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Stochastic optimization of sustainable hybrid generation bioethanol supply chains



Vinay Gonela^{a,*}, Jun Zhang^b, Atif Osmani^c, Raphael Onyeaghala^a

^a Department of Management, Southwest Minnesota State University, 1501 State Street, Marshall, MN 56258, United States

^b School of Engineering, California Baptist University, 8432 Magnolia Ave, Riverside, CA 92504, United States

^c College of Business & Innovation, Minnesota State University Moorhead, Moorhead, MN 56563, United States

ARTICLE INFO

Article history:

Received 28 August 2014

Received in revised form 23 January 2015

Accepted 7 February 2015

Available online 13 March 2015

Keywords:

Bioethanol supply chain

Sustainability

Uncertainty

Hybrid generation

Tax credits

ABSTRACT

This paper focuses on designing a hybrid generation bioethanol supply chain (HGBSC) that will account for economic, environmental and social aspects of sustainability under various uncertainties. A stochastic mixed integer linear programming model is proposed to design an optimal HGBSC. A case study set in the state of North Dakota in the United States is used as an application of the proposed model. The results suggest that the designs of optimal HGBSC change when different sustainability standards are applied. In addition, sensitivity analysis is conducted to provide deeper understanding of the proposed model.

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1. Introduction

A sustainable energy future calls for a wide range of alternative sources of energy that can reduce fossil fuel dependency (Chen and Fan, 2012). Bioethanol is viewed as one of the potential solutions as it is both renewable and environmental friendly energy source, especially for transportation sector. As a result, 1st generation bioethanol has been produced widely in various nations. However, the wide use of 1st generation bioethanol has given rise to new social issues such as the food versus fuel debate and the extensive use of irrigation land for energy purposes, since 1st generation bioethanol is produced from food-based biomass, such as corn, sugarcane, and soybean. This results in increased cost of food products and reduced available land (resource) footprint for cultivation of food products. In addition, 1st generation bioethanol production emits higher levels of greenhouse gases (GHG) compared to 2nd generation (Charles et al., 2007). Therefore, 2nd generation bioethanol has gained great attraction from both researchers and investors, because 2nd generation bioethanol is produced from lignocellulosic-based biomass, such as woody materials, crop residue, or dedicated energy crops (e.g. switchgrass, miscanthus etc.) that can be cultivated on marginal land and consume less water and fertilizers. It is both environmentally and socially beneficial to produce and use 2nd generation bioethanol.

In recent years, numerous standards in United States (US) have been developed to promote 2nd generation bioethanol. For example, the renewable fuel standard (RFS) mandates that 36 billion gallons of biofuels should be produced by 2022, and among which, 21 billion gallons should be produced from 2nd generation biomass (Schnepf, 2011). While 1st generation bioethanol is widely in use and 2nd generation bioethanol provides sustainability benefits (compared to 1st generation), it is necessary to integrate 2nd generation bioethanol production with the existing 1st generation bioethanol production.

* Corresponding author. Tel.: +1 507 537 6359; fax: +1 507 537 6227.

E-mail address: vinay.gonela@smsu.edu (V. Gonela).

Therefore, a hybrid generation bioethanol supply chain (HGBSC) is essential to sustainably meet the bioethanol demand. In addition, HGBSC is exposed to a number of uncertainties such as bioethanol price, demand and biomass yield. Thus, a robust HGBSC has to be designed by considering the uncertainties.

Review of literature suggests that none of the up-to-date research has focused on designing optimal HGBSC that considers both sustainability and uncertainties. In addition, none of the up-to-date literature considered existing 1st generation bioethanol supply chain while designing new bioethanol supply chain. Therefore, this paper will bridge the gap. In this paper, a stochastic mixed integer linear programming (SMILP) model is proposed to design the optimal HGBSC where the objective is to maximize economic benefits under environmental and social restrictions. In this study, GHG emission is used to measure the environmental impact, and the amount of irrigation land used for biomass cultivation is used to measure the social impact. The SMILP model will determine: (1) whether the existing 1st generation bioethanol plants should operate with the same capacity, expand the capacity or should be closed; (2) optimal locations and capacities for new 2nd generation bioethanol plants; (3) optimal collection center locations for both 1st generation and 2nd generation biomass; (4) optimal biomass that should be used and their cultivation locations; and (5) optimal transportation modes. A case study of North Dakota (ND) in US is used as an application of the proposed model. The proposed model provides the economic, environmental and social insights under different standards. In addition to providing supply chain and logistic decisions to investors, the proposed model provides tax credit estimates to the policy makers when it is needed to reach a higher state of sustainability from a lower state of sustainability.

The rest of the paper is organized as follows. Section 2 provides comprehensive literature review on the design of bioethanol supply chains. Section 3 presents the problem statement where the activities of the bioethanol supply chain is discussed in details. Section 4 proposes the mathematical model. Section 5 presents a case study setting where the proposed model is applied to the state of ND. Section 6 explains the comprehensive analysis of the results and Section 7 discusses conclusions and future research.

2. Literature review

A considerable amount of research has been conducted to design a bioethanol supply chain. The literature can be classified into three categories:

1. Type of bioethanol supply chain designed. These include: (1) 1st generation bioethanol supply chain in which bioethanol is produced from food-based biomass such as corn, sugarcane and soybean; (2) 2nd generation bioethanol supply chain in which bioethanol is produced from lignocellulosic-based biomass such as woody materials, crop residue, and dedicated energy crops; and (3) HGBSC in which bioethanol is produced from a combination of 1st generation and 2nd generation biomass.
2. Type of mathematical model developed. They include: (1) deterministic or static model and (2) stochastic model (that incorporates uncertainties).
3. Type of sustainability concepts incorporated. They include: (1) economic; (2) environmental; and (3) social.

Tables 1–3 present review of up-to-date literature on 1st generation, 2nd generation and hybrid generation bioethanol supply chains respectively. The tables highlight the type of mathematical model used, sustainability aspects studies, and limitations of each of the studies. From the literature review, it is clearly evident that none-of-the up-to-date literatures have focused on designing a HGBSC that includes uncertainties and all the three key aspects of sustainability. In addition, one of the major drawbacks is none of the up-to-date studies have considered the available/existing production capacities while

Table 1
Up-to-date literature on 1st generation bioethanol supply chain.

Author	Model type	Sustainability	Limitations
Zamboni et al. (2009a)	Deterministic	Economic	Supply chain uncertainties are not studied. Environmental and social aspects of sustainability are not studied. The research considers designing a new bioethanol supply chain. However, existing bioethanol production capacities in a given geographical area are not considered
Zamboni et al. (2009b)	Deterministic	Economic Environmental	Supply chain uncertainties are not studied. The social aspect of sustainability is not studied. Existing bioethanol production capacities in a given geographical area are not considered
Dal-Mas et al. (2011)	Stochastic	Economic	Environmental and social aspects of sustainability are not studied. Existing production capacities in the given geographical area are not considered
Kostin et al. (2012)	Deterministic	Environmental	Supply chain uncertainties are not studied. The proposed model conducts life cycle assessments by considering numerous environmental metrics. However, economic and social aspects of sustainability are not studied
Awudu and Zhang (2013)	Stochastic	Economic	Environmental and social aspects of sustainability are not studied. The study addresses operational decisions within an existing bioethanol supply chain. However strategic decisions such as production capacity (if additional production is required) are not addressed

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