INTEGRATION OF A HEMICELLULOSE EXTRACTION PROCESS INTO A BIOMASS BASED HEAT AND POWER PLANT

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Abstract. The development of processes where lignocellulosic biomass can be refined to several different end-products in the same plant, i.e. a biorefinery, will be important in the development towards a more sustainable society where fossil fuels are replaced. This paper presents the idea to integrate the production of green chemicals via hot water hemicellulose extraction of birch wood (hardwood) into a small-scale combined heat and power plant (CHP), in this case an externally fired gas turbine. A techno-economically successful concept could provide the option to turn a small- to medium scale CHP plant into a small- to medium scale biorefinery. The results show that the extracted wood-chips would serve very well as a fuel for combustion and gasification processes due to the relatively high heating value, low ash content and significantly lower concentrations of alkali metals. Under the assumed economic conditions, electricity can be produced to a cost in the range of €0.44 to €0.45/L and a fermentable feedstock stream with a xylose concentration of 65 g/L to a cost in between €0.44 to €0.45 per kg xylose depending on plant size and number of annual operational hours.

Keywords: biomass, hemicellulose extraction, CHP, biorefinery

1. INTRODUCTION

Sustainable use of forest- and agricultural resources will play an important role in help solving urgent global challenges such as the enhanced green house effect and the ever increasing demand for fossil fuels. The development of processes where lignocellulosic biomass can be refined to several different end-products in the same plant, i.e. a biorefinery, will be important in the development towards a more sustainable society where fossil fuels are replaced. To be able to compete with fossil resources, an efficient production of biomass based products is necessary to maximize overall process economics and to minimize negative environmental impact (René van Ree, 2007).

Currently, very large biorefinery plants are required in order to reach favourable economy-of-scale effects and consequently reasonable production costs. Some of the larger first-generation biofuel plants require in the vicinity of 3,000 tonnes per day of feedstock (such as plants that produce ethanol from corn). The next-generation facilities are envisioned that would call for 6,000 tonnes per day or more of feedstock (such as gasification/Fischer-Tropsch facilities that will convert wood to synthetic diesel). To enable the expansion of biofuel production in such facilities, as well as provide for associated distribution requirements, it is clear that substantial infrastructure planning and development will be needed. It is also important to situate the plant so that the residual heat can be sold as district heating or process heat (Leduc et al., 2009). On the countryside, it may be difficult to find a heat demand matching such a large amount of residual heat generated from large scale production plants. For these reasons, it would be desirable to put efforts in developing small scale biorefinery plants that can be located near the raw material resource and at the same time as competitive production costs are reached. Such plants are requested for example by the National Science Foundation in USA (2008).

The combination of hemicelluloses extraction with combined small-scale heat and power production (CHP) could be one way to generate a sugar feedstock amenable to biochemical conversion to fuels and chemical intermediates, such as ethanol, butanol, succinic acid and lactic acid (Hahn-Hägerdal et al., 2007; Werpy et al., 2004, 2006) at the same time as heat and power is generated. Hemicelluloses have a low heating value (13.6 MJ/kg) compared to lignin (27.0 MJ/kg) (Van Heiningen, 2006), and therefore recovery of hemicelluloses from lignocellulosic material prior heat and power production followed by biochemical conversion into value-added products might offer a better process economy. This paper presents the idea to integrate the production of green chemicals via hot water hemicellulose extraction of birch wood (hardwood) into a small-scale combined heat and power plant, in this case an externally fired gas turbine. If the concept turns out to be techno-economically viable, it provides the option to turn a small- to medium scale biomass heating- or CHP plant into a biorefinery.

1.1. Hot-water extraction of hemicellulose

The carbohydrate portion of lignocellulosic feedstock is ideally suited for conversion via biochemical transformations due to their crucial role in cellular metabolism. Many enzymes and metabolic pathways exist in which carbohydrates can be converted to a wide range of metabolites. Through metabolic engineering, microbial catalysts can be optimized for the production of transportation fuels, biodegradable polymers and chemical intermediates (Willke and Vorlop, 2001).
Hardwood hemicelluloses consist of mainly glucuronoxylan, while galactoglucomannan is the major part of softwood hemicelluloses. Glucuronoxylan in hardwood contribute with 15-30% of the total dry weight and softwood contains 7-12% arabinoglucuronoxylan (Polizeli et al., 2005). Hot water pre-treatment of wood materials is less severe compared to acid or alkali pre-treatment. Hot water pre-treatment of wood increases the accessible surface area, removes hemicelluloses and alters the lignin structure to a minor degree. Diluted acid treatment has similar effects on wood, but alters the lignin structure to a significant extent (Mosier et al., 2005). Hot water pre-treatment is a self catalytic process and the mechanism of hydrolysis lies in cleavage of O-acetyl and uronic acid substitutions that result in the formation of acetic and other organic acids, with further hydrolysis of polysaccharides to oligomers and monomers possible (Nikitin, 1962). If hemicelluloses are to be extracted from wood, it is important to obtain high final sugar concentration in extracted liquid that can be utilised by organisms in fermentation processes. However, the generation of compounds that are inhibitory to microbial processing such acetic acid, hydroxymethylfurfural (HMF) and furfural need to be considered in the extracted liquid (Palmqvist and Hahn-Hägerdal, 2000).

The residue from the extraction process consists of intact “washed” wood chips, which may be suitable as a fuel for thermochemical conversion process, such as combustion and gasification for CHP production.

1.2. Externally fired gas turbine (EFGT)

A promising concept for small- to medium scale biomass based CHP are externally fired gas turbines (EFGT) (Kautz and Hansen, 2007; Kjellström, 2007). The technology may be considered to be under development, but the company Talbott’s Biomass Energy LTD already provides a commercial module producing 100 kWel.

In an EFGT plant, a conventional atmospheric combustion chamber can be used to heat up compressed ambient air using the combustion gases via a heat exchanger. The hot air, heated to 800-900°C is expanded in the turbine generating electricity via a power generator. The turbine exhaust, i.e. pure air, may be used as pre-heated combustion air in the furnace and the excess heat in the flue gases can be used to generate district heating or process heat.

It is of great importance to avoid fouling at the gas side of the heat exchanger surface, which would decrease the heat transfer between gas and air leading to lower electrical efficiency and thereby higher electricity production costs. If advanced gas cleaning equipment must be installed, it may lead to unprofitable plants. The fouling is mainly caused by high concentrations of alkali metals in the fuel. It is therefore desirable to generate a cleaner gas, which could be accomplished by using a fuel with low alkali content.

1.3. Objectives

The overall objectives of this paper are to present and describe the idea to integrate the production of green chemicals via hot water hemicellulose extraction of birch wood (hardwood) into an externally fired gas turbine plant and to make an introductory techno-economic evaluation of the integrated process. Specific objectives are

- To investigate how the chemical properties and characteristics of the wood-chips changes after the hot water extraction process. This is done in order to evaluate how the extraction residue will serve as a fuel for combustion and/or gasification processes.
- To carry out hot-water extraction lab-scale experiments using birch wood chips (Betula pendula) from northern Sweden to get a fermentable feedstock mainly containing the 5-carbon sugar xylose at a high concentration. Analysis of the free liquor will provide data of the composition of liquor from the extractions including resulting concentration of xylose, acetic acid, HMF and furfural.
- To find an appropriate extraction temperature range to obtain an as high yield of xylose as possible.
- To make estimations of the costs for electricity production as well as of the fermentable feedstock stream with high xylose concentration for plant sizes in the range of 200-800 kWel. Parts of the results from the extraction experiments will serve as input data for the economic evaluation of the extraction process.

2. DESCRIPTION OF THE INTEGRATED PROCESS

The idea is to integrate a process for hot water extraction of birch-wood chips (hardwood) into a heat- and power production plant consisting of an externally fired gas turbine. Figure 1 shows a preliminary schematic layout of the proposed process.

The processes within the dotted areas are considered in this study meaning that heat, electricity and a fermentable feedstock stream are produced. The acetic acid may be separated from the stream prior the fermentation and partly used in upstream hydrolysis and partly as a final product. A variety of products such as succinic acid, butanol, ethanol etc, may be produced via fermentation and required downstream processes.
The extraction process is at this stage assumed to be performed batch wise in a pressurized vessel with a slowly rotating mixer. The wood-chips are first extracted during 90 minutes at a temperature in the range of 160°C-180°C. Then the free liquor is separated from the wood chips and the temperature in the vessel decreased to 121°C, which takes approximately 30 minutes. Secondary hydrolysis is performed during 60 minutes at 121°C. To process one batch takes around three hours excluding water filling. It is further assumed that the hydrolysis can be carried out in the same pressurised vessel.

The wood-chips after the extraction contain water up to around 70% wt. This water contains a high sugar concentration, which is desirable to recover for hydrolysis. Therefore, the extracted wood-chips will be mechanically pressed to squeeze out the remaining liquor. The extracted, pressed wood-chips is stored in a container and self-dried until fed into the combustion chamber by screw conveyors.

The excess heat from the exhaust gases may be used for district heating production, heating of the extraction process or for other downstream processes such as distillation. In this paper, only the district heating option is considered. The exhaust temperature will vary depending on a number of parameters.

3. METHODS AND INPUT DATA

3.1 Chemical analysis of feedstock and extraction residue

The dry solid content of the birch wood chips was measured by conventional methods. The composition of the raw birch wood chips was determined by the method suggested by Sluiter et al. (2008a). The elementary analysis of the extraction residue as well as the birch wood-chips was carried out by an accredited laboratory (ALS Scandinavia AB).

3.2 Extraction experiments in lab-scale

The birch wood chips were sieved with the acceptable fraction less than 45 mm length and width, less than 8 mm thick and greater than 7 mm in length and width. Hot-water extractions of the wood-chips were performed in rotating autoclave cylinders for 90 minutes isothermally at a pressure of approximately 7 bar. Heating to target temperatures, 160-180°C, was carried out at a rate of approximately 1.6 °C/min. A weighed amount of water was added to each autoclave cylinder filled with a weighed amount of chips. The cylinders were sealed and put in the rotating heating device and heated to the target temperature. After 90 minutes at steady-state each cylinder was cooled to approximately 60°C and the free liquid was separated from the wood-chips. The liquid was collected for subsequent hydrolysis and analysis, and the chips were put in a bucket of water overnight. The day after, the water was separated from the chips, which were left to dry in ambient temperature. The water/wood ratio was based on dry wood, liquid/dry wood ratio (L/DW).
The final pH was measured by conventional methods. The acetate and xylan (xylose) concentrations in the extraction liquors were determined by HPLC analysis (RI detection, Aminex HPX-87H column at 65°C with 0.005 M H₂SO₄ at 0.6 mL/min flowrate) after dilute acid sulphuric acid hydrolysis at 121°C for 1 hour to hydrolyze oligomeric xylan (Sluiter et al., 2008b).

3.3 Economic evaluation

Based on the elementary composition of the extracted wood-chips, an assumed fuel water content of 35%wt (as received) and an excess air factor of 1.5, the actual specific combustion air flow (lₐ) and resulting exhaust gas mass flow per unit of fuel (gₑ) were estimated via stoechiometric calculations.

Gas turbine cycle calculations based on the input data presented in Tab. 1 were carried out in order to estimate the required air mass flow through the turbine for different power outputs. The inlet air conditions were assumed to be 288 K and 1.013 bar. A mechanical efficiency was assumed to 98%.

Table 1. Assumed gas turbine cycle data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor pressure ratio (1)</td>
<td>4.5</td>
</tr>
<tr>
<td>Turbine inlet temperature (°C)</td>
<td>1223</td>
</tr>
<tr>
<td>Isentropic compr. efficiency (3)</td>
<td>0.768</td>
</tr>
<tr>
<td>Isentropic turbine efficiency (3)</td>
<td>0.826</td>
</tr>
<tr>
<td>Combustion efficiency (ηₜ)</td>
<td>0.90</td>
</tr>
<tr>
<td>Heat exchanger efficiency (η_HE)</td>
<td>0.80</td>
</tr>
<tr>
<td>Pressure loss heat-exchanger air side (2)</td>
<td>2% of compressor delivery pressure</td>
</tr>
<tr>
<td>Pressure loss heat-exchanger gas side (2)</td>
<td>0.04 bar</td>
</tr>
</tbody>
</table>


The required air mass flow (mₐ) through the turbine was calculated from the desired power output and the difference between the resulting specific turbine work and compressor work. The required thermal input was calculated according to Eq. (1)

\[ P₉ = \frac{mₐ \cdot cₚ,a \cdot ΔT}{η_HE} \]  \hspace{1cm} (1)

where \( cₚ,a \) is the specific heat for air (assumed constant, 1.005 kJ/kg K), \( ΔT \) is the air temperature difference between compressor outlet and turbine inlet. The fuel mass flow to the combustion chamber was calculated according to Eq. (2).

\[ \dot{m}_{fuel} = \frac{P_{in}}{η_t (H_i + lₐ h_{air} - gₑ h_{exh})} \]  \hspace{1cm} (2)

where \( P_{in} \) is the required thermal input (kW), \( H_i \) is the lower heating value of the fuel (as received), \( h_{air} \) is the enthalpy of the turbine outlet air which is supplied to the combustion chamber and \( h_{exh} \) is the enthalpy of the exhaust gas leaving the air/gas heat exchanger.

The required mass flow of fuel gives the average daily demand of extracted wood-chips. Based on the assumption that three batches of extractions are carried out daily, the required volume of the pressurised extraction vessel and equipment costs for the extraction process can be calculated via the method suggested by Sinnott (1998).

Table 2 summarises the general conditions assumed in the economic evaluation.

Table 2. Assumed general economics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest rate</td>
<td>5%</td>
</tr>
<tr>
<td>Economic lifetime</td>
<td>20 years</td>
</tr>
<tr>
<td>Technical lifetime</td>
<td>20 years</td>
</tr>
<tr>
<td>Annuity factor</td>
<td>0.0802</td>
</tr>
<tr>
<td>O&amp;M factor</td>
<td>2% of capital</td>
</tr>
<tr>
<td>Additional cost for CHP (1)</td>
<td>2.2 €/MWh bloodstream</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>15 €/MWh</td>
</tr>
<tr>
<td>Operational hours</td>
<td>Variable</td>
</tr>
<tr>
<td>Labor</td>
<td>30000 €/year</td>
</tr>
<tr>
<td>Plant overhead</td>
<td>15000 €/year</td>
</tr>
</tbody>
</table>


The size of a small-scale CHP plants are generally determined by the heat demand, meaning that the electricity producing part can be seen as an additional investment to conventional district heating plant. In this study, the cost of electricity (COE) and a cost of heat (COH) were therefore separated.

As there are only a few commercial plants in operation, it is difficult to get accurate investment figures as a function of plant size. Therefore, as a reference case, the initial investment of a 100 kW module from Talbott’s Biomass Energy
LTD was used (Gard, 2008). Kjellström (2007) suggests to calculate the specific investment of the heat producing part (€ per kW\textsubscript{heat}) according to Eq. (3). That amount was subtracted from the total investment to get the specific investment of the electricity producing part. Thereafter, it is assumed that the specific electricity investment follows the same economy-of-scale effects as the heating part, i.e. the same power exponent as in Eq. (3).

\[
I_{\text{heat}} = \left(3384 \cdot P_{\text{heat}}^{-0.2652}\right)
\]  

(3)

The annual fuel cost was also separated into a heat and electricity part, where the latter was calculated as the difference between the fuel cost for CHP production and the cost if only heat would be produced.

The cost of the production of the fermentable feedstock stream mainly includes the capital cost for the extraction process and operation and maintenance. However, extraction experiments have shown that the dry mass output of extracted wood-chips is 77% of the dry mass input of the birch wood-chips. Therefore, 23% extra mass of dry birch-wood chips must be fed into the extraction plant to fulfil the fuel demand of the CHP process. The cost for that extra fuel is put on the cost of the production of the fermentable feedstock stream.

4. RESULTS

4.1. Chemical analysis of feedstock and extraction residue

The compositions of birch wood from northern Sweden and the extracted wood chips are presented in Fig. 2.

![Figure 2. Compositions of birch wood (left) and extracted wood-chips (right)](image)

In the fresh birch wood, the total lignin content, acid insoluble lignin (AIL) and acid soluble lignin (ASL) were found to represent approximately 20.6%. The hemicelluloses part, mostly xylose and acetic acid, was 29.3% and the cellulose content, mostly glucose, was 42.5%. The composition of the extracted wood chips showed higher lignin content, higher glucose content together with lower acetic acid content and lower xylose content compared to the fresh birch wood. This indicates that the major part of the hemicellulose was extracted with low final glucose concentration in the extracted liquor and that the cellulose remained mostly intact. It also indicates that most of the lignin stayed in extracted wood-chips.

Table 3 shows the heating values and the ultimate analysis of the birch wood chips used in the extraction experiments as well as of the extracted wood-chips.

Table 3. Heating values and ultimate analysis (%wt dry, ash-free) of the birch wood-chips and the extraction residue

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Birch wood-chips</th>
<th>Extracted wood-chips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating value, calorimetric (MJ/kg)</td>
<td>18.09</td>
<td>19.54</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg, dry ash free)</td>
<td>17.26</td>
<td>18.71</td>
</tr>
<tr>
<td>Volatiles (%wt, dry basis)</td>
<td>84.4</td>
<td>85.4</td>
</tr>
<tr>
<td>Ash content (%wt, dry basis)</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Carbon</td>
<td>49.6</td>
<td>51.0</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>&lt;0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.005</td>
<td>0.006</td>
</tr>
<tr>
<td>Oxygen</td>
<td>43.6</td>
<td>42.2</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Table 3 shows that the heating values of the extracted wood-chips are higher than for the birch-wood chips, due to the increased lignin concentration and the lower ash content. The considerably lower ash content means that ash forming elements have left the fuel during the extraction process. Figure 3 shows the results from analysis of the ash forming elements in the original birch wood-chips and the extracted wood-chips.

As shown in Fig 3, all the main alkali metals have decreased significantly after extraction. For example, 86% of the Potassium, more than 80% of the Phosphorus and Magnesium and more than 70% of the Calcium and the Mangan have left the wood-chips during the extraction process. Only Iron has increased slightly, most probably due to contamination of stainless steel from the autoclave cylinders.

4.2. Hemicellulose extraction experiments

The glucose concentration in the extracted liquors did not exceed 4.5 g/L in any hot-water extractions performed, indicating that the cellulose remained mostly intact after the extraction. Table 4 shows the xylose and acetic acid concentrations in extracted liquors, the water/dry wood ratio (L/DW) in the extraction experiments and the final pH. The hemicelluloses in birch also contain low concentrations of other sugars than xylose, such as mannose, which are not shown in the table. The amount of extracted material from the wood chips was approximately 23% (HWE2 and HWE5). Previous, not yet published studies have shown approximately same result. The share of extracted xylose after hydrolysis was at an average of 58.4% of the total content in dry wood in the experiments HWE1-HWE5 and 35.6% in HWE6-HWE8.

<table>
<thead>
<tr>
<th>Name</th>
<th>L/DW (g/g)</th>
<th>pH (final)</th>
<th>Xylose (g/L)</th>
<th>Acetic acid (g/L)</th>
<th>Xylose (g/L)</th>
<th>Acetic acid (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWE1</td>
<td>2.06</td>
<td>3.20</td>
<td>18.3</td>
<td>10.9</td>
<td>68.0</td>
<td>20.3</td>
</tr>
<tr>
<td>HWE2</td>
<td>1.90</td>
<td>3.17</td>
<td>26.0</td>
<td>14.2</td>
<td>68.3</td>
<td>25.2</td>
</tr>
<tr>
<td>HWE3</td>
<td>1.84</td>
<td>3.15</td>
<td>22.0</td>
<td>12.4</td>
<td>69.4</td>
<td>24.9</td>
</tr>
<tr>
<td>HWE4</td>
<td>2.34</td>
<td>3.10</td>
<td>21.1</td>
<td>9.8</td>
<td>63.0</td>
<td>21.3</td>
</tr>
<tr>
<td>HWE5</td>
<td>2.37</td>
<td>3.09</td>
<td>25.3</td>
<td>10.9</td>
<td>62.0</td>
<td>21.8</td>
</tr>
<tr>
<td>HWE6</td>
<td>2.36</td>
<td>2.99</td>
<td>37.7</td>
<td>18.7</td>
<td>47.3</td>
<td>24.8</td>
</tr>
<tr>
<td>HWE7</td>
<td>1.44</td>
<td>2.90</td>
<td>39.5</td>
<td>32.6</td>
<td>41.9</td>
<td>40.3</td>
</tr>
<tr>
<td>HWE8</td>
<td>1.87</td>
<td>2.92</td>
<td>34.2</td>
<td>28.8</td>
<td>40.9</td>
<td>34.9</td>
</tr>
</tbody>
</table>

The maximum concentrations of furfural and HMF were obtained after extraction HWE8, 2.31 g/L and 2.22 g/L, respectively. No HMF was detected after hydrolysis in any extracted liquors, probably due to degradation. The highest concentration of furfural after hydrolysis was in HWE7, 2.30 g/L. The trend was that HWE1-HWE5 had lower concentrations of furfural and HMF than in HWE6-HWE8, probably due to the lower extraction temperature used in extraction HWE1-HWE5. This is illustrated in Figure 4, which shows the extraction temperature levels in the experiments HWE1-HWE8.
A correlation between lower final pH and higher extraction temperatures together with lower final xylose concentrations is found, see Fig. 4 and Tab. 4. This is probably due to a higher rate of xylose degradation at higher temperatures. Hot-water extraction experiments performed at 160-165°C (HWE1-5) gives after secondary hydrolysis extracted liquor containing around 65 g/L xylose. An extraction temperature between 170-180°C (HWE6-8) gives decreased final xylose concentration compared to extraction temperature between 160-165°C.

The final acetic acid concentration in the extracted liquid gives an indication how much xylan that is extracted and further how much xylose that is degraded since each xylose unit in birch wood, xylan has 0.7 acetate units attached to it (Theander and Nelson, 1988). If the acetic acid/xylose ratio is considered from extractions performed (see Tab. 4) acetic acid 60.05 g/mole and xylose 150.13 g/mole, it will give ratios for HWE1-HWE5 at an average of 0.86 and for HWE6-HWE8 at an average of 1.95, indicating degradation of xylose. Most of carbohydrates have increasing stability with decreasing pH, with the highest stability at pH 3-4 (Robyt, 1998). However, a pH below 3 is probably too severe in combination with a high temperature and longer hold time, see Tab.4 and Fig. 4 (Palmqvist and Hahn-Hägerdahl, 2000). If the extraction temperature is decreased, the final xylose concentration will decrease significantly as illustrated in Fig. 5. The hot-water extractions were performed with a L/DW ratio of 4 g/g.

4.3. Economic evaluation

Figure 6 shows production levels of electricity, heat and xylose as a function of plant size measured in electrical power output. The calculations are based on an annual plant operational time of 6000 hours.
Figure 6. Annual production levels of electricity, heat (left y-axis) and xylose (right y-axis)

Figure 7 shows the resulting electricity cost as a function of the power output at different annual operational hours.

Figure 7. COE (€ per MWhel) in the power output range 200-800 kWel at different annual operational hours of the plant

The electricity production costs vary in range of €85.6 to €196.2 per MWhel. No green electricity certificates have been accounted for. The resulting cost for heat production is in the range of €23.5 to €51 per MWhheat. As Fig. 7 illustrates, the annual operational time has a large influence on the electricity production cost, which underlines the importance to avoid fouling on heat exchanger surfaces.

Figure 8 shows the resulting costs for producing fermentable liquor mainly consisting of xylose and acetic acid.

Figure 8. The cost to produce fermentable liquor with a xylose concentration of 65 g/L at different annual operational hours of the plant

The results show that a fermentable liquor stream containing 65 g/L can be produced to within a cost range of €0.44 to €4.15 depending on plant size and number of annual operational hours. It is difficult to assess the competitiveness of this process as various degree of downstream processing is required to have a final sellable product. For comparison, it can be mentioned that in the year 2005, the international market price of xylose was US$ 5.0/kg (Murthy et al., 2005) which with the 2005 average exchange rate corresponds to approximately €6/kg.
5. DISCUSSION

The proposed integrated process seems to be a promising concept for small-scale production of heat, electricity and green chemicals. The hot-extraction process gives a high yield of xylose to a reasonable cost and the extracted wood chips are well suited as a fuel for CHP production. The low ash- and alkali contents might even make it possible to use it as a fuel in directly fired gas turbines in pulverised form. It would also be possible to use the fuel in ORC (Organic Rankine Cycles) for CHP production. These technologies should also be evaluated in order to investigate the influence on plant economics.

In a Swedish perspective, the estimated electricity production cost is too high at current conditions and requires higher electricity prices, subsidies and/or technological learning effect to reduce the specific investment. In this study, the latter varies in between €1700-€2500 per kW_{el}, which agrees fairly well with the values presented by Kautz and Hansen (2007).

The free extraction liquor contains acetic acid at concentrations in the range of 25-30 g/L which can be inhibitory to organisms used in the fermentation processes. Therefore, it is likely that the acetic acid must be separated from the stream. This will on the one hand add a cost, but on the other, the acid can be used in the secondary hydrolysis process and/or sold as a product. The acetic acid may also be used for extraction of soft wood.

Furthermore, it may be possible to also extract parts of the cellulose of the birch wood to increase the lignin content and thereby the heating value of the extraction residue. The sugar stream would then also increase, which would be beneficial during fermentation.

There are some practical issues that need to be considered and solved. It would for example be beneficial if the extraction process could be operated continuously instead of in batch mode. The pressing process must also be designed in a way that recovers a large share of the fuel bound liquid. Large volumes of water are required in the extraction process, which may make it difficult to commercialize the concept in water-scarce regions unless the water can be recycled to a reasonable cost.

6. CONCLUSIONS

The extracted wood-chips would serve very well as a fuel for combustion and gasification processes due to the relatively high heating value, low ash content and significantly lower concentrations of alkali metals than in the birch wood chips. This may lead to increased plant availability and better environmental performance, i.e. lower emissions of particulate matter.

The extraction experiments showed that it is possible to extract approximately 58.6% of the xylan (measured as xylose) hemicelluloses from birch wood chips with hot-water at a temperature of 160°C during 90 minutes. The final liquor contains mostly xylose after the secondary hydrolysis, but also other sugars at low concentrations that can be utilised by organisms for growth and product formation. The xylose concentration in the final liquor was approximately 65 g/L. If the acetic acid is separated, it can be used within the process and/or sold as a final product. It is also possible to extract the birch wood without any significant degradation of xylose resulting in decreased xylose concentration and accumulation of inhibitory compounds. An extraction temperature above approximately 170°C (90 minutes) degraded xylose resulting in decreased final xylose concentration together with formation of inhibitory compounds for organisms. Extraction temperatures below 160° together with shorter hold time results in a significant decrease of the final xylose concentration in extracted liquor. The next step should be to investigate a cost-effective process to separate liquor from inside the chips, recover more fermentable xylose, together with a cost-effective and environmental sustainable separation of acetic acid from the fermentable liquor stream.

The results of the economic evaluation show that electricity can be produced to a cost in the range of €85.6 to €196.2 per MWh_{el} in the investigated power output span. The cost for producing fermentable liquor with 65 g/L of xylose is estimated to be in between €0.44 to €4.15 per kg of xylose depending on plant size and number of annual operational hours.

The economic analysis shows that the number of annual operational hours is very important for the plant economy. This parameter has a larger influence on the total production costs than the actual size of the plant during the assumed conditions. Therefore, the use of the extracted wood-chips as a fuel for CHP production would be beneficial from the economic as well as the environmental points of view.

REFERENCES


Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D., 2008b. Determination


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