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Preliminary Design and Energy Efficiency Analysis of a Kraft Pulp Mill Converted to a Biorefinery Producing Ethanol and DME from Softwood

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In this study a conceptual biorefinery process is evaluated. The process is based on conversion of softwood to biofuels, and consists of a digester according to the soda cooking principle, a cellulose to ethanol production line, and a black liquor gasification line. The main products are ethanol and DME. The focus of the study is to combine knowledge from previous research in order to generate a preliminary design and energy balance for the process. This information is then used as input in a heat integration analysis in order to assess the potential for energy efficiency measures. Since the gasification leg of the process is a heat source and the ethanol leg, pretreatment and evaporation plant are heat sinks, an important result of the heat integration analysis is to give an indication of whether the process is self sufficient with respect to heat. The study shows that large opportunities for heat integration exist. The results from the study indicate that the steam surplus from the gasification plant cannot fully satisfy the steam demand of the balance of the process, even if the process is well heat-integrated. The demand is however considerably lower compared to when pulp is produced.

1. Introduction

The pulp and paper industry in North America and Northern Europe is losing ground on the global market for forest products. The main reasons for this are that softwood and hardwood feedstocks used in these areas are more expensive than feedstocks in new pulping countries such as Brazil, South Africa, China and Indonesia, and many pulp mills in the traditional pulping countries are older and less efficient than the ones being built in the new countries. In order for many mills in e.g. Sweden, Finland, Canada and the USA to remain competitive, new markets need to be addressed, and new products introduced.

At our department several studies have been made on new alternatives for kraft pulp mills in Sweden. Extraction of lignin from the black liquor, replacing the recovery boiler with a BLGMF (Black Liquor Gasification to Motor Fuels) plant, and converting the pulping line to ethanol production (including lignin extraction from the black liquor)

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are three alternatives that have been assessed from an economic and energy perspective (Figure 1).

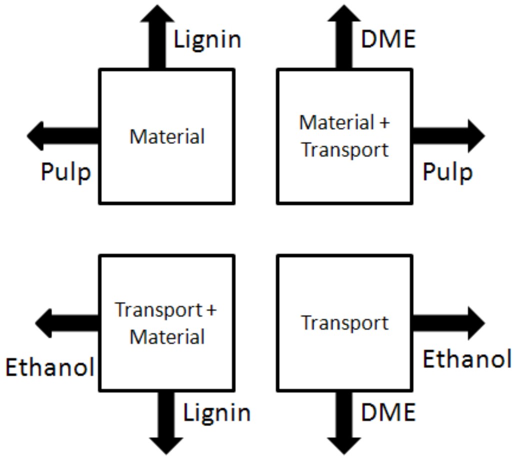

Figure 1: Different alternative production pathways that have been/are being studied at the department, based on a kraft pulp mill.

The biofuel market is a growing market but the current technology, i.e. 1^{st} generation biofuels, are under some strain due to the uncertainties regarding environmental benefits and negative impact on food production from using e.g. corn or cereals for biofuel production. Thus the commercialisation of 2^{nd} generation biofuels, produced from lignocellulosic biomass, is strongly anticipated.

Unprofitable pulp mills might play an important role in this development, since there are several synergetic aspects which can prove to be competitive advantages for this implementation. For example the infrastructure for raw materials, possibilities to reuse existing unit operations, the existence of skilled personnel, and a simplified environmental permitting process (Phillips et al., 2008) might play an important role in tearing down the wall that hinders the development of these types of plants.

In this paper a process for producing transport biofuels from softwood biomass is presented. The concept is based on converting a kraft pulp mill into a biorefinery where ethanol is being produced from the pulp (hexoses only) and the black liquor is gasified in order to produce DME (Di-Methyl-Ether) (Figure 1). The reason for this division is that cellulose is most efficiently used in producing ethanol, whilst the remaining biomass needs to be gasified in order to produce transport fuels.

The BLGMF plant is a heat source which to some degree can compensate for the lack of a steam boiler in a conventional pulp mill. In previous studies (Ekbom et al., 2005; Pettersson and Harvey, 2009) it is shown that there is a need for external energy in the form of wood fuel and electricity when a kraft pulp mill recovery boiler is replaced with a BLGMF plant.

The focus of the paper presented here is to study the energy balance of the process, and assess the potential for generating a process which is self-sufficient in terms of heat and electricity. High energy efficiency is important since this would imply that more transport fuels could be produced per unit of feedstock.

2. Process Description

The studied biorefinery is conceptual, with its basis in previous studies done at the department on black liquor gasification and cellulosic ethanol production in converted kraft pulp mills (Pettersson and Harvey, 2009; Fornell, 2010). The model kraft pulp mill that is being converted is an average Scandinavian mill as defined in a previous Swedish research programme (Future-Resource-Adapted-Mill, or FRAM). Further information on the pulp mill model can be found in Fornell (2010) and Axelsson et al. (2006).

Instead of pulp the cellulose in the raw material is fed to an ethanol production line. The design of this part of the process is based on the work by von Schenck et al. (2007) and Fornell (2010). Alkaline pretreatment and delignification is used in the process, which means that no sulphur is required. The delignified pulp containing mainly cellulose is sent to hydrolysis and fermentation for production of ethanol, whilst the lignin containing liquor is sent to the chemical recovery cycle (Figure 2).

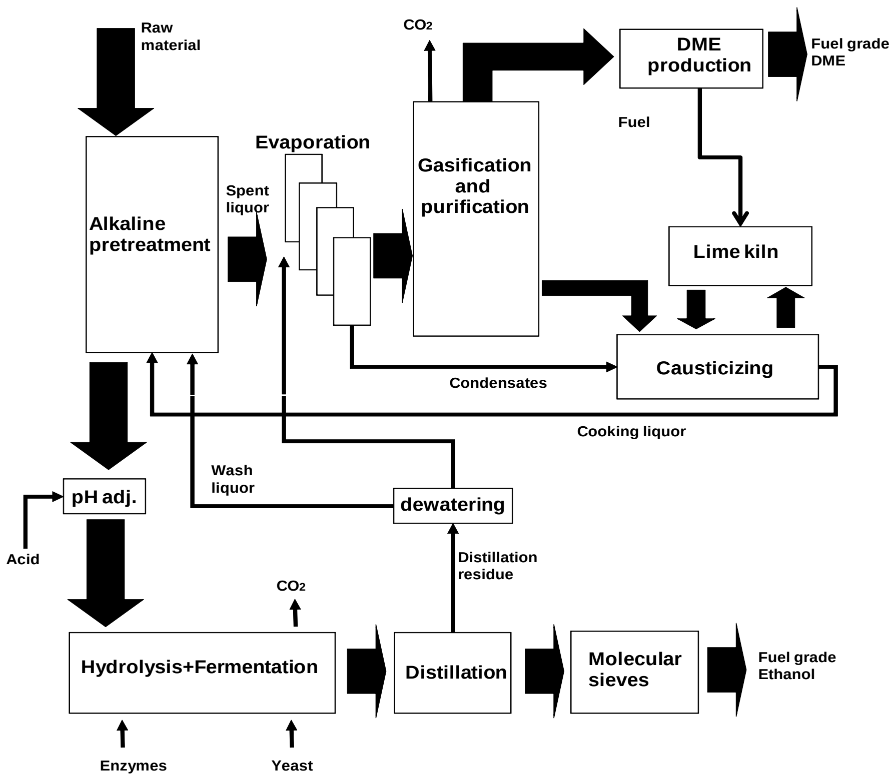

Figure 2: Block diagram of the biorefinery process.

It is assumed in this process that the recovery boiler has been replaced with a gasification unit, where the spent liquor is gasified after the dry substance has been increased to approximately 80% in the evaporation plant. The gasification process used in this study is described in detail in Ekbom et al. (2005) and Pettersson and Harvey (2009). Since the liquor in this process is assumed to have much lower sulphur content than black liquor in a conventional kraft pulp mill, gasification of spent liquor in a biorefinery with alkaline pretreatment should be a simpler process than in a kraft pulp mill. In this study it is assumed that the process is the same however. There are several different potential products which could be produced from the syngas exiting the gasification plant. In this study it is assumed that DME (Di-Methyl-Ether) is produced in the BLGMF plant. DME is a product which has been used in several previous BLGMF studies (e.g. Pettersson and Harvey, 2009; Ekblom et al., 2005). It is assumed that purge gas from the DME plant is used as fuel for the lime kiln, thus the process should not use any fossil fuels (Figure 2).

3. Methods

In order to assess the suggested process, energy and material balances were determined by combining knowledge from previous research. The typical Scandinavian kraft pulp mill (Axelsson et al., 2006; Fornell, 2010) was used as a basis for the study. The studies on a pulp mill converted to ethanol plant (Fornell, 2010) are based on the same mill as this study, thus no re-scaling of this part of the process is needed. The black liquor gasification plant is based on a different kraft pulp mill (Pettersson and Harvey, 2009); this data has thus been rescaled and modified in order to match the size of the mill in this study.

After having generated the energy and material balances of the biorefinery process, a heat integration study was performed using pinch analysis tools. The feedstock is constant at 1800 tonnes dry wood/day, and the yield of ethanol and DME are also assumed constant. Thus the heat integration study focuses on assessing the potential for improving the energy balance in order to reduce the deficit of steam and electricity in the process, which in turn reduces external wood fuel and electricity demands.

4. Results and Discussion

4.1 Energy balance – Base case

The biorefinery produces 90 MW ethanol and 138 MW DME from about 330 MW softwood. The energy balance (Figure 3) indicates that it is not possible for the plant to achieve energy self-sufficiency. Approximately 21 MW of wood fuel is needed in order to generate enough steam to satisfy the process demand. In addition, about 23 MW of externally generated electricity is needed in the process. In the BLGMF plant some low low pressure (LLP) steam (1.4 bar) is produced. This steam is compressed to low pressure (LP) steam (4.5 bar) in the base case since it has no use in the original process.

4.2 Energy balance – Heat integrated process

The pinch analysis indicates that energy efficiency measures are possible. The process steam demand can be decreased by integrating the evaporation plant and improving the heat recovery in the heat exchanger network of the process. One benefit of heat integration is that the LLP steam at 1.4 bar could be used in the process. Thus no compression of LLP steam to LP steam is needed.

The need for external wood fuel to the bark boiler will decrease from 21 to 10 MW when heat integrating the process, but the external electricity demand will remain the same (Figure 3).

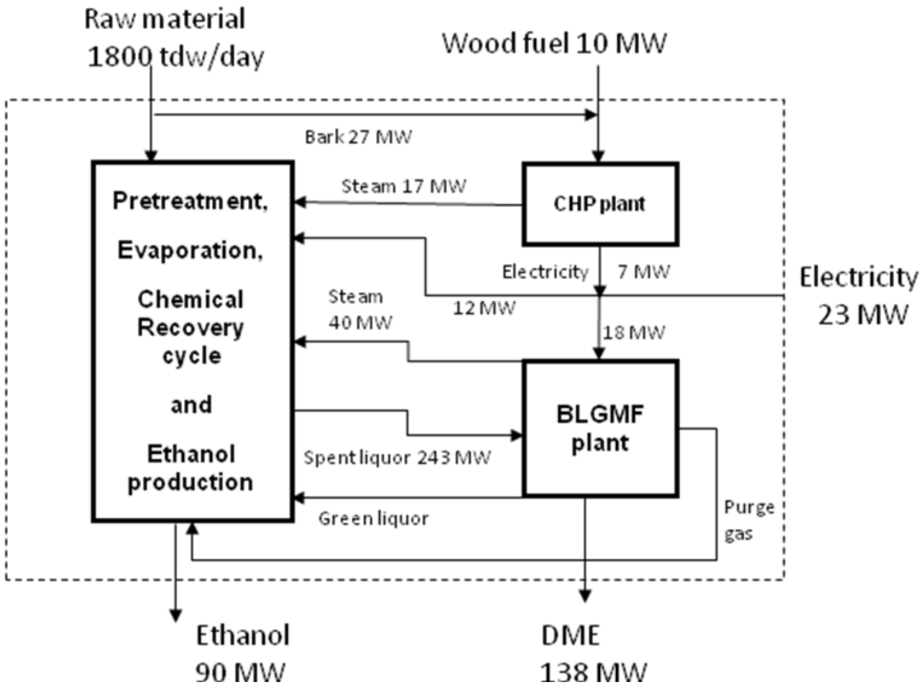

Figure 3: Energy streams in the biorefinery, including inputs and outputs.

5. Conclusions

It is indicated in this study that it is not possible to reach a process which is self sufficient in energy, given the conditions in this study. The wood fuel deficit is 10 MW, which could be solved by either decreasing the yield of ethanol (less steam needed, more steam produced) or by buying external fuel. The electricity deficit is 23 MW; this needs to be bought externally which might imply that a low electricity price and high biofuel price would benefit this process.
An economic assessment of the alternative studied in this paper, and a comparative analysis with respect to the other alternatives presented in Figure 1 will be done in the near future in order to more fully assess the potentials of the biorefinery concept.

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