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Research paper

Economics of biofuels: Market potential of furfural and its derivatives

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ABSTRACT

Production of biofuels from cellulosic materials continues to face major challenges in terms of economic profitability. Our research focuses on evaluating the economic potential of several major biochemical co-products derived from renewable fuel production that may help to overcome these challenges. In our thermal deoxygenation (TDO) process of renewable fuel production, furfural (a platform chemical) is produced in significant volumes. The quantity of furfural produced at commercial scale, however, will likely impact the national and world price of this industrial chemical. This will reduce its ability to play an important role in the total economic viability of the renewable fuel process. Thus, it is better to convert furfural to other products to have a smaller impact on market prices and, consequently, a higher profit margin for the renewable fuel process as a whole. In this paper we identify the furfural derivatives that have a considerable market size and can be derived from furfural in one or two steps of conversion. We then look at maximizing the profits of a multiproduct biofuel producer facing world demand curves that consider the effect of the producer's output on market prices. We solve the parameterized model using nonlinear optimization method under a variety of alternative assumptions and scenarios. Our results show that renewable fuel production can be made significantly more financially attractive through sales of furfural derivatives. A key issue to resolve is the elasticity and cross-elasticity of demand for our identified industrial chemical.

1. Introduction

One of the major challenges in making renewable fuels is reaching to the target price of 0.79 $ L^{-1} which has been set by the Bioenergy Technologies Office (BETO) [1]. The economic viability of a renewable fuel production facility can be improved by using non-merchandisable biomass such as forest residues as a feedstock, and by generating revenue from selling co-products. However, the production volumes of co-products such as industrial chemicals made in a large scale renewable fuel plants could lower the market prices of respective co-products that eventually decrease the profitability of renewable fuel investments. Thus, it is necessary to identify co-products of a new renewable fuel plant that do not influence the market prices upon the renewable fuel production facility is commenced its production.

In our process of renewable fuel production (described below), furfural - identified by the United States Department of Energy as a promising chemical platform - is produced in significant volumes [2]. The quantity of furfural produced at commercial scale, however, will likely impact the national and world price of this industrial chemical. This will lower its economic return from production. Thus, it is better to convert furfural to other products in order to have a smaller impact on market prices and, consequently, higher revenue for the renewable fuel process as a whole. In this paper, we look at the market response of introducing furfural and its derivatives into the market to determine the best mix of furfural and its derivatives to produce using data on market price, market size and plausible ranges for the price elasticities of demand for our identified industrial chemicals.

The process we examine uses a combined acid hydration and dehydration (AHDH) and thermal deoxygenation (TDO) process to convert woody biomass to furfural and renewable fuel [3]. The five- and six-carbon complex sugars in wood are converted into a liquid intermediate consisting of a mixture of furfural, levulinic acid, and formic acid. Furfural is recovered as a co-product, and the mixture of calcium levulinate and calcium formate salts is prepared for further processing. The process simulations performed by Gunukula et al. [2] has shown that approximately 247 t d^{-1} of furfural and 196 t d^{-1} of TDO oil are made from 2 kt d^{-1} of wood via combined AHDH/TDO processes. The importance of furfural returns in the combined AHDH/TDO processes is due to the large amount of furfural being produced (247 t d^{-1}). This quantity is about 22%, by mass, of the global market size for furfural.

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However, the large quantity of furfural produced at a commercial-scale of TDO production will likely decrease the national and world price of this industrial chemical. This will reduce the significance of furfural in increasing the profit earned by the whole process. Thus, converting furfural to other products may provide additional revenue streams and, consequently, a higher profit margin for the renewable fuel process as a whole.

Furfural can be converted to more than 80 chemicals that are currently used, or could be substituted for industrial chemicals [4,5]. It is a daunting task to evaluate the production of all the furfural derivatives. Thus, we qualitatively screened to identify a set of six furfural derivatives. After selecting high potential furfural derivatives, we determine the best combination of furfural derivatives and what proportion of furfural should be turned into each derivative to maximize the profit of a multiproduct biofuel producer facing world demand curves that consider the effect of the producer's output on the market prices.

2. Selected furfural derivatives

2.1. Furfural

Furfural is commercially produced through acid-catalyzed transformation of 5-carbon sugar molecules (Fig. 1). The major industrial users of furfural are the steel/foundry, pharmaceutical, agricultural chemicals, plastics, and wood treatment industries [6]. A few bioplastics companies make use of furfural as a building block in their bioplastics chemistry or have expressed an interest in using furfural provided that there are supply and price security [7]. Today, the major part of furfural production (90%) is carried out in three countries, with China leading the market followed by South Africa and the Dominican Republic [8]. China is the major producer as well as major consumer of furfural in the world. Low production cost of furfural in China is expected to remain a key driving factor for the domestic market. However, the furfural industry in China has been facing an issue of availability of corn cob [9]. Furfural has found applications as an organic solvent, a fungicide, and a nematocide [10]. Also significant is a mixture of solid residues from seaweed and furfural that is used as an organic fertilizer [11].

We used a strategy to identify a set of the furfural derivatives that have a considerable market size (> 50 kt y-1) and can be derived from furfural in one or two steps of conversion. The selected furfural derivatives are: furfuryl alcohol (FA), 2-methyltetrahydrofuran (2-MTHF), tetrahydrofuran (THF), tetrahydrofurfuryl alcohol (THFA), Maleic anhydride (MA), and 1,5-pentanediol (1,5-PDO). In Fig. 2, we show the whole schematic for the process - one for the main process where TDO oil and furfural are produced, and another for converting furfural into value-added biochemicals. The blue line area represents the market and indicates the products that can be sold in the market. One point to be considered here is that the whole furfural volume is not necessarily converted into its derivatives. Furfural itself can also be directly sold in the market and doing this may increase profitability depending on the cost of production for each furfural derivative and the corresponding market prices. Please refer to the supplementary material for the description of the production of these furfural derivatives and their applications.

3. Model for maximizing the revenue from furfural derivatives

We build a mathematical model to estimate the quantity produced of each furfural derivative which maximizes the profit. This assumes that the total quantity of furfural is fixed and predetermined (i.e., fixed plant size). Due to the large quantity of furfural produced, the quantity of furfural and its derivatives would alter the market prices given that the demand is price sensitive in the relevant range of production. Furthermore, finished furfural is a homogenous product in consumption. Thus, we model our producer as a large producer in this competitive market whose output reduces market prices.

Change in the market price (as the result of supply change) depends on the price elasticity of demand for furfural and its derivatives. For some goods a small change in price results in a large change in the quantity demanded, for other goods a large change in price results in a small change in the quantity demanded. The responsiveness of the quantity demanded to price is measured by the price elasticity of demand defined in terms of percentage changes [12]. As furfural and its derivatives are biochemicals which are likely to be a substitute for some petrochemicals, then it is assumed that the market structure for these biochemicals is similar to petrochemicals; hence the price elasticities across two markets should be similar. Beckman et al. [13] by using CGE models indicated that the price elasticity of demand for oil products in different regions of the world is in the range of −1.49 to −0.56. Shapiro [14] shows that the price elasticities of demand for both petroleum and petrochemicals are equal to −1.5. Hence, we make the assumption that furfural and its derivatives respond similarly to petroleum and petroleum byproducts in terms of their price responsiveness to output with a range of elasticities from −1.5 to −0.5. Furthermore, we assume that other producers of furfural and its derivatives will not change their output in response our production, but the whole market would grow at a certain annual rate based on world GDP growth rate or specific market growth rate when available. This assumption of no reaction from existing suppliers is a conservative assumption in that it implies that our demand curves absorb all price impacts from increased output rather than assuming a shared burden of reduced prices.

3.1. Mathematical framework for demand of furfural and its derivatives

Absent more specific information, we use constant price elasticity of demand functional form:

$$Q_i = AP_i^{\varepsilon_p}, \quad -1.5 < \varepsilon_p < -0.50 \tag{1}$$

$$\varepsilon_p = \frac{dQ}{dP}\cdot\frac{P}{Q} = \text{constant} \tag{2}$$

Where ε_p is the price elasticity of demand. Shown in Fig. 3 are the constant elasticities curves for furfural given our range of elasticities.

Each line represents a constant elasticity (- 0.5, −1, −1.5), showing how the price might change in the market as the result of supply change. Solving for the ith furfural derivative in terms of P_i, we get:

$$P_i = \left(\frac{Q_i}{A_i}\right)^{\frac{1}{\varepsilon_p}} \tag{3}$$

Letting $\overline{Q}_{it}^{M}$ equal the total market level of production for world suppliers, which we take as fixed at each time step, and Q_{it} as the

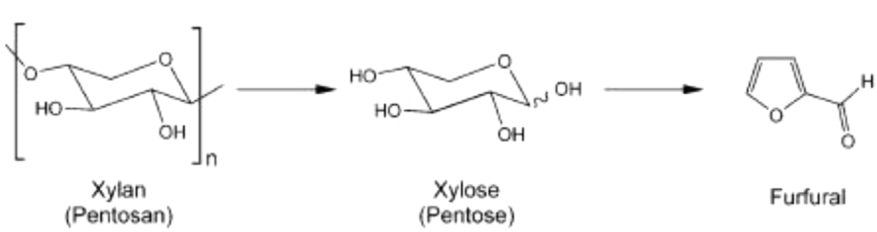

Fig. 1. Acid-catalyzed conversion of pentosan into furfural.