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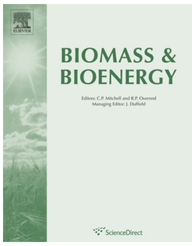

An optimization approach to biorefinery setup planning

Lars-Peter Lauven

Georg-August-Universitaet Goettingen, Platz der Goettinger Sieben 3, 37073 Goettingen, Germany

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ABSTRACT

As the production of first generation biofuels from corn or rape seed is facing severe criticism due to the perceived competition with food production, second generation biofuels made from non-food biomass are being developed to fill the gap. These can be made from lignocellulosic residues instead of agricultural products, which is commonly considered to make competition for soils and land-use change less severe. Economic competitiveness for this kind of biofuels could however not be established so far for various reasons, such as complex and expensive plant technology and the need of biomass transportation to the plant. In contrast to large fossil plants, economies of scale are overcompensated by increasing specific biomass transportation cost for large biorefineries. In order to suitably approximate these effects, a nonlinear optimization model is presented in this paper to simultaneously identify optimal plant setups and capacities. In this model, the co-production of other hydrocarbon products in addition to fuels in biorefineries through different combinations of Fischer–Tropsch product upgrading processes is considered. As the optimal plant capacity also depends on the economic value of the plant's products, several biorefinery process setups and their corresponding process-specific economies of scale are compared with regard to their economic viability.

1. Introduction

In a world faced with climate change and rising prices for fossil fuels, the versatile usage of biomass in biorefineries becomes increasingly promising. Nevertheless, the economic viability of biorefineries is still uncertain. The expected value of the product spectrum and the corresponding required investment need to be considered, as well as factors relating to biomass availability and price. Hydrocarbon processes are a well-known application of Operations Research methods, more specifically of Linear Programming. On a tactical level, optimal production plans are usually determined to maximize profits, which are subject to the composition of the crude oil in question, the amount of available hydrogen and various other restrictions [1–3]. If biomass is converted to liquid hydrocarbons using the Fischer–Tropsch synthesis, the resulting product substances are largely the same ones that can be found in mineral oil. Therefore, strategic planning for synthesis gas biorefineries has similar features compared to that for mineral oil refineries, in which a variety of products is produced from a few input streams of mineral oil. As an established technology for the conversion of coal and natural gas to liquid hydrocarbons, Fischer–Tropsch synthesis is also a promising technology for the production of sustainable biofuels in so-called biomass-to-liquid (BtL) plants. Several technical and economic difficulties concerning the conversion of biomass hamper the competitiveness of BtL plants or

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E-mail addresses: lplauven@aol.com, llauven@gwdg.de.

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synthesis gas biorefineries so far [4]. While mineral oil refineries are generally built in a capacity range from 2 to 15 million tons of hydrocarbon products per year in order to maximize the beneficial impact of economies of scale, processes that utilize biomass are usually realized on a much smaller scale. This is due to the decentralized growth of biomass on agricultural soils and in forests, as opposed to the centralized extraction of fossil fuels from oil or gas wells or coal mines. As biomass has to be transported from the surrounding area over distances that increase with the plant's capacity, specific biomass transportation cost increasingly compensates the favorable effect of economies of scale if plant capacities increase. Therefore, optimal plant capacities are subject to both economies of scale for investment-related cost and diseconomies of scale for specific transportation cost, instead of the highest technically feasible process capacities as is in the case of refineries.

This biomass-specific antagonism has repeatedly been discussed in bioenergy-related publications. While the development of haul distances for biomass deliveries was described as early as 1982 [5], Jenkins [6] was among the first to use a nonlinear approach to determine optimal plant sizes. Considering a rectangle to represent the catchment area around the plant, Jenkins objective was to minimize the unit prices of a biomass conversion plant. If investigations are carried out independent of a specific location, the shape of the catchment area remains unknown. [7–9] assumed a circular catchment area surrounding a bioenergy plant for their investigations. Under this assumption, the haul distance of the input biomass increases proportionally to the square root of plant size [10,11]. If average transportation cost is expressed as a function of plant size, the resulting term usually features an exponent of 1.5 with respect to the plant size [9].

In these papers, the nonlinear effects were expressed as a mathematical function for biomass-converting plants with a given process configuration and product composition.

While this approach allows for the determination of a one-dimensional function that facilitates approximation of optimal plant capacities, it does not cover the differences in the optimal plant configuration resulting from changes in the plant's overall capacity. In the modeling approach presented in this paper, the effects of economies of scale are therefore included on the basis of individual upgrading processes instead of the plant as a whole. Consequently, the relative advantage of separation and upgrading equipment can change with increasing plant capacity. This is especially important for the combined production of fuels and chemicals from Fischer–Tropsch synthesis, as upgrading several parts of the product stream means that a corresponding number of upgrading units has to be installed at relatively low capacities. Given that upgrading processes, e.g. paraffin/olefin splitters or alkylation units, are quite capital-intensive, process specific economies of scale are a decisive factor for their economic viability [12]. In this paper, a nonlinear optimization model is therefore applied to determine whether the simultaneous optimization of synthesis gas biorefinery plant configurations and capacities results in a co-production of biofuels and biochemicals instead of the fuel-only configurations of previously discussed Biomass-to-Liquid (BtL) plant concepts. The focus of this investigation is the effect of the existing exemptions from the German energy tax for second generation biofuels, which is analyzed by comparing model results for a number of scenarios. By contrast, the consequences of other governmental policy options, such as mandatory blending targets [13], could not be included into the scope of this investigation.

2. Materials and methods

The integrated optimization of plant configuration and capacity can be achieved by expressing the total plant capacity through the sum of the plant's upgrading and separation processes' capacities. The choice of these processes determines the value of the plant's products and its total capacity, given that all hydrocarbons streams leaving the plant undergo upgrading or separation treatment. In the following, a choice of common unit operations is briefly introduced.

2.1. *Hydrocarbon product upgrading processes*

To cover a meaningful selection of product treatments, fourteen different processes were considered (see Fig. 1, separation processes for C_2,C_3 and C_4 olefins are subsumed in “light olefins”). The capacities of these processes are implemented as the decision variables x_1 through x_{14} of the optimization model.

2.1.1. *Combustion in a turbine*

Hydrocarbons, or a mixture of such, can be combusted for electricity generation [14]. The value of the electricity, and potentially of the by-product heat, is usually lower than the material value of the combusted hydrocarbons, but purification of chemical substances only pays out if the extractable amounts are large enough to justify costly separation equipment. If this is not the case, combustion, represented by the variable x_1, can be a more economic option.

2.1.2. *Separation*

If certain kinds of valuable hydrocarbons are available in sufficient amounts, it becomes economic to install equipment for their separation from the product stream with subsequent purification to achieve marketable qualities. Potential products of interest from the Fischer–Tropsch product spectrum are described in Table 1.

2.1.3. *Fuel upgrading*

The main alternative to separation of individual hydrocarbons of high purity is to form groups of hydrocarbons that meet the requirements for hydrocarbon fuels. As these requirements, such as the octane rating of gasoline fuel, cannot always be met without chemical modification of the synthesis products, the upgrading processes compiled in Table 2 were implemented as well.

2.1.4. *Cracking*

Lack of selectivity, meaning lacking ability to convert the input synthesis gas into specific hydrocarbons of choice, is one of the major problems of the Fischer–Tropsch synthesis.

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