Ablative fast pyrolysis – potential for cost effective conversion of agricultural residues

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Abstract

Biomass from agricultural residues and food production will become a major source for energy and chemicals production. Straw as an example of agricultural residues—though abundantly available—occurs sparsely distributed and its price is dominated by logistic cost. By converting straw into pyrolysis oil directly in the field, this logistic cost can be drastically reduced. A major outcome of the present study is that the intermediate product from ablative flash pyrolysis can be delivered to subsequent utilization plants at approximately the same price as baled straw, provided some underlying assumptions are met. One aim of the Fraunhofer innovation cluster »bioenergy« is to determine, whether the existing concept for an ablative flash pyrolysis process can be scaled-up to a capacity of 10 t/h and still could be mounted on a mobile platform.

Keywords: cost analysis, economics, flash pyrolysis, straw, agricultural residues

Introduction

Today, world wide energy systems depend predominantly on nuclear and fossil sources. Their acceptance (for nuclear sources) and availability (for fossil sources) is predicted to reach a peak and afterwards decline. Several studies [1-3] give different timeframes for the occurrence of this peak in the current decade, but the appearance of the peak as such is beyond question. Additionally, the use of fossil fuel contributes to the global climate change due to the emission of the greenhouse gas CO$_2$ as a primary product of combustion. On the other hand there are several forecasts of a still increasing worldwide energy demand [2, 3]. Even in the most optimistic scenarios for the share of wind, solar and hydro power as renewable, CO$_2$-neutral sources in the final energy demand [4], there is an increasing gap between predicted availability and demand. This gap can only be closed by further efforts in energy efficiency [5] and an increased utilization of biomass, especially as an energy carrier/storage and feedstock for chemical production.

Figure 1 shows the usage of the world’s landmass. Due to increasing human population the use of arable land for the production of dedicated energy crops cannot be increased. Therefore the biomass resources
for future energy and chemicals production must originate from residuals either directly from agriculture or indirectly as byproducts from food/fodder production. Fraunhofer UMSICHT organizes a group of companies from farming, agricultural machinery, food industry, chemical engineering, municipal waste management companies and additional research institutions to collaboratively develop solutions for the thermo-chemical conversion of such residual biomass to intermediate energy carriers within the Fraunhofer Innovation-cluster »Bioenergy«.

![Figure 1: Land usage worldwide [6]](image)

**Organizational framework**

**Fraunhofer Innovation-cluster »Bioenergy«**

Fraunhofer innovation-cluster are prestigious projects of the Fraunhofer Gesellschaft (FhG). They foster the application of new technological and scientific results of fundamental research into new commercial products by increasing the networking between regional companies and universities on one topic with a Fraunhofer Institute as central node and catalyst. At present, there are 20 such Fraunhofer Innovation-cluster in action distributed all over Germany, each working on a different topic. The budget for the effort of a Fraunhofer Institute in these clusters is covered jointly by the Fraunhofer Head Office (25 %) and the
The work is organized in 4 lighthouse projects L1 – L4. Lighthouse project L1 deals with the (pre-)processing of “wet” distributed biomass like grass or undersown crop. The purpose of this project is to deliver “dry” matter to subsequent thermal conversion processes and creation of value from the liquid fraction. The aim is to dry the biomass by mechanical means such as presses to the extent possible and to
apply low temperature heat to achieve the desired degree of dry matter content in the residual solid fraction.

Lighthouse project L2 focuses on the thermal conversion of “dry”, stalk-like biomass into a pyrolysis oil and char. The main industrial partner in this project, which is described in more detail in the following sub-section, is the Claas Group, a manufacturer of agricultural machinery.

Lighthouse project L3 further develops the process of hydrothermal carbonization of biogenic residues from food and fodder production processes like pericarp, press cake of oil seeds, rejected material, leaves, etc. and solid residues from anaerobic digestion or even sewage sludge. As these materials are quite high in water content, hydrothermal carbonization lends itself to convert them to coal-like biochar. Hydrothermal carbonization can also be looked at as means of dewatering, because the produced char can easily be separated from the process water and has much higher dry matter content than the input material.

Finally, lighthouse project L4 concerns itself with the post-processing and marketing of primary products from the other lighthouse projects. The aim is to find commercial applications for the aforementioned products: squeezed juice, pyrolysis oil and biochar or fractions/components thereof either as fuel or for material utilization.

**Lighthouse project L2 Mobile Pyrolysis**

Agricultural residues like straw (from cereals, sun flower, canola, maize, etc.) occur distributed over large areas after harvesting the primary fruit. If it is not left in the field and either burnt or ploughed in, a recovery procedure is usually implemented [7] as depicted in Figure 3. After grabbing the straw is baled and then transported to a storage facility, either as a heap alongside the field or in a barn, which is preferable for a later thermal conversion process due to better protection against weather. From the storage it is transported to the place of utilization, e.g. a thermal conversion plant.
The straw removed from the field contains several nutrients, which must be replaced by mineral fertilizer. The cost for the fertilizer replacement is the basis for the cost calculation for recovered straw, because if revenues for straw are below fertilizer price it would be more economic to leave it in the field. Therefore the minimum selling price for loose straw in the field is in the range of 20 €/t [8]. The additional costs for the straw logistic are shown in Figure 4. The minimum selling price of straw from storage is about 100 €/t [8]. So, only one fifth of the cost originates from the nutrient value of the straw, four fifth from the logistic procedures. This high share of logistic cost in the selling price is the motivation for the development of a conversion process alongside the field, or even better, directly in the field combined with grabbing.
One possible process for straw conversion could be direct pelletizing. Such a process is technically realizable and would lead to a freely-flowing solid fuel. Straw pellets can be used as additional fuel in coal-fired power stations. Due to the mineral content of the straw, which lowers the ash melting temperature, straw co-combustion is limited. Also the cost for such straw pellets delivered to thermal conversion plants is in the same range compared to baled straw, and therefore the purchase of additional machinery is not economically justifiable.

Alternatively, pyrolysis processes would lead to a liquid (pyrolysis oil) and a solid (biochar) intermediate product, which both can be used later on for different applications. Figure 5 depicts the logistic chain for the mobile pyrolysis processing of straw directly in the field, while Figure 6 shows the potential utilization pathways for pyrolysis oil.

Figure 4: Distribution of cost for straw recovery [8]
There are many different pyrolysis technologies described in literature [9-12]. From these publications it becomes clear that ablative flash pyrolysis might not be the best process for the pyrolytic conversion of straw into pyrolysis oil and biochar from an efficiency perspective, but it seems to be the only process with the potential of being operated on a moving platform. In ablative flash pyrolysis the biomass is pressed against a hot surface either by mechanical [13] or centrifugal force [14] and the pyrolytic process occurs while the biomass is in contact with the heated surface.

Figure 5: Logistic chain for mobile pyrolysis [8]

Figure 6: Utilization pathways for pyrolysis oil
The biomass heats up to around 500 °C and the biomass constituents cellulose, hemicellulose and lignin decompose to a long list of volatile organic compounds leaving the reactor as vapor and a solid residual char. For systems using centrifugal force the biomass needs to be milled to very small particle sizes (below 1.4 mm [14]), while systems using mechanical force can apply the biomass as grabbed. Therefore, the principle of using mechanical force to press the biomass against the hot surface was chosen for the further development of the pyrolysis process for a future mobile application.

The development of a pyrolysis unit mountable on a mobile platform is done in cooperation with the industrial cluster partner Claas KGaA mbH by means of two experimental facilities: a laboratory plant and a pilot plant. These are described elsewhere [15].

**Economic evaluation**

**General Assumptions**

The main target of this investigation is a theoretical estimation of production cost of pyrolysis oil using the future mobile pyrolysis plant. This plant will be designed for a capacity of 10 t/h of straw and the target investment price $I_0$, estimated from market analysis for the machine and not based on equipment cost for the pilot plant, is given by the industrial partner Claas KGaA mbH to be 1 Mio. € for such plant. From literature [12] the yield for pyrolysis oil is assumed to be 60 weight-%. As the plant will be operated in close conjunction to the grain harvest, the yearly operating hours of a single plant will only be in the range of 1,120 h/a. Most operating cost for agricultural machinery and transport units are taken from [16] for German circumstances.

The cost calculation follows the annuity method described in [17] and results in production cost per operating hour $\Theta_P$ in the first step. The calculation is performed following equation 1.

$$\Theta_P = \Theta_{Ca} + \Theta_F + \Theta_{Co} + \Theta_{Op} + \Theta_O$$  \hspace{1cm} (1)
wherein $\Theta_{Ca}$ represents capital cost, $\Theta_F$ feedstock cost, $\Theta_{Co}$ other consumption-related cost, $\Theta_{Op}$ operation-related cost and $\Theta_O$ other cost, mostly calculated initially as annual cost and then using the annual operating hours to convert the result to cost per operating hour.

The calculatory interest rate was assumed to be 6 %, resulting in an interest factor of $q=1.06$, and the machine life $T$ was estimated to be 8 years. The residual value of the machine was linearly depreciated over the expected life time. Following the annuity method [17] this gives an annuity factor $a$ of

$$a = \frac{q^T (q - 1)}{q^T - 1} = 0.1610359$$

(2)

The annual capital cost $K_{Ca}$ result from the initial investment and the annuity factor following

$$K_{Ca} = I_0 a = 161.036 \, \text{€/a}$$

(3)

Dividing the annual capital cost by the estimated yearly operating hours results in the hourly capital cost $\Theta_{Ca}=K_{Ca}/1.120 \, \text{h/a}=143.78 \, \text{€/h}$.

The feedstock cost are calculated from the straw price in the field (including 20 % profit) and the machine capacity as follows:

$$\Theta_F = 23.76 \, \text{€/t} \times 10 \, \text{t/h} = 237.60 \, \text{€/h}$$

(4)

The other consumption-related cost $\Theta_{Co}$ are calculated from estimations for utility consumption (propane for preheating the machine, diesel for running the machine) and an extra add on of 5 % of the investment. Operation related cost $\Theta_{Op}$ consist of personnel cost for machine operator, and a lumped sum of annually 1.5 % of the investment for repair, servicing and inspection. Other cost $\Theta_O$ consist of insurance and proportionate administrational disbursements, roughly estimated to be 1 % of the initial investment annually. All details are described elsewhere [8].

**Results**

The results of the calculations are summarized in table I. With the assumptions concerning hourly capacity and pyrolysis oil yield the hourly cost can be converted to weight-specific production cost. The
on-field production cost per ton of pyrolysis oil are calculated as 104.71 €. This is in the same order of magnitude as the minimum selling price of straw from the intermediate storage without profit (89.20 €/t). As the utilization for straw as well as for pyrolysis oil can be thermal processes, the price per MWh is more interesting, especially if compared to fossil fuels. The heating value of straw is assumed to be around 4.02 MWh/t as an average value and the value for pyrolysis oil is taken as 4.44 MWh/t. With these values the specific cost are 22.19 €/MWh for straw and 23.58 €/MWh for pyrolysis oil, which is even closer than the price per ton.

Table I: Results of cost calculation [8]

<table>
<thead>
<tr>
<th>Cost categories</th>
<th>[ €/h ]</th>
<th>[ €/t ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost $\Theta_{Ca}$</td>
<td>143.78</td>
<td>23.96</td>
</tr>
<tr>
<td>Feedstock cost $\Theta_{F}$</td>
<td>237.60</td>
<td>39.60</td>
</tr>
<tr>
<td>other Consumption-related cost $\Theta_{Co}$</td>
<td>209.58</td>
<td>34.93</td>
</tr>
<tr>
<td>operation-related cost $\Theta_{Op}$</td>
<td>28.39</td>
<td>4.73</td>
</tr>
<tr>
<td>other cost $\Theta_{O}$</td>
<td>8.93</td>
<td>1.49</td>
</tr>
<tr>
<td>Production cost $\Theta_{P}$</td>
<td>628.28</td>
<td>104.71</td>
</tr>
</tbody>
</table>

These results show promise for the proposed mobile pyrolysis conversion plant, because the pyrolysis oil can be produced in the field roughly at the same price as straw would be delivered as feedstock to a stationary pyrolysis plant even in a small, decentralized size. This conclusion depends on the mobile conversion plant achieving the assumed values for capacity, yield and investment cost.

Sensitivity Analysis

To determine the most relevant factors which influence the production price of pyrolysis oil most, a sensitivity analysis was performed. As can clearly be seen from Figure 7, the pyrolysis oil yield has the largest influence on pyrolysis oil production cost followed by the hourly capacity and the yearly operating hours. The cost for the biomass feedstock, auxiliary power demand, investment cost and other consumption related cost all have a very similar influence on production cost compared to each other, but this influence is less pronounced in comparison to the three parameters mentioned first. The remaining parameters operation-related cost, calculatory interest rate, other cost and maintenance cost are of negligible influence.
Broadening the Range of Feedstock

For a given machine the hourly capacity and the pyrolysis oil yield cannot be influenced by the operator. Therefore it is important to increase the operating hours to improve the overall economics. As the harvesting period of the plants giving the straw used as feedstock is limited (and by that the availability of straw) there is only the option to use different sources of feedstock: at the end of the grain harvesting period the use of hay from grassland, which is only mown once a year, and in the beginning of the year

Figure 7: Sensitivity analysis for pyrolysis oil production cost [8]
the use of miscanthus. For both additional feedstocks it is assumed that the annual operating hours can be increased by 672 h/a each. Also it is assumed that the pyrolysis plant cannot be moved across the grassland, so the hay has to be collected and transported to the plant, which is positioned alongside the hayfield. Table II summarizes the resulting pyrolysis oil production cost for the investigated options. The production cost of pyrolysis oil from miscanthus and hay are calculated as additional cost, because all annual cost like capital cost $\Theta_{CA}$ and other cost $\Theta_O$ are already covered by the main production period based on straw. Figure 8 depicts the share of each cost component in the resulting pyrolysis oil production cost.

**Table II:** Pyrolysis oil production cost for additional feedstock [8]

<table>
<thead>
<tr>
<th>Pyrolysis oil cost</th>
<th>[ €/t ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw pyrolysis (SP)</td>
<td>104.71</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>147.67</td>
</tr>
<tr>
<td>Grassland cuttings</td>
<td>54.99</td>
</tr>
<tr>
<td>Straw pyrolysis &amp; Miscanthus &amp; Grassland cuttings</td>
<td>102.97</td>
</tr>
</tbody>
</table>

As hay from grassland cuttings is considered as waste and must be withdrawn from the hayfield, only the low cost for transport to the field margin is calculated as feedstock cost. Although the plant has to be transported to several hayfields, the resulting price for pyrolysis oil is the lowest of all options. At the other end of the spectrum the additional use of miscanthus has the highest production cost of the pyrolysis oil, because miscanthus has a comparatively high feedstock price, as it represents not an agricultural residue but a rather a dedicated energy crop.
Figure 8: share of cost components for different biomass feedstock [8]

Combining both options for broadening the biomass feedstock for the mobile pyrolysis plant, now including all cost components to give an average value, leads to twice the amount of pyrolysis oil produced per year with roughly the same specific price (6,720 tons for straw as the only feedstock compared to 14,784 tons for the combination of all 3 feedstocks).

Conclusion

As shown by the theoretical economic evaluation, mobile pyrolysis of agricultural residues like straw has the potential to deliver pyrolysis oil directly from the field at a competitive price compared to straw on mass as well as on lower heating value as a basis for comparison. If either straw or pyrolysis oil can be used in the same subsequent process, there is no financial disadvantage to convert straw to pyrolysis oil first. The bulk density of pyrolys is oil is larger than that of straw by a factor of around 8. Therefore, the oil can be stored in a smaller storage volume. If the straw has to be converted to pyrolysis oil prior to utilization, e.g. for entrained flow gasification, the price for the pyrolysis oil from a mobile conversion plant is much cheaper than from stationary conversion, as the cost for straw logistic is completely saved. The future investigations carried out with the laboratory and the pilot plant at Fraunhofer UMSICHT together with the partners in the Fraunhofer Innovation Cluster »Bioenergy« will answer the question
whether the existing technological concept for the mobile pyrolysis process can be scaled-up to the desired capacity of at least 10 t/h. Additionally it must be examined whether the target price of 1 Mio. € per plant can be achieved. Only if both these prerequisites are met, the calculated potential economic feasibility of this approach can be realized.

Literature

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Acknowledgement

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