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Bioethanol supply chain system planning under supply and demand uncertainties

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ABSTRACT

A mixed integer stochastic programming model is established to support strategic planning of bioenergy supply chain systems and optimal feedstock resource allocation in an uncertain decision environment. The two-stage stochastic programming model, together with a Lagrange relaxation based decomposition solution algorithm, was implemented in a real-world case study in California to explore the potential of waste-based bioethanol production. The model results show that biowaste-based ethanol can be a viable part of sustainable energy solution for the future.

1. Introduction

A sustainable energy future calls for a more diversified energy portfolio that could alleviate the pressing issues of oil dependence and greenhouse gas emission. Bioenergy has been strongly promoted by US federal policy as part of the solution (US Congress, 2007). However, the challenge of realizing cost-effective energy solutions with minimal impact on food and other natural resource supplies has not been thoroughly investigated (International Energy Agency, 2006; United Nation, 2007). In this study, we emphasize on lignocellulosic biomass as an ideal feedstock source compared to corn grain for its following advantages (Farrell et al., 2006; Hill et al., 2006; Jenkins et al., 2007): better efficiency in terms of life-cycle environmental performance, higher per-acre ethanol yields, lower impact on land use and agriculture, and the variety of resources.

A biofuel pathway concerns all the facilities and operations involved in the supply chain, including feedstock resources, production and delivery infrastructures, and the end users. The true potential of bioenergy at a sustainable level needs to be sought through rigorous system analyses for the entire energy supply system. Such a system approach requires an integrated knowledge in alternative energy technologies, spatial economics, and operations research.

Some existing studies attempt to separately analyze individual process of a bioenergy pathway, such as cost estimation for feedstock processing and transportation (Atchison and Hettenhaus, 2004; Graham et al., 2000; Hamelinck et al., 2005; Kumar et al., 2005; Mahmudi and Flynn, 2006) and economic feasibility analysis of the conversion technologies (Kaylen et al., 2000; Kumar et al., 2003; Petrolia, 2008; Wallace et al., 2005; Zhan et al., 2005). However, it has become evident that the cost-effectiveness and life-cycle-impact of biofuel production depends on the design of the entire biofuel supply chain (Farrell et al., 2006; Hill et al., 2006). The efficiency of the entire supply system depends on the geography of the feedstock

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resources, the layout and operation of the biorefineries, and the cost of accessing the energy market. These factors are not independent of each other. For example, a larger-size biorefinery may provide better energy conversion efficiency due to economy of scale, but may impose higher transportation cost due to the need for accessing a more dispersed biomass resource supply.

A few studies emphasized on optimizing biofuel supply problems from a supply chain perspective considering both strategic- and tactical-level decisions (Ekşioğlu et al., 2009, 2010; Gunnarsson et al., 2004; Sokhansanj et al., 2006; Tembo et al., 2003; Zhu et al., 2011). Most of these studies focused only on the upstream of the supply chain from biomass feedstock to refineries. The models developed in Ekşioğlu et al. (2009, 2010) included the supply chain from biomass resource all the way to biofuel terminals, which are probably the most comprehensive (in terms of supply chain echelon) studies available in the literature so far. Besides establishing system-oriented decision tools for biomass and biofuel logistics, these studies also contributed to the literature by establishing multi-period models to incorporate seasonal variation of biomass supplies.

In addition to the system dependencies, uncertainty is another major challenge in long-term strategic planning of biofuel supply systems. Cellulosic biofuels, compared with conventional fuels, face more uncertainties in future feedstock supply and biofuel demand, due to unpredictable weather conditions (Persson et al., 2009) and changing regulations and policies. For example, Fig. 1a shows how some of the biomass yields in California fluctuate over 1999–2008 (normalized by the 10-year average). Fig. 1b shows different demand projections under different environmental policy scenarios (Yeh et al., 2008). Despite of the importance of addressing uncertainties in biofuel supply system planning as identified in Eksioglu et al. (2009) and IEA (2006), there is only one stochastic model in biofuel supply chain literature (Cundiff et al., 1997), which focused only on storage facilities for herbaceous biomass. The goal of this study is to establish a stochastic model that can be used to provide reliable solutions for the design of the entire biofuel supply chain under potential future supply and demand uncertainties.

To handle uncertainties, a commonly used engineering approach is to examine each scenario separately. This is also called wait-and-see approach (Birge and Louveaux, 1997), as if one could wait and see the actual realization of random events and then make decisions accordingly. Another simple approach is to aggregate all scenarios to a single scenario (such as using expected value) and then solve the corresponding deterministic problem. Solution produced by this approach is called expected-value solution. These deterministic approaches are conceptually and computationally simple, but may generate unreliable solutions. For example, a wait-and-see solution may perform well in one scenario, but may cause extremely bad consequence (very costly or even infeasible) in other possible scenarios.

In this study, we emphasize on developing a stochastic approach that hedges well against a wide range of future possibilities. A mixed integer stochastic programming model is developed to achieve the least expected system cost. Optimal strategies on bioethanol production, feedstock procurement, and fuel delivery are solved simultaneously within the integrated system. The stochastic mathematical model is used to evaluate the economic feasibility and system robustness in a case study of California. Specific questions to be answered via the model include:

- Can ethanol converted from wastes be part of a sustainable energy solution that is economically viable and environmentally acceptable?
- What are the infrastructure requirements to support the production and delivery of such a bioethanol system?

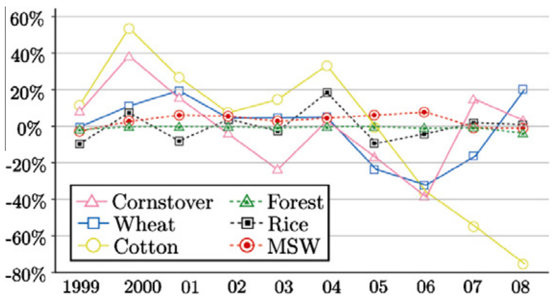

Fig. 1a. 1999–2008 California biomass yields (normalized by the 10-year average).

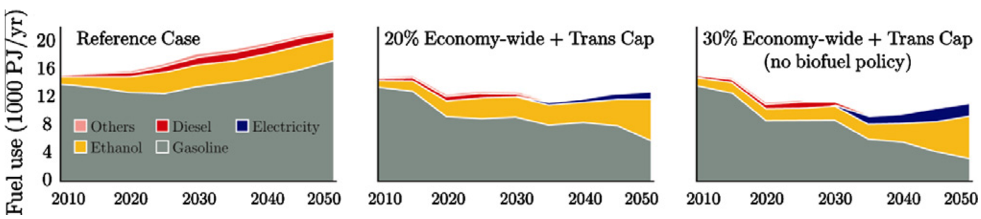

Fig. 1b. Transportation energy demand projection under different environmental policy scenarios.