ever-changing composition of the biomass feed, such as in the case of wastes. In addition, the high water content of these wastes is a drawback to their economic exploitation through thermo-chemical processes, and the biomass conversion is usually directed to a wet system, such as anaerobic digestion.

A very interesting option could be thermo-liquefaction, or direct liquefaction: this process has been studied extensively since the '80s, and the most known process of this kind is the HTU® (Hydrothermal Thermal-Upgrading) process. The key step of this process is the conversion of the biomass substrate under severe

* Corresponding author. Tel.: +39 011 090 4670; fax: +39 011 090 4699.
E-mail address: debora.fino@polito.it (D. Fino).

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pressure (150–250 bar) and temperature (330–370 °C) conditions, with a high water-to-biomass ratio (3:1–10:1) and for a residence time of 4–10 min. A good de-oxygenation is reached at these conditions, and a bio-oil that contains less than 10% oxygen is obtained [2–5]. Other process conditions and reactor configurations have been devised, such as the CatLiq® process [6] by SCF Technologies and the CWT Thermal Process [7] by Changing World Technologies, the latter being used in some commercial applications [8].

Starting from the specifications of the liquefaction reaction indicated in patents and publications [2,3,5], the whole process was studied in order to apply suitable technologies to the specific needs of each stage of the process: the pre-treatment and the separation of the products were investigated in particular, since there is very little information in the literature concerning these two aspects. The final outcome was the quantification of the heat and power needs of the process, in relation to the yield of the bio-oil converted from the original biomass feed, for a nominal plant size of 50,000 tons/year (based on a dry and ash free – hereafter called DAF – biomass feed).

A crucial factor of a plant that processes wastes as the main feed, is the availability of the feed itself. Therefore, a survey has been conducted on the territory, in order to quantify the potential of this application. In many cases, the profitability of the process is offset by the cost of transporting the required feed long distances, which makes it mandatory to locate the plant next to the biomass source; if either the biomass reservoir is limited to feeding a medium-scale plant (like the one considered in this work), or the reservoir is far away from refining sites where the bio-oil can be upgraded, then the overall process is not profitable. The territorial yield was investigated for the case of wastes, and it emerged that there was a very consistent potential for energetic valorization, and in particular for liquid production.

The Piedmont Region, in North-West Italy, was chosen as the case study for this investigation, since it has a considerable stock of municipal wastes from urban areas (especially from Turin) to be disposed of, but it also has a developed agricultural sector with a large production of residues that have to be treated [9].

2. Availability of biomass residues

This study concerns the optimization of biomass waste and agro-industry residue valorization, within the Piedmont Region; the main aim is the production of synthetic liquid fuels. The potential which could come from the cultivation of dedicated energy crops is also taken into account. To this end, several feedstocks have been considered in this section, on the basis of their abundance and seasonality. The categories that emerged from an accurate territory survey were: dedicated arborous cultivations; organic fraction, pruning residues and wood refuse from the separate collection of municipal solid wastes; agricultural residues. The yield and the recoverable energy were calculated for each category.

2.1. Arborous cultivations

Woody biomass is here intended as the ligno-cellulosic based biomass, which may come from the forestry sector, in the form of forest residues, from wood processing industry wastes, or even from dedicated arborous cultivations. In 2009, more than 100 Mtoe of the EU's energy consumption was obtained from biomass, 11% for electricity, 10% for transportation fuels and 79% for heat. Today, wood is the main renewable energy source in Europe, representing more than 60% of all non-conventional energies used in the EU-27 [10]. Timber is an excellent raw material to produce liquid fuels, since it appears to have very low concentrations of impurities and harmful substances, which would otherwise be removed during the conversion process. However, for the same reasons, the energy use of this organic matter has to compete with other traditional uses (i.e. the paper industry, construction), and this results in a high purchasing price of this high-quality material, which therefore virtually precludes its use for bio-energy. For this reason, the possibility of using tailored ligno-cellulosic energy crops, with short rotation times, was investigated. Willow, poplar, but also local plants such as Black Locust, which is a naturally occurring species throughout the territory, and which therefore facilitates its adaptation, are all excellent woody biomasses for this type of cultivation. Clearly, the cultivation of these species must also consider economic profitability in comparison to the other land exploitation possibilities, legislation limitations, and social acceptance of land use reconversion.

As already mentioned, another source of woody material is represented by the wood wastes from processing industries (sawdust and scraps from sawmills) and forest industries (twigs, debris, demolitions, etc.): these wastes appear to be good candidates for conversion to fuels as they are available in large quantities and at negligible prices compared to timber. This fraction has been taken into account in the next section, which is dedicated to the selected collection of wastes, in the wood residue category.

The various forms of woody organic matter are characterized by parameters (particle size, moisture, impurities) that require a preliminary treatment to standardize the material and turn it into a user-friendly form such as chips, sawdust, wood flour or wood pellets, for transport purposes.

In order to evaluate the potential of the Piedmont Region to grow dedicated arborous cultivations, it was assumed to replace the cultivation of 3% of the Currently Cultivated Land (CCL) with a Black Locust monoculture (local *Robinia Pseudoacacia*), and to exploit 10% of the Non-Cultivated Land (NCL) for the same cultivation. On the basis of the actual values of the extension of only hilly and flat CCL and NCL (no mountainous fields) [11], a considerable potential for dedicated energy crops can be discerned in the Piedmont Region (Table 1). The productivity of 10 $tons_{DRY}$/ha/year (average values found in literature, for different sites, cultivars, production systems, and rotations) [12], and a lower calorific value of 20.6 MJ/kg_{DRY}, were used for Black Locust trees to calculate the total recoverable energy output. Clearly, the substitution of current cultivations for dedicated energy crops (even to a low extent), or the production of energy crops in currently unexploited or marginal fields, is not a simple task, and the obtained values are only representative of the margins that such an application would be able to reach. However, the assumptions of CCL and NCL exploitation are conservative if one considers that farmers are keen to replace current cultivations with long-term contracts of dedicated crop furniture to a biomass-based plant, since it represents a secure asset.

2.2. Selected fractions from the separate collection of MSW

The fractions from the separate collection of Municipal Solid Wastes (MSW) which could be used for energy recovery purposes are: organic fraction, pruning residues and wood refuse.

The organic fraction from MSW can be divided into two types, namely from large users and from households. These two types of organic fraction are generally treated together, as there is no

Table 1
Dedicated arborous cultivations: Maximum land exploitation and recoverable energy potential.

Land Exploitation	Yield (tons/year)	Recoverable energy (GJ/year)
% CCL	605,275	11.50×10^6
% NCL	175,552	3.32×10^6
Total	780,827	14.82×10^6