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Analysis of an imperfectly competitive cellulosic biofuel supply chain

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ABSTRACT

We study the strategic behavior in an imperfectly competitive cellulosic biofuel supply chain. An optimization-based supply chain model is used to obtain long-run planning outcomes, based on which we develop market models considering both perfect and imperfect competitions. The equilibrium among stakeholders in the multi-echelon supply chain can be obtained by solving a collection of first-order conditions associated with their profit-maximization problems. For the imperfect competition, the model, additionally, allows firms with significant market share at different segment of the supply chain to exercise market power. We apply the models to an illustrative case study of California.

1. Introduction

Biofuels are liquid fuels that are used in a combination with fossil fuels such as gasoline and diesel. Currently, ethanol *blend wall*, which is defined as a technical barrier to accommodating additional ethanol supply (Energy Information Administration, 2010), is limited to E10, i.e., gasoline mixed with 10% ethanol. To promote biofuel, the Renewable Fuel Standard (RFS) in the Energy Independence and Security Act of 2007 requires an increase of the minimum annual level of renewable fuels used in U.S. transportation fuel from 9 billion gallons in 2008 to 36 in 2022, of which 21 billion gallons are cellulosic-based biofuel produced from agricultural residues, forest residues, wastes, or energy crops (EISA, 2007). Reaching the 2022 goal requires almost all new infrastructures in support of supply chain of *cellulosic biofuels*.

One emerging issue that has received limited attention so far is the implications of firms' *strategic behavior* along the supply chain of biofuel markets, including the cellulosic biofuel. In the current content, the strategic behavior refers to a situation in which the participants in the market possess ability to raise price above the marginal cost.[1] The consequences of strategic behaviors include price distortions, productive and allocative inefficiencies, and redistribution of income among entities in the market. There are a few reasons why the *strategic behavior* possibly could be present in the biofuel supply chain. *First*, the facilities' siting and operational permitting process is typically lengthy, and could involve delays due to compliance

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[1] "Raising price above the marginal cost" or "raising price above the cost of marginal unit" is a generic concept that describes the economic purpose when a firm engages in *any sort* of strategic behavior. By doing so, a firm can increase its gross margin, thereby increasing its profit. In a centralized market in which a firm needs to submit a bid to supply goods, it can bid above its marginal cost to inflate the price if the bid is accepted. In this paper, we applied a quantity-based or Cournot assumption in modeling strategic behavior. That is, a firm recognizes that demand is price responsive and therefore could withhold its output level in order to elevate the biofuel prices in equilibrium. Please also see footnote 7 for discussion on various ways to model strategic behavior.

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with environmental regulation, opposition from local communities and competing interest groups (White, 2010).[2] *Second*, a multi-echelon biofuel supply chain network is capital intensive, including multiple layers such as feedstock logistics, fuel production and distribution. New entries might find it difficult to access to low-cost capital to finance new projects (Solecki et al., 2013). Also related, the economies of scale of infrastructure imply that excessive capacity could be used by incumbent producers to deter small investors from entering biofuel markets, resulting in local demand to be satisfied by only a few biofuel producers or blenders (Tirole, 1988). *Third*, coordination of logistics among entities in the supply chain is daunting, at least in the early stage of its development prior to the formation of centralized markets (EPA, 2011). Thus, new entries need adequate time to retain sufficient knowledge in order to be successful in the markets. *Fourth*, existing transportation system might not be sufficient to support the increasing transportation demand of procuring biomass (Solecki et al., 2013). This suggests that isolated local markets would emerge, in which supply and demand is controlled by a few local entities, before long-distance procurement options become economically viable. *Finally*, historically, several network industries, such as railroad, electricity, and airlines, have experienced some degree of local market manipulation, leading to less competitive market outcomes.[3] With biofuel markets sharing some of the similar traits of these network industries (e.g., both involve multi-echelon network structure), it is reasonable to believe that local market power could be a concern. Therefore, analyses of biofuel supply chain markets need to explicitly account for strategic behaviors.

Despite the implications of strategic behaviors in the biofuel supply chain and the associated economic consequences, most of research so far has been concerted on developing a cost-effective biofuel infrastructure system by solving an optimization-based supply chain design model that is based on social-surplus-maximization or cost-minimization principles (Beamon, 1998; Geunes and Pardalos, 2003; Meixell and Gargeya, 2005; Melo et al., 2009; Min and Zhou, 2002). The related studies in biofuel supply chain design can be broadly classified into three general categories: (1) deterministic biofuel supply chain optimization (Bai et al., 2011; Ekşioğlu et al., 2010; Ekşioğlu et al., 2009; Parker, 2007), (2) biofuel supply chain design under uncertainty (Chen and Fan, 2012; Cundiff et al., 1997), and (3) multistage biofuel supply chain expansions (Acharya et al., 2008; Gunnarsson et al., 2004; Huang et al., 2010; Walther et al., 2012). For a comprehensive reviews on biofuel supply chain design, please refer to An et al. (2011) and Awudu and Zhang (2012).

On the other hand, modeling firms' strategic behavior is methodically challenging. It typically requires explicitly solving individual firms' or entities' profit-maximization problems simultaneously. A common approach is to solve a collection of first-order conditions derived from each individual's optimization problem.[4] When considering non-interior or corner solutions of those optimization problems, the resulting model is a complementarity problem. Examples of studies using this approach include following references (Hobbs, 2001; Jing-Yuan and Smeers, 1999; Limpaitoon et al., 2011). Nagurney et al. (2002) was the first paper that developed a supply chain network equilibrium model as a variational inequality formulation. That model was later analyzed for the similarities and difference between transportation network equilibrium and supply chain network equilibrium problems. Variants of the model have been developed in subsequent years to adapt different market structures (Nagurney, 2006; Nagurney et al., 2002; Zhang, 2006; Zhang et al., 2003). More recently, a general supply chain design in an oligopolistic setting has been conducted in Nagurney (2010), in which a general supply chain network design problem under oligopoly competition was considered and formulated as a variational inequality problem based on a Nash-Cournot equilibrium condition. With the regard to the biofuel market, however, few recent papers have addressed the impacts of strategic behaviors. For example, Chen et al. (2011a) developed a dynamic, spatial, and multi-market equilibrium model to estimate the effects of public policies on cropland allocation, food and fuel prices, and the mix of biofuels from corn and cellulosic feedstocks. Bai et al. (2012) developed Stackelberg game models to integrate strategic behaviors of farmers and biofuel manufactures in determining locations and capacities of biorefineries as well as supply chain operations. Wang et al. (in press), also based on Stackelberg game models, considered the influence of renewable identification number (RIN) trading market in the biofuel supply chain design. Our contribution is to use long-run planning outcomes to analyze imperfect competitive cellulosic biofuel sector.

Our approach is to examine the market equilibrium as if entities in the supply chain are allowed to behave strategically in *market models*. The market models are built on individual's optimization problems by treating the location and capacity from a cost-minimization planning model[5] as given and solve for biomass/biofuel transportation, biofuel production, and biofuel blending activities. The biofuel prices in the market are determined endogenously by supply and demand conditions. We consider two scenarios in the market models, one under perfect competition and the other under imperfect competition when

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[2] For example, New Source Review (NSR) under the Clean Air Act (CAA) is a pre-construction permitting process that requires that the operator of a large new (or modified) stationary source controls its air pollution using advanced pollution-control technologies (EPA, 2013; Evans et al., 2007). The owner or operator also needs to show that the construction would neither exacerbate the attainment of national ambient air quality standards nor worsen the air quality in clean air areas. Other related legislations include New source Performance Standards (NSPS) under the CAA section 111 (EPA, 2013).

[3] For example, a well-known situation in the power sector is that when transmission line connecting a load center (e.g., a city) to the rest of the power grid is congested, creating so-called a "load pocket." The local power supplier, facing an inelastic demand, can theoretically possess significant market power (as a monopoly) and increase its profit substantially when reducing its sales to the locally isolated markets (Stoft, 2002).

[4] As an example, a duopoly game involves a production decision q_i and q_j of two entities. The standard technique for solving the equilibrium is, first, to find each firm's best-response function by representing each firm's decision as a function of its rival's decision $q_i(q_j)$ or $q_j(q_i)$ using the first-order condition of each entity's profit-maximization problem. The equilibrium can then be identified as the intersection of the two best-response functions. Mathematically, this is equivalent to solving for a system of two equations or two first-order conditions.

[5] The planning model presented in Section 2.1, similar to other existing studies examining cost-effective biofuel supply chain design, yields a least-cost cellulosic biofuel infrastructure system.