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A techno-economic comparison between two technologies for bioethanol production from lignocellulose

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ABSTRACT

The conversion of biomass into biofuels can reduce the strategic vulnerability of petroleum-based transportation systems. Bioethanol has received considerable attention over the last years as a fuel extender or even as a neat liquid fuel. Lignocellulosic materials are very attractive substrates for the production of bioethanol because of their low cost and their great potential availability. Two different process alternatives (i.e. the enzymatic hydrolysis and fermentation process and the gasification and fermentation process) for the production of fuel ethanol from lignocellulosic feedstock are considered and analysed. After a rigorous mass and energy balance, design optimisation is carried out. Both processes are assessed in terms of ethanol yield and power generation as well as from a financial point of view. A sensitivity analysis on critical parameters of the processes' productivity and profitability is performed.

1. Introduction

The search for alternativ and sustainable energy sources has become more and more important due to the possible short-term shortage of fossil oil and the environmental threats that the exploitation of non-renewable sources is causing, particularly in terms of CO_2 emissions. Energy for the transport sector represents a particularly critical area as it accounts for more than 30% of total energy demand in developed countries. Furthermore, it is 98% dependent on fossil fuel and is considered one of the main causes for CO_2 increase [1,2]. It is clear that a diversification of primary energy for fuel production will be necessary, for environmental and supply security concerns. The USA government has recently committed to increase bio-energy threefold in 10 years. The EU aims to replace diesel and gasoline in fuel to the level of 5.75% by 2010 and 10% by 2020. However, it is clear to anyone that such goals can be achieved only through further advancements in existing processes and new concept technologies.

Ethanol is one of the most promising biofuels, as in principle it could be derived from any material containing simple or complex sugars. Industrial ethanol production has been reported using sugar cane and various starchy materials (corn, wheat, potatoes). However, the most promising raw material is represented by lignocellulose: cellulose is the most common biopolymer on Earth (present in wood, organic industrial wastes, etc.) and is a polysaccharide, i.e. it can be converted into sugars and fermented. Although estimations from different sources may vary considerably, a general result is that resources of cellulose are usually abundant and locally available [3] and that its use for biofuels' production can play an important role in reducing greenhouse emissions [4]. Thus, ethanol produced from lignocellulosic materials has the potential to be a valuable substitute for, or complement to, gasoline.

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A wide variety of processes for the production of ethanol from cellulosic materials have been studied and are currently under development. In fact, the large amount of technologies and processing options advocates for a more diffuse application of process engineering modelling, design and optimisation in order to help the research effort and guide investors and policy-makers towards the most effective technologies [5]. In this paper, two of the most promising processes will be analysed and assessed: these are the conversion of lignocellulosic biomass by hydrolysis and subsequent fermentation and the gasification of lignocellulose followed by syngas fermentation.

The first process (that here will be called the enzymatic hydrolysis and fermentation process or EHF process) is possibly the most mature process for the transformation of lignocellulosic materials into ethanol. It has been extensively described and studied (e.g. [6–8]), and pilot plants and pre-industrial facilities have recently being brought to operation. In the literature, several flowsheeting designs have been reported: for instance, Wooley et al. [7] describe the global process for ethanol production from wood chips and Cardona and Sànchez [9] use a process simulator to assess the energy consumption for several process configurations; other works have analysed the techno-economic performance of the production process [10–12].

On the other hand, the second process (that will be referred to as the gasification and fermentation process or GF process) has been somehow neglected in the scientific literature (at least when compared to the EHF process), notwithstanding the promising results demonstrated in the few works appeared so far (e.g. [13]). Although biomass gasification has long been studied [14], its integration with the fermentation process has been studied only in few reports [15]. To the authors' knowledge, no complete flowsheeting analysis and financial assessment has never been published in the scientific literature. However, the technology potential (which is already available as a commercial process) has nonetheless been widely recognised [16] and recently awarded through financing by the U.S.A. Department of Energy. Therefore, here the process has been chosen and assessed as a possible alternative to EHF for the production of bioethanol.

This paper aims at achieving the following goals. The first one is to deliver a technical and economical comparison between two of the most important processes for the conversion of lignocellulose to bioethanol. In general, it is difficult to assess different processes when analysed by different research groups as preliminary assumptions, process design, financial modelling and data are rather "sensitive" to specific expertise, simplifying hypotheses and data availability. We believe that one strength in our technical and financial analyses is that the same methodology is carried out for both processes so that the final results are indeed comparable.

Secondly, this paper represents the first comprehensive analysis of the GF process (with the partial exception of Ref. [17]). Although the process is still in its early development (at least from what can be derived from published material) and some data definitely still exhibit a significant uncertainty, the work aims at assessing process design, potential optimisation directions and the effect of most important parameters on the overall yield and financial indexes.

Finally, a step forward is taken in the optimisation and analysis of the EHF process, too. The use of pinch analysis and a new design approach demonstrate that further reduction in the utilities' demand is still possible. The effect of the improved design is assessed in terms of energy efficiency, overall yield, product costs and financial profitability.

The paper is structured as follows: sections from 2 to 6 consider the EHF process in terms of modelling, process optimisation, heat and power generation and assess its performance when varying some critical parameters. Section 7 is dedicated to the financial assessment of the process. The GF process is then taken into account: sections from 8 to 11 mirror the analysis and optimisation previously carried out for the EHF process. Similarly, Section 12 defines a financial evaluation for the process. The last section discusses and compares the main results concerning the two production processes and draws some conclusions. A processing capacity of 700,000 t/yr of dry biomass wood is assumed throughout the paper.

2. The EHF process: process overview

The EHF process is possibly the most mature technology for the conversion of lignocellulosic material into ethanol. As sketched in Fig. 1, the overall ethanol production process includes five main steps: biomass pre-treatment, cellulose hydrolysis, fermentation, separation and effluent treatment.

During biomass pre-treatment, the structure of cellulosic biomass is altered, lignin seal is broken, hemicellulose is reduced to sugar monomers (mainly xylose, a C5 sugar) and cellulose is made more accessible to the enzymes that convert the carbohydrate polymers into fermentable sugars. Several technological options are possible, which are classified into either physical or chemical methods [18]. The soluble solution

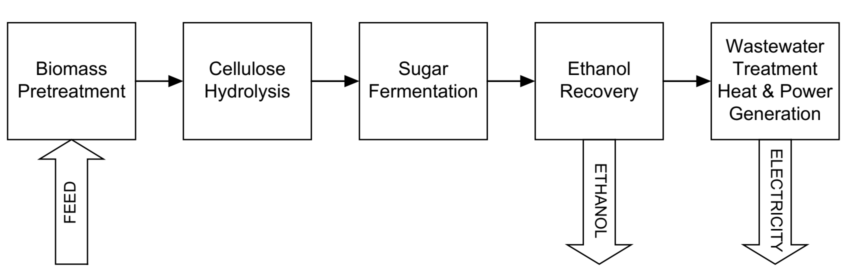

Fig. 1 – Process block diagram for the HF process.