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Biomass transportation model and optimum plant size for the production of ethanol

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ABSTRACT

A detailed model based on a non-dimensional transportation factor is developed to assess the economics of biomass collection, transportation, and storage. The optimum plant size for bio-refineries is investigated; ethanol production from corn stover via dilute acid hydrolysis is presented as a case study. The conversion of straight-line, farm-to-plant distances to road distances via a winding factor leads to a shift in the distribution of transportation distances towards shorter hauls. The capital investment scaling exponent was calculated using the model developed at the National Renewable Energy Laboratory (Aden et al., NREL/TP-510-32438, 2002) and found to be 0.7. The cost of the delivered corn stover is proportional to the square root of the inverse of the farmer participation; as a consequence, bio-fuel producers intending to use agricultural residues as feedstock should work towards a farmer participation of fifty percent. Costs associated with storage represent a significant portion of the production cost.

1. Introduction

The increasing costs of fossil fuels, along with environmental concerns associated with green house gas emissions, have sparked great interest in bio-fuels. Corn-based ethanol, a first generation bio-fuel, has led the way for three decades. Cellulosic-based second generation bio-fuels present a significant lower greenhouse gas emissions compared to gasoline (MacLean and Lave, 2003; Sheehan et al., 2003) and corn-base ethanol (Wu et al., 2006). Corn stover is an abundant agricultural residue in the Midwest and is a potential feedstock for cellulosic bio-fuels. It is estimated that 100 million Mg of corn stover could be harvested annually (Graham et al., 2007). The use of agricultural residues as feedstock for bio-fuels may be limited by the logistics of harvesting, collection, storage, and transportation. To a great extent, the economic viability of second generation bio-fuels from agricultural residues and the reduction of greenhouse gas emissions depend on resolving the logistic complexity (Overend, 1982).

The scale of bio-refineries is limited by the logistic hurdles and the low energy density feedstock, which is not the case in traditional petroleum refineries. As the plant size of a bio-refinery increases, economies of scale leads to a reduction in the production cost; however, the greater mass of feedstock needed to satisfy plant demand requires it to be transported greater distances, thus increasing the transportation cost. As a result of these competing factors, an optimum plant size must exist which minimizes the total production cost. Contrary to the bio-fuels industry, the absence of the logistic hurdles along with the economy of scale for the petroleum industry has led to large plants constrained by the size of fluid catalytic cracking (FCC) reactors. Even the expected long term maximum plant size for bio-refineries estimated at 10,000 Mg/d of feedstock (Hamelinck et al., 2005) that is smaller than an average petroleum refinery that processes 13,600 Mg/d (100,000 barrels per day) of crude.

One of the competing components that determines the optimum plant size is feedstock transportation cost. Several researchers have developed models to quantify transportation costs. Overend (1982) developed a simplified model to compute the transportation cost of harvesting and delivering agricultural residues to a central facility. Following a similar approach, other researchers assessed the transportation of biomass by means of general models (Nguyen and Prince, 1996; Jenkins, 1997; McIlveen-Wright et al., 2001; Perlack and Turhollow, 2003; Wright and Brown, 2007). In calculating the transportation cost in these simplified models, the road distance is calculated from the straight-line, farm-to-plant distance by means of a winding factor. The simplified models assume a circular collection area with the plant at the center; no discrete farm locations are considered and it is assumed that the farmland is uniformly distributed.

An important aspect for minimizing the production cost of bio-fuels is the determination of the optimum plant size which has been the focus of previous research. Jenkins (1997) looked at the optimum plant size for bio-refineries via a simplified model in which the total production cost was broken down into annual capital charges (depreciation), operating expenses, feedstock delivery, and production cost. Nguyen and Prince (1996) developed a model

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to determine the optimum capacity for the production of ethanol from sugar cane and sweet sorghum via a simplified model in which the production cost associated with the capital investment and transportation cost were scaled with exponential functions; the authors reported that an increase in the transportation efficiency allows the operation of larger facilities. Kaylen et al. (2000) developed a detailed mathematical model to analyze the economic feasibility of producing ethanol from lignocellulosic feedstock via dilute acid hydrolysis in which capital investment, maintenance, labor, and administrative costs scale with exponential functions; the production cost was broken-down into its individual components; the authors included furfural as a co-product in the economic analysis. Following the approach of Nguyen and Prince (1996), Wright and Brown (2007) analyzed the optimum plant size of bio-refineries for several technologies including the production of ethanol from energy crops (with a relative high yield) via the bio-chemical route. Searcy and Flynn (2009) also investigated the optimum plant size for a bio-ethanol plant via fermentation using a simplified model based on regressing a capital investment power law function from data reported in the literature; the authors reported that allowing a 3% increase in production cost leads to a reduction of more than 50% in the optimum plant size.

The optimum plant size is significantly impacted by the scaling exponent for the capital investment associated to depreciation, which is a major component of the production cost. Historical data from the chemical industry indicates that the scaling exponent is on average between 0.6 and 0.7 (Peters and Timmerhaus, 1991) commonly known as the six-tenth rule of thumb; these values have been greatly influenced by plant costs for petroleum refineries and petrochemicals plants. Some ambiguity exists regarding the capital investment scaling exponent for bio-refineries. Previous research indicates that the investment for biomass-based plants scale with higher values of the exponent than petroleum refineries and are in the range of 0.70–0.94 (Fisher et al., 1986; Nguyen and Prince, 1996; Jenkins, 1997; Larson and Marrison, 1997; Bain et al., 1998; Kumar et al., 2003; Cameron et al., 2007; Searcy and Flynn, 2009). Even though higher scaling exponents for bio-based plants have been reported, several researchers have used petroleum based scaling exponents in the economic analysis of bio-fuel plants. Kaylen et al. (2000) assumed a scaling exponent of 0.67 for a bio-ethanol plant via the bio-chemical route; the authors presented a sensitivity analysis to the scaling exponent for the capital investment in the range between 0.5 and 0.7. Wright and Brown (2007) studied the production of various bio-fuels and performed a sensitivity analysis of the plant size to the scaling exponent for values in the range between 0.5 and 0.8; a value of 0.6 was used as the baseline case. Given the ambiguity on the value of the scaling exponent and the uncertainty caused by the lack of accurate values for bio-refineries, further work is needed to generate reliable scaling exponents.

A detailed model is developed to assess the economics of biomass collection, transportation, and storage in order to evaluate the optimum plant size for bio-refineries. The transportation cost model is based on a non-dimensional transportation factor from which the transportation cost is scaled with plant capacity. The non-dimensional parameter is obtained from a model that includes discrete farm locations. The production of ethanol from corn stover via the bio-chemical route is used as a case study for the model. A simplified case study for a plant located in central Illinois is presented. The exponent to scale the capital investment for a bio-ethanol plants is calculated from a detailed model developed at the National Renewable Energy Laboratory (NREL) and presented by Aden et al. (2002). The impact of several factors on the optimum plant size and production cost are investigated.

2. Model development

The model is developed to evaluate biomass collection, transportation costs, and optimum plant size of bio-refineries. The two main elements of the model are the production and transportation cost components. The model is developed so that both components scale with capacity, the required characteristic to determine the optimum plant size. Ethanol, produced via the bio-chemical route, is the fuel of choice for the present study; the production cost component is based on work performed at the National Renewable Energy Laboratory (NREL) and reported by Aden et al. (2002). The transportation component is developed in a two-step manner. In the first step, a detailed model referred to as the "Farm Model", in which individual farms are modeled, is used to determine a non-dimensional transportation factor for a single plant size. In the second step, the dimensionless factor is used to develop a simplified transportation model that scales the transportation cost with plant capacity. The simplified transportation model along with the production cost model are used to perform the optimization analysis. The combined model is referred to as the "Optimization Model".

2.1. Collection radius

The transportation cost is directly proportional to the distance that the corn stover is hauled from the farm to the processing facility. For a given plant size, there is a collection area needed to harvest corn stover to meet annual feedstock demand. The collection area is site specific and depends on several geographic and agricultural factors. The collection area, A_c, needed to supply the feedstock is given by:

$$A_c = \frac{P \cdot O}{Y_s \cdot F_f \cdot F_c \cdot F_p \cdot F_a \cdot (1 - F_l)}, \quad (1)$$

where P is the daily plant capacity, O is the plant operating days per year, Y_s is the corn stover yield per area, F_f is the farmland fraction, F_c is the fraction of total farmland planted with corn or crop rotation factor, F_p is the fraction of farmers selling corn stover or farmer participation, F_a is the accessibility factor, and F_l is the loss factor. All mass related quantities are on a dry basis unless otherwise specified. The above equation is based on the assumption that the farmland is uniformly distributed. The present study assumes the plant operates 350 days per year.

In the present study, the five factors in the denominator of Eq. (1) are based on data from several sources. The plant is assumed to be located in Macon county in central Illinois and that corn stover is collected in this county as well as the surrounding counties of Christian, DeWitt, Logan, Moultrie, Piatt, Sangamon, and Shelby. The farmland factor, F_f, is the fraction of area used as farmland around the processing facility; the crop rotation factor, F_c, represents the fraction of total farmland planted with corn. The values of these two factors are calculated from crop data reported by the U.S. Department of Agriculture (USDA) for the eight counties considered in the present scenario. The 2007 crop data reported by the USDA for the eight counties in central Illinois (USDA, 2007) along with the total surface area are presented in Table 1. The data show that F_f is 0.78 (ratio between surface area and total farmland) and F_c is 0.65 (ratio between area used to plant corn and total farmland). The farmer participation factor, F_p, represents the proportion of farmers that are willing to sell corn stover and it is a strong function of the economic incentive. Due to a lack of data on the farmer participation, a value of 0.2 for F_p was used as a base case following the assumption made by Aden et al. (2002); sensitivity of the model's results to the farmer participation is included in the analysis. The accessibility factor, F_a, accounts for the corn