Biomass and Bioenergy 80 (2015) 267–277

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Industrial sugar beets to biofuel: Field to fuel production system and cost estimates

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ARTICLE INFO

Article history:
Received 23 February 2015
Received in revised form
28 May 2015
Accepted 31 May 2015
Available online 12 June 2015

Keywords:
Beta vulgaris
Breakeven price
Biorefinery
Brassica napus
Canola
Cooperative
Crop rotation
Energy beets
Ethanol
Industrial beets
Triticum aestivum
Wheat

ABSTRACT

Specialized varieties of sugar beets (*Beta vulgaris* L.) may be an eligible feedstock for advanced biofuel designation under the USA Energy Independence and Security Act of 2007. These non-food industrial beets could double ethanol production per hectare compared to alternative feedstocks. A mixed-integer mathematical programming model was constructed to determine the breakeven price of ethanol produced from industrial beets, and to determine the optimal size and biorefinery location. The model, based on limited field data, evaluates Southern Plains beet production in a 3-year crop rotation, and beet harvest, transportation, and processing. The optimal strategy depends critically on several assumptions including a just-in-time harvest and delivery system that remains to be tested in field trials. Based on a wet beet to ethanol conversion rate of 110 dm^3 Mg^{-1} and capital cost of 128 M$ for a 152 dam^3 y^{-1} biorefinery, the estimated breakeven ethanol price was 507 $ m^{-3}. The average breakeven production cost of corn (*Zea mays* L.) grain ethanol ranged from 430 to 552 $ m^{-3} based on average net corn feedstock cost of 254 and 396 $ m^{-3} in 2014 and 2013, respectively. The estimated net beet ethanol delivered cost of 207 $ m^{-3} was lower than the average net corn feedstock cost of 254–396$ m^{-3} in 2013 and 2014. If for a mature industry, the cost to process beets was equal to the cost to process corn, the beet breakeven ethanol price would be $387 m^{-3} (587 $ m^{-3} gasoline equivalent).

1. Introduction

The USA Renewable Fuels Standard (RFS) legislation mandates the use (if produced) of 136 hm^3 y^{-1} of renewable fuels by 2022, of which 79 hm^3 would come from advanced biofuels. Advanced biofuels are classified as non-grain based biofuels including ethanol derived from lignocellulosic biomass such as timber chips and perennial grasses, ethanol from sugar crops, and ethanol derived from waste material including crop residues and urban waste [1,2]. Based on the USA Energy Independence and Security Act (EISA) of 2007, sugar beets (*Beta vulgaris* L.) may be an eligible feedstock for advanced biofuel provided that production and conversion to biofuel meets the 50% greenhouse gas reduction threshold required for advanced biofuel designation [1,2]. Prior to certification of a renewable fuel feedstock pathway, the USA Environmental Protection Agency (EPA) evaluates petitions for the lifecycle assessments of greenhouse gas (GHG) emissions (including emissions from land use change) of each proposed biofuel pathway. As of this writing, requests for assessment of industrial beets had been submitted to, and were under review by EPA [3]. Most ethanol produced in the USA is corn (*Zea mays* L.) grain based but a growing interest to diversify biofuel feedstock sources has encouraged field trial research of industrial beets across several geographical regions in the USA including the Southern Great Plains [4–7]. Interest in beets is growing also because sugar crops have successfully been used commercially for ethanol production in Europe (sugar beets) and in Brazil (sugar cane (*Saccharum officinarum*)) and have demonstrated great potential to lower GHG emissions than other feedstocks (corn, rapeseed (*Brassica napus*)) [4,8].

USA sugar beets are predominantly grown in the northern plains and some parts of the central plains and far west. The 11 sugar beet producing states include North Dakota, Minnesota, Michigan, Wyoming, Montana, Colorado, Nebraska, Idaho, Washington, Oregon, and California [9]. Sugar beets perform well in temperate climate but due to genetic enhancement, the crop has proven to

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http://dx.doi.org/10.1016/j.biombioe.2015.05.027
0961-9534/

adapt to various soil and climatic conditions [9,10]. Sugar beets are tuber crops composed of about 75% water, 18% sugar (sucrose), and 7% insoluble and soluble materials (which are required to be at low levels). Unlike conventional sugar beets that are bred to produce sucrose for table sugar, biofuel feedstock industrial beets are specialized non-grade varieties bred for total sugar production. In addition to sucrose, these beets may produce glucose, fructose, maltose, and inverted sugars. Industrial beets are not required to be low in nitrogen, sodium, and potassium, enabling easier crop management. The presence of sugars in addition to sucrose, does not interfere with fermentation and distillation [11–13]. These non-food beets would not be efficient feedstock for the production of table sugar for human consumption, but are under development for industrial use including bioenergy production.

In the USA, conventional sugar beets produced for processing into edible sugar are heavily regulated. The USA sugar program uses marketing allotments to restrict domestic production of sugar cane and sugar beets [14]. Marketing allotments are assigned to seven processers that process beets contracted for production from the eleven beet producing states. The seven processers are Amalgamated Sugar Co., American Crystal Sugar Co., Michigan Sugar Co., Southern Minnesota Beet Sugar Cooperative, Minnesota–Dakota Farmers' Cooperative, Western Sugar Company, and Wyoming Sugar Growers Association [15]. Federal law caps the volume of sugar that can be sold in the USA by domestic sugarcane and sugar beet processors for domestic human consumption. For fiscal year 2014, overall sugar beet and sugar cane allotments were set at 4.8 Tg and 4.1 Tg, respectively [15]. If domestic production and the Commodity Credit Corporation (CCC) inventory falls short of these quotas, then reassignment could be made to imports. A provision under the 2014 farm bill feedstock flexibility program permits the CCC to sell excess sugar for use as a bioenergy feedstock [14]. Contrary to conventional sugar beets, there is currently no federal restriction on the production and marketing of biofuel feedstock beets [6]. As such, it is anticipated that industrial feedstock beets could be legally grown and processed into biofuels in regions that do not have a sugar allotment such as the southern Great Plains.

Industrial beets are being considered for biofuel production because they have high sugar content and could potentially double ethanol production per hectare compared to other feedstocks (corn, cellulose) [16,17]. In addition, the process to convert industrial beets to biofuel is known and relatively less complex than conversion of other potential advanced biofuels such as corn stover to ethanol [16,18,19]. However, to compete with other potential feedstocks for fulfilling the “advanced biofuels” mandate, the cost to produce biofuels from industrial beets must be competitive. Cost estimates are required to encompass the complete chain from the cost of bidding cropland from current use to the cost of marketing the biofuel. These cost estimates would be necessary to determine if an industrial beet-to-biofuel system would be able to compete with other advanced biofuel alternatives as defined by EISA.

Several studies have evaluated the economic feasibility of the production of ethanol from sugarcane and sugar beets [16,19–24]. These studies have produced different conclusions depending on the geographic region and the assumptions made. In addition to feedstock yield and price assumptions, the number of days per year during which the biorefinery can operate at full capacity is critical to the overall economics. A plant with a shorter processing window would have relatively greater capital costs per unit processed.

Maung and Gustafson [19] calibrated a stochastic simulation financial model using sugar beet yield data in North Dakota to examine the economic feasibility of producing ethanol from sugar beets. They used a conversion rate of about 110 $dm^3\ Mg^{-1}$ for two plant sizes (38 dam^3 and 76 dam^3 per year) that they assumed could process 333 days per year. The reported breakeven ethanol price ranged from 400 $ m^{-3} and 450 $ m^{-3} for the larger and smaller sized plants, respectively. For Washington state, Yoder et al. [10] found that the production of sugar beets failed to cover production costs and or transportation costs and concluded that the conversion of both raw beet juice and beet pulp to ethanol was not profitable under Washington agronomic and economic conditions. The estimated breakeven ethanol price was about 560 $ m^{-3} (beet acquisition and processing) when a more cost efficient conversion process was considered. Similarly, a study by the USDA [16] for a plant operating about 180 days per year found that ethanol production from sugar beets could only be profitable in the USA if the market price of ethanol was no less than 1060 $ m^{-3}. For comparison, the production cost of European ethanol from beets was reported to range from 574 to 740$ m^{-3} [22–24]. However, the estimated cost of 159 $ m^{-3} to produce ethanol from Brazilian sugar cane is substantially less than that estimated for USA or European beet ethanol [22].

Prior studies have produced cost estimates for regions in which sugar beets or sugar cane are currently grown to produce sugar (in USA) and or ethanol (in Brazil and Europe). The expected cost to produce beets in nontraditional sugar beet production regions such as the southern Great Plains is unknown. The objective of the current study is to determine the most economically efficient industrial beet field-to-biofuel system that can be envisioned for conditions in a case study region of Oklahoma. In particular, a model is developed to determine the most cost-efficient feedstock production system, to include description of crop rotations, location of production, location and size of the biorefinery, harvest timing and number of harvest machines, feedstock transportation flows and product sales. The model is designed to estimate specific costs along the entire value chain. The research presented in this study will contribute towards ongoing research in assessing the economic viability of ethanol production from a biorefinery that uses industrial beets exclusively.

2. Conceptual framework

About 4.2 million hectares are planted to annual crops in the case study region of Oklahoma. Winter wheat (*Triticum aestivum*) is the main crop with 2.2 million hectares. Some producers rotate winter wheat with winter canola (*B. napus*). Grain sorghum (*Sorghum bicolor*) is also grown in the region and may be no-till planted into wheat stubble immediately after wheat grain harvest [25].

Oklahoma has not had a sugar beet allotment and beets have not been grown in Oklahoma. A limited number of field trials have found that some specialized non-grade varieties of beets bred for high sugar content may produce reasonable yields (53.1 Mg ha^{-1}) in Oklahoma [5,13] which are comparable to dryland beet trial yields in North Dakota (56.5 Mg ha^{-1}) [26]. In regions of mild winters beets may be seeded in the fall. Based on field trials in the region of the study, planting beets prior to the first week of November enables plants to become established and be at the 8–10 leaf stage prior to the onset of winter. These plants survive winter weather encountered in the region [5]. The beets may be harvested as early as June, or they may be left in the ground and harvested as late as March of the following year. This wide 10-month harvest window would enable a just-in-time harvest and delivery system for at least 300 days per year. Zhang et al. [27] reported harvesting healthy looking beets that had been maintained in the ground for over 12 months. The fixed costs of harvest and transportation machines could be spread over a substantial number of hectares. Since the beets could be left in the field until required for processing, storage requirements and storage costs for harvested beets would be minimal.

A business plan for an industrial beet biorefinery in the