Biofuel supply chain, market, and policy analysis

by

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ABSTRACT

Renewable fuel is receiving an increasing attention as a substitute for fossil based energy. The US Department of Energy (DOE) has employed increasing effort on promoting the advanced biofuel productions. Although the advanced biofuel remains at its early stage, it is expected to play an important role in climate policy in the future in the transportation sector. This dissertation studies the emerging biofuel supply chain and markets by analyzing the production cost, and the outcomes of the biofuel market, including blended fuel market price and quantity, biofuel contract price and quantity, profitability of each stakeholder (farmers, biofuel producers, biofuel blenders) in the market. I also address government policy impacts on the emerging biofuel market.

The dissertation is composed with three parts, each in a paper format. The first part studies the supply chain of emerging biofuel industry. Two optimization-based models are built to determine the number of facilities to deploy, facility locations, facility capacities, and operational planning within facilities. Cost analyses have been conducted under a variety of biofuel demand scenarios. It is my intention that this model will shed light on biofuel supply chain design considering operational planning under uncertain demand situations. The second part of the dissertation work focuses on analyzing the interaction between the key stakeholders along the supply chain. A bottom-up equilibrium model is built for the emerging biofuel market to study the competition in the advanced biofuel market, explicitly formulating the interactions between farmers, biofuel producers, blenders, and consumers. The model simulates the profit maximization of multiple market entities by incorporating their competitive decisions in farmers' land allocation, biomass transportation, biofuel production, and biofuel blending. As such, the equilibrium model is capable of and appropriate for policy analysis, especially for those policies that have complex ramifications and result in sophisticate interactions among multiple stakeholders. The third part of the dissertation investigates the impacts of flexible fuel vehicles (FFVs) market penetration levels on the market outcomes, including cellulosic biofuel production and price, blended fuel market price, and profitability of each stakeholder in the biofuel supply chain for imperfectly compet-

itive biofuel markets. In this paper, I investigate the penetration levels of FFVs by incorporating the substitution among different fuels in blended fuel demand functions through “cross price elasticity” in a bottom-up equilibrium model framework. The complementarity based problem is solved by a Taylor expansion-based iterative procedure. At each step of the iteration, the highly nonlinear complementarity problems with constant elasticity of demand functions are linearized into linear complimentarity problems and solved unitill it converges. This model can be applied to investigate the interaction between the stakeholders in the biofuel market, and to assist decision making for both cellulosic biofuel investors and government.

CHAPTER 1. INTRODUCTION

The concerns of national energy security and environmental impacts have brought increasing interests in biofuels in recent years. Biofuels are substitutes of fossil fuels. Biofuels include first generation biofuels made from sugar, starch, vegetable oil, etc., second generation biofuels made from non-food crops such as cornstover, switchgrass, forest, etc., and third generation biofuels mainly from extracting oil of algae.

Second generation biofuels are made from nonedible biomass, such as corn stover, switchgrass, wood chips, etc. Not competing with food supply and the potential to lower greenhouse gas emission are the two main advantages for second generation biofuels comparing to the first generation biofuels. Biochemical conversion and thermochemical conversion are the two main types of conversion platforms to produce second generation biofuels. Among the thermochemical pathways, fast pyrolysis and hydrothermal liquefaction conversions are identified as the most promising pathways to produce liquid fuels [53]. Techno-economic analyses of different pathways have been conducted to evaluate the economic feasibility of commercialization. Wright [102] presented the experiment and economic analysis of corn stover fast pyrolysis to produce naphtha and diesel range stock fuel. The report showed that the competitive product value for the biofuel is $3.09/gal, which is promising for the investors of cellulosic biofuel industry. Pacific Northwest National Laboratory (PNNL) [60] has conducted economic analysis for woody biomass to produce biogasoline and biodiesel, the minimum fuel selling price for gasoline is $2.04/gal. The economic analyses showed that it is now possible for the commercialization of the biofuel plant.

Various government policies have been proposed and implemented to stimulate national biofuel production and consumption. Renewable Fuel Standards (RFS) was proposed by US Environmental Protection Agency (EPA) in 2005. RFS requires that at least 7.5 billion gallons of renewable fuels be blended with conventional gasoline by the year 2012. To promote advanced biofuels, which are produced from nonedible renewable sources, the revised RFS (RFS2) in 2007 requires that at least 21 billion gallons of advanced biofuels being produced, and out of which at least 16 billions should be cellulosic biofuel by 2022 [79] (see Figure 1.1 for cellulosic biofuel volume mandate. The mandate for cellulosic biofuel increases dramatically from 0 to 16 billion gallons in 2022. The mandate for corn ethanol, on the other hand, keeps constant around 15 billion gallons to the year of 2022). Food, Conservation, Energy Act (FECA) of 2008 offers a $1.01/gal of subsidy for cellulosic biofuel produced and consumed in US. Up to $45 subsidy for each ton of biomass collected, harvested, processed and transported as cellulosic feedstock is provided by Biomass Crop Assistance Program (BCAP). Other policies, such as $0.45/gal of ethanol blending credit-Volumetric Ethanol Excise Tax Credit (VEETC), and $0.54/gal tariff levied against imported ethanol, have also been implemented [94, 26].

Different from the successful development of the corn ethanol, advanced biofuels are far from achieving the RFS2 target. In addition to the immaturity of production technology, the supply chain design, operational planning, market dynamics, and uncertain federal and local policies have been raised among the major obstacles in advanced biofuel production. This is the major motivation for this dissertation study.

There has been an emerging literature on biofuel supply chain. Typical models for biofuel supply chain design are facility location allocation models, in which decisions are made on the number of facilities to build, facility locations, facility capacities, and logistic flows, such as transportation quantities of biomass and biofuels are evaluated [90, 32, 33, 6, 12]. There are also studies considering biomass supply and biofuel demand, price uncertainty [24, 62, 4, 46]. Most of the optimization models make ideal assumptions that the farmers, producers and consumers are independent of each other and make rational decisions according to the optimization model. However, in reality, farmers could exchange information with each other, or sign contract with producers to reduce risk in production. In the recent years, the agent-based simulation models have been applied to biofuel supply chain to study the entire biofuel supply chain [61, 86]. Game theory and Monte Carlo methods have also been incorporated to better design the biofuel supply chain in a competitive and uncertain setting [7, 55]. However, operational decisions are often ignored in the decision making process, which might impact the cost analysis for the biofuel plant commercialization.

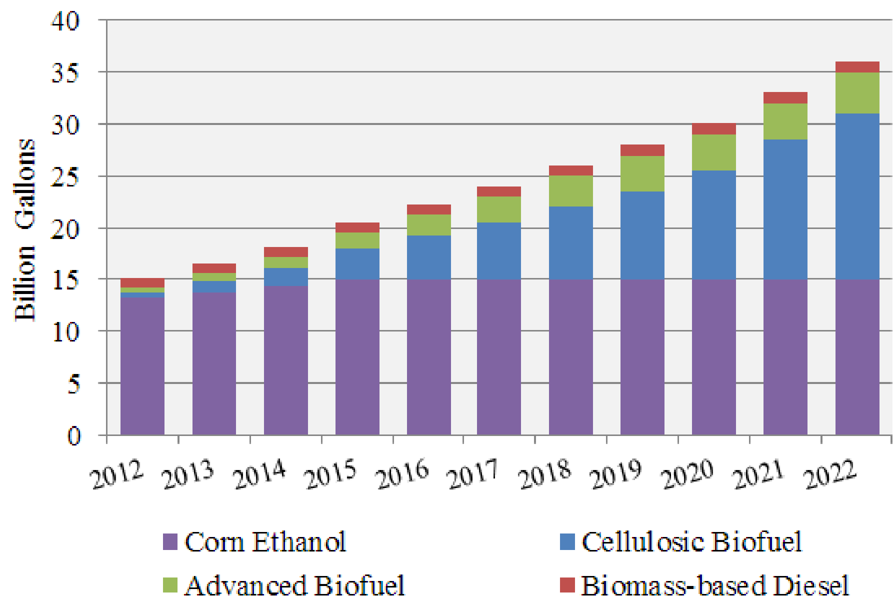

Figure 1.1 Revised Renewable Fuel Standards [79]

In the first part of the dissertation, we propose a biofuel supply chain model to study the supply chain design and operational planning for advanced biofuel production, then a biofuel market model is developed to study the interactions between farmers, biofuel producers, blenders, and consumers along the biofuel supply chain in the competitive market setting. To better reflect the actual situations, the biofuel market model is further expanded to consider the impacts of fuel substitution on biofuel markets for imperfectly competitive biofuel markets. For the biofuel supply chain model, the focused production pathway is corn stover fast pyrolysis with upgrading to hydrocarbon gasoline equivalent fuel. The mathematical model is formulated as a Mixed Integer Linear Programming (MILP) to investigate facility locations, facility capacities at the planning level, and feedstock flow and biofuel production decisions at the operational level. In the model, we investigated different biomass supply and biofuel demand scenarios considering supply shortage penalty and storage cost for excess biofuel production. Numerical results illustrate the importance of supply chain design and operational planning decision making for advanced biofuel production. Unit costs for advanced biofuel under a variety of scenarios are also analyzed. The case study demonstrates the economic feasibility of biofuel production at a commercial scale in Iowa.

Since advanced biofuel market is at its early stage, besides cost analysis of biofuel production and facility building, research studies have been conducted to analyze social welfare and policy impact on biofuel market [99, 67, 64, 10, 20, 66, 96]. Most of the models analyzed the social welfare using a single optimization model under the assumption that the market is perfectly competitive, while only a few models evaluated each entity's profit (e.g., farmers, biofuel producers, and biofuel blenders).

In the second part of the dissertation, complementarity-based models [1] are developed to study the interactions between the stakeholders in the biofuel supply chain. Profitability of each stakeholder has been analyzed under different market structures and various policy scenarios. The market structures of the model could significantly affect the interactions between the stakeholders in the markets, and therefore impact the market outcomes. Government policies could also affect the biofuel market outcomes by impacting each stakeholder's decision making. This model is capable for analysis of all above aspects for biofuel markets. For example, the model can be used to analyze the impact of biofuel policies on market outcomes, pass-through of taxes or subsidies, and consumers' surplus or producers' profit implications. The model can also serve as an analytical tool to derive market prices of biomass, advanced biofuel, and the value of the Renewable Identification Numbers (RINs). Moreover, the model can be used to analyze the impact of the market structure or firms' ownership setting that may arise due to oligopoly competition in the advanced biofuel market.

Flexible Fuel Vehicles (FFVs) are expected to play an critical role in improving the national energy independency and reducing greenhouse gas emission [43, 97]. FFVs run on gasoline-ethanol blend fuels with up to 85% of ethanol blended into gasoline (E85). With the advanced cellulosic ethanol technology and government policies promoting cellulosic ethanol production and consumption [79, 40, 85, 94], FFVs become economically acceptable by consumers. In the same time, infrastructure, including E85 stations, is gradually rolled out to serve increased demand [31, 30]. As a result, tools that allow for examining impacts of FFVs penetration on cellulosic biofuel markets becomes important to facilitate the development of biofuel market. The study of impacts of FFVs on cellulosic biofuel market outcomes and the interactions of the stakeholders in emerging biofuel supply chain is needed to

[1] complementarity-based models are mathematical models that include complementarity constraints $x \geq 0 \perp f(x) \geq 0$ where x is decision variable, $f(x)$ refers to constraint depends on x, and $x \geq 0 \perp f(x) \geq 0$ indicates $x^T f(x) = 0$.

assist new investors of the emerging biofuel industry for decision making. Some literature assumes the ethanol is perfect substitute for conventional gasoline [21]. It is, however, not true due to the limited penetration of flexible fuels [31, 30] in the transportation vehicle markets.

In the third part of this dissertation, we study the impacts of FFVs penetration on the emerging biofuel markets that biofuel blenders face. The interactions among the stakeholders and the implications on their profits are also analyzed in this chapter. The problem is modeled as bottom-up equilibrium models with constant elasticity of demand functions. Cross price elasticities in the constant elasticity of demand functions are used to represent the penetration levels of FFVs in the markets. The model is solved using a recursive Taylor expansion approach. I applied the methodology to a case study in California. The results indicate that with the increase of FFVs penetration levels in imperfectly competitive biofuel markets, blenders posses more market power to distort blended fuels sale and manipulate the markets. Therefore, it is important for the government to regulate the biofuel markets at the early stage and allow more competition in the markets.

The rest of the dissertation is organized as follows. In Chapter 2, a biofuel supply chain design and operational planning model is formulated to analyze the facility location and sizing, biomass and biofuel transportation. Operational planning for a biorefinery facility under a variety of biofuel demand scenarios is also presented. In Chapter 3, we present a bottom-up equilibrium model to investigate the emerging biofuel market. Impacts of market structure and government policy are investigated to promote the marginal insights for investors and regulatory agencies. In Chapter 4, constant elasticity of demand functions are included in the complementarity-based model to study the impacts of flexible fuel vehicle penetration level on the emerging biofuel markets to assist decision making for each entity in the biofuel supply chain. Chapter 5 concludes the dissertation with a summary of the research findings and proposed future research directions.

CHAPTER 2. SUPPLY CHAIN DESIGN AND OPERATIONAL PLANNING MODELS FOR BIOMASS TO DROP-IN FUEL PRODUCTION[1]

2.1 Introduction

Second generation biofuel is attracting increasing attention as a substitute for fossil oil from environmental, economic, and social perspectives. Second generation biofuels are made from nonfood crop or crop residues, such as corn stover, switchgrass, woody biomass, and miscanthus. Thus, the production of biofuel will not be in direct competition with food production. Biomass has different physical properties and component elements, therefore, various products yields can be seen with different thermochemical pathways [9, 14]. According to the revised Renewable Fuel Standard (RFS) proposed by US Environmental Protection Agency (EPA), at least 36 billion gallons of renewable fuels will be produced annually by 2022, and at least 16 billion gallons will be from cellulosic biofuels [83].

Drop-in biofuels are hydrocarbon fuels compared to gasoline and diesel, which can be transported through the existing petroleum pipeline and are ready for vehicles to use without any modification to engines. There are two main processing platforms: thermochemical and biochemical [103]. Thermochemical processes utilize heat to facilitate the depolymerization of biomass compounds which are further processed into biofuel and co-products [5, 39, 8, 15]. Biochemical processes involve living organisms to convert organic materials to fuels, chemicals, and other products. Thermochemical pathways are identified as promising pathways by the Department of Energy (DOE). This paper focuses on the thermochemical pathways. The biofuel products vary based upon the conversion configuration and reacting conditions.

The general framework for the biofuel supply chain is as follows. Biomass feedstocks are first collected and processed into bale (corn stover) or pellets (woody biomass) for easier storage and trans-

[1] **This part of the dissertation is published in Biomass and Bioenergy [107]**

portation [56]. For example, corn stover bales typically have a moisture mass fraction of 30%. The bales are stored on the farm before transported to preprocessing facilities. The physical and chemical properties, information related to corn stover harvesting, storage, and transportation are detailed in [87, 65]. In the preprocessing facility, corn stover is chopped into size (2.5-5.0) cm, then further dried to moisture level of around 7% and grind to (1-2) mm preferably [56]. Preprocessed biomass is then sent to biorefinery facilities to be converted into raw bio-oil and other byproducts. The raw bio-oil is then sent to upgrading facilities to be refined into drop-in biofuels [75, 25, 98]. The drop-in biofuels can be transported to Metropolis Statistics Areas (MSAs) for blending or end use.

Supply chain design and operational planning is among the biggest challenges to the cellulosic biofuel industry [90, 6, 24, 46]. Feedstock production and logistics constitute 35% or more of the total production costs of advanced biofuel [1, 73], and logistics costs can make up (50 to 75)% of the feedstock costs [49]. To facilitate the commercialization of biofuel production, it is important to investigate the optimal number and locations for biorefinery facilities, and to find the optimal allocation of feedstock and biofuel. There has been an emerging literature in the biofuel supply chain design [90, 33, 102, 12, 50, 6].

Operational planning is also essential for biofuel supply chain and network design. A stochastic multi-period model is proposed in [46] for hydrocarbon biofuel production from cellulosic biomass, and results for the optimal design of the hydrocarbon biorefinery supply chain are presented under biomass supply and biofuel demand uncertainties. Dal-Mas et al. [24] presented a dynamic multi-echelon Mixed Integer Linear Program (MILP) to assess the economic performance and risk on investment of the biomass-based ethanol plant. Zhu et al. [105] presented a multi-period MILP model to show the feasibility of commercially producing biofuel from switchgrass. Another model also presented by Zhu et al. [109] showed seasonal results for second generation biofuel from a mixture of biomass, and analyzed the effects of biomass yields on biofuel production planning and profit change. In this study, motivated by the real world scenarios, we accommodate the flexibility of fuel demand satisfaction by allowing the shortage of biofuel, which will incur a subjective penalty cost. This is similar to the concept of biofuel importation in [24].

In addition, this study considers the impact of operational constraints by incorporating the temporal inventory metrics. A multi-period optimization model is also formulated to study the detailed operational planning for biomass collection and drop-in fuel production and distribution. Sensitivity of different biofuel demand patterns is also analyzed.

The rest of the paper is organized as follows. In Section 2.2, model assumptions and formulation for both annual and operational planning model are presented. In Section 2.3, we demonstrate a case study in the state of Iowa and numerical results are presented in the same section. Results are summarized in Section 3.5 along with a discussion of future research directions.

2.2 Model formulation

This study aims to minimize total biofuel production cost using a Mixed Integer Linear Programming model (MILP). In addition to optimizing the number of biorefinery facilities and locations [102], the proposed model aims to optimize the number of biorefinery facilities, facility capacities, locations, biomass and biofuel allocations considering a variety of biofuel demand scenarios.

As illustrated in Figure 2.1, biomass is collected and pretreated at farms into small particles ready for biofuel conversion. Pretreated biomass is transported to biorefinery facilities to go through conversion and upgrading processes to produce advanced biofuel. In this study, it is assumed that biofuel conversion and upgrading are conducted in the same facility, and then transported to the biofuel demand locations, which are Metropolitan Statistical Areas (MSA).

In the following sections, we present an annual based optimization model in Section 2.2.2 to study the strategic decisions for biofuel supply chain. Analogous to the annual based model, an more detailed operational planning model is presented in Section 2.2.3 to to shed a light on managing the production, allocation and inventory of the biofuel.

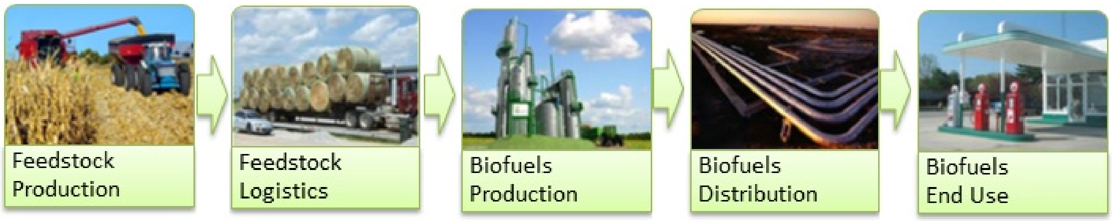

Figure 2.1 Biomass supply chain framework for biofuel production and distribution

2.2.1 Notations and terminologies

Sets

I	i, j	Set for biomass supply farms (i) and for biorefinery locations (j)
K	k	Set for MSAs (biofuel demand locations)
L	l	Set for biorefinery capacity levels
T	t	Set of all time periods within a year

Feedstock parameters

N		Number of counties producing feedstock
A_i	ton	Available feedstock at county i in one year
A_{it}	ton	Available feedstock at county i in month t
h_i^S	\$/ton	Unit feedstock holding cost at county i per month
U_i^S	ton	Maximum storage capacity for county i
D_{ij}	mile	Great circle distance from county i to county j
S_i		Sustainability factor for county i
ℓ_1		Material loss factor for feedstock over each year
ℓ_2		Material loss factor for feedstock over each month
τ		Tortuosity factor
$C_i^{S,CL}$	\$/ton	Feedstock collecting and loading cost at county i
$C_{ij}^{S,T}$	\$/ton/mile	Feedstock transportation cost from county i to county j

Biorefinery parameters

$\underline{U}_{lt}^{B}$	ton	Minimum biomass processing quantity in month t for capacity level l
$\overline{U}_{lt}^{B}$	ton	Maximum biomass processing quantity in month t for capacity level l
$h_j^{B,B}$	\$/ton	Biomass unit holding cost at biorefinery facility j per month
$h_j^{B,G}$	\$/gal	Biofuel unit holding cost at biorefinery facility j per month
$U_j^{B,B}$	ton	Maximum biomass storage level at biorefinery facility j
$U_j^{B,G}$	gal	Maximum biofuel storage level at biorefinery facility j
U_l^B	ton	Fixed biorefinery capacity for capacity level l in one year
C_l^B	\$	Fixed biorefinery cost for capacity level l
Y_j		Biomass to biofuel conversion rate at biorefinery facility j
$C_j^{G,C}$	\$/gal	Biofuel unit conversion cost at biorefinery facility j
γ	ton/gal	Unit conversion coefficient of gallon to ton
Q	\$	Budget for the biorefinery facilities
H	year	Long term planning horizon
r		Annual interest for investment

MSA and biofuel demand parameters

M		Number of MSAs
G_k	gal	Total biofuel demand for MSA k
G_{kt}	gal	Total biofuel demand for MSA k in month t
$C_{jk}^{G,T}$	\$/ton/mile	Biofuel transportation cost from facility location j to MSA k
h_k^M	\$/gal	Unit holding cost for biofuel at MSA k per month
U_k^M	gal	Biofuel inventory level at MSA k

Continuous variables

f_{ij}	ton	Biomass feedstock flow from county i to county j
f_{ijt}	ton	Biomass feedstock flow from county i to county j in month t
q_{jk}	gal	Biofuel flow from county j to MSA k
q_{jkt}	gal	Biofuel flow from county j to MSA k in month t
v_{it}	ton	Feedstock harvest quantity in county i at time t
q^B_{jt}	ton	Biomass process quantity in biorefinery j at time t
I^S_{it}	ton	Inventory level of feedstock in county i at time t
$I^{B,B}_{jt}$	ton	Inventory level of feedstock in biorefinery facility j at time t
$I^{B,G}_{jt}$	gal	Inventory level of biofuel in biorefinery facility j at time t
I^M_{kt}	gal	Inventory level of biofuel in MSA k at time t

Binary variables

δ_{jl}		Binary variable for biorefinery facility of level l built in county j.

2.2.2 Annually based model formulation

The annual based model aims to determine the number of facilities, facility sizes, and facility locations for the biofuel supply chain for a long term planning horizon. In this model, we assume that biorefinery facilities will run according to optimal allocation of general biomass and biofuels, constrained by the capacity of storage and refinery facilities, but flexible for storage and production levels. The objective is to minimize total annual cost including biomass transportation, biofuel conversion, biofuel transportation, facility cost, and biofuel shortage penalty. The level of biofuel demand fulfillment also depends on the market price of biofuel, which will be discussed in the case study. The schematic of this model is illustrated in Figure 2.2.

The general annual based model formulation is shown in Equations (2.1a)-(2.1i).

Figure 2.2 Biofuel supply chain framework

$$
\begin{aligned}
\min \quad & \textstyle\sum_{i=1}^{N}\sum_{j=1}^{N}(C_i^{S,CL}+\tau D_{ij}C_{ij}^{S,T})f_{ij}+\sum_{j=1}^{N}\sum_{k=1}^{M}(C_j^{G,C}+\tau\gamma D_{jk}C_{jk}^{G,T})q_{jk} \\
& +\textstyle\sum_{k=1}^{M}\lambda_k(G_k-\sum_{j=1}^{N}q_{jk})_+ +\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C_l^B\delta_{jl}}{\frac{(1+r)^H-1}{r(1+r)^H}} && \text{(2.1a)}\\
s.t. \quad & \textstyle\sum_{j=1}^{N} f_{ij}\le(1-S_i)A_i, \forall i\in I && \text{(2.1b)}\\
& (1-\ell_1)\textstyle\sum_{i=1}^{N} f_{ij}\le\sum_{l=1}^{L}U_l^B\delta_{jl}, \forall j\in I && \text{(2.1c)}\\
& (1-\ell_1)\textstyle\sum_{i=1}^{N} f_{ij}Y_j=\gamma\sum_{k=1}^{M}q_{jk}, \forall j\in I && \text{(2.1d)}\\
& \textstyle\sum_{l=1}^{L}\delta_{jl}\le 1, \forall j\in I && \text{(2.1e)}\\
& \textstyle\sum_{j=1}^{N}\sum_{l=1}^{L}C_l^B\delta_{jl}\le Q && \text{(2.1f)}\\
& f_{ij}\ge 0, \forall i,j\in I && \text{(2.1g)}\\
& q_{jk}\ge 0, \forall j\in I, k\in K && \text{(2.1h)}\\
& \delta_{jl}\in\{0,1\}. && \text{(2.1i)}
\end{aligned}
$$

The objective function (2.1a) is to minimize total system costs including biomass collecting and loading cost $\sum_{i=1}^{N}\sum_{j=1}^{N}C_i^{S,CL}f_{ij}$, biomass transportation cost $\sum_{i=1}^{N}\sum_{j=1}^{N}\tau D_{ij}C_{ij}^{S,T}f_{ij}$, biofuel conversion cost $\sum_{j=1}^{N}\sum_{k=1}^{M}C_j^{G,C}q_{jk}$, biofuel transportation cost $\sum_{j=1}^{N}\sum_{k=1}^{M}\tau\gamma D_{jk}C_{jk}^{G,T}q_{jk}$, penalty cost for biofuel demand shortage $\sum_{k=1}^{M}\lambda_k(G_k-\sum_{j=1}^{N}q_{jk})_+$, and aggregated biorefinery facility building cost $\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C_l^B\delta_{jl}}{\frac{(1+r)^H-1}{r(1+r)^H}}$. In the penalty cost for biofuel demand shortage, $(\cdot)_+=\max\{\cdot,0\}$. The term λ_k is the penalty for biofuel demand shortage. It is assumed to be the conventional fuel market price, which means if the fuel demand is not satisfied by the biofuel producers, it will be fulfilled with the petroleum based fuel.

Constraint (2.1b) denotes that for each county i, the shipped-out feedstock $\sum_{j=1}^{N} f_{ij}$ should be no more than available feedstock. Constraint (2.1c) means that if biorefinery facility j operates ($\sum_{l=1}^{L} \delta_{jl} = 1$), then feedstock shipped to j should be no more than the capacity. Constraint (2.1d) indicates the mass balance of biomass and biofuel for each biorefinery facility j. Biofuel produced $(1-\ell_1)\sum_{i=1}^{N} f_{ij}Y_j$ should be equal to biofuel shipping quantity $\gamma\sum_{k=1}^{M} q_{jk}$. Constraint (2.1e) sets that facilities can only built at one levee capacity level. Constraint (2.1f) included the budget limit for the total investment.

This optimization model includes a nonlinear objective function and linear constraints. Here we propose to linearize the model formulation by adding ancillary continuous variables y_k:

$$\min \quad \sum_{i=1}^{N}\sum_{j=1}^{N}(C_i^{S,CL}+\tau D_{ij}C_{ij}^{S,T})f_{ij}+\sum_{j=1}^{N}\sum_{k=1}^{M}(C_j^{G,C}+\tau\gamma D_{jk}C_{jk}^{G,T})q_{jk}$$

$$+\sum_{k=1}^{M}\lambda_k y_k+\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C_l^B\delta_{jl}}{\frac{(1+r)^H-1}{r(1+r)^H}} \tag{2.2a}$$

$$s.t. \quad \text{Constraints (2.1b)-(2.1f)} \tag{2.2b}$$

$$y_k \geq G_k - \sum_{j=1}^{N} q_{jk}, \forall k \in K \tag{2.2c}$$

$$\text{Constraints (2.1g)-(2.1i)} \tag{2.2d}$$

$$y_k \geq 0. \tag{2.2e}$$

The total annual cost divided by the annual biofuel production would be the average unit cost for biofuel.

2.2.3 Model formulation with operational planning

With the annual based optimization model, the optimal biorefinery location, and biomass and biofuel distribution can be analyzed. In addition to the strategic decision making, the operational planning is also essential for the commercialization of advanced biofuel production. In this section, we present a multi-period MILP model for biomass-based biofuel supply chain. In addition to the strategic decision variables, operational planning design, such as monthly biorefinery production level, biomass and biofuel inventory control and allocation. It should be noted that the multi-period model will increase the computational effort due to the increase in problem size. The modeling schematic is shown in Figure 2.3.

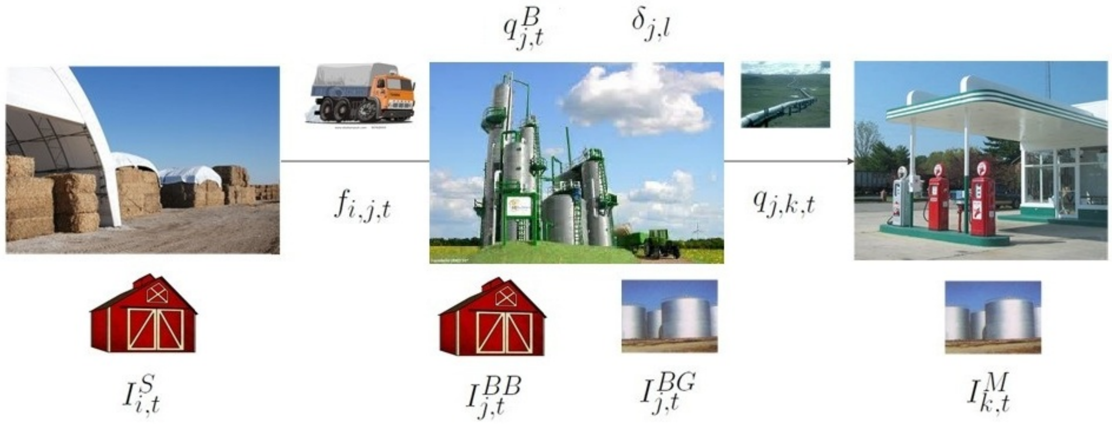

Figure 2.3 Multi-period model framework of biofuel production and distribution

$$\min \quad \sum_{t=1}^{T}\{\sum_{i=1}^{N}\sum_{j=1}^{N}\tau D_{ij}C_{ij}^{S,T}f_{ijt}+\sum_{j=1}^{N}\sum_{k=1}^{M}\tau\gamma D_{jk}C_{jk}^{G,T}q_{jkt}$$

$$+\sum_{i=1}^{N}C^{S,CL}v_{it}+\sum_{j=1}^{N}\frac{1}{\gamma}C_{j}^{G,C}q_{jt}^{B}+\sum_{k=1}^{M}\lambda_{kt}(G_{kt}-\sum_{j=1}^{N}q_{jkt})_{+}$$

$$+\sum_{i=1}^{N}h_{i}^{S}I_{it}^{S}+\sum_{j=1}^{N}h_{j}^{B,B}I_{jt}^{B,B}+\sum_{j=1}^{N}h_{j}^{B,G}I_{jt}^{B,G}+\sum_{k=1}^{M}h_{k}^{M}I_{kt}^{M}\}$$

$$+\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C_{l}^{B}\delta_{jl}}{\frac{(1+r)^{H}-1}{r(1+r)^{H}}} \tag{2.3a}$$

$$v_{it}\leq(1-S_{i})A_{it},\forall i\in I,t\in T \tag{2.3b}$$

$$\delta_{jl}\underline{U}_{lt}^{B}\leq q_{jt}^{B}\leq\delta_{jl}\overline{U}_{lt}^{B},\forall j\in I,t\in T,l\in L \tag{2.3c}$$

$$I_{it}^{S}=(1-\ell_{2})I_{i,t-1}^{S}+v_{it}-\sum_{j=1}^{N}f_{ijt},\forall i\in I,t\in T \tag{2.3d}$$

$$I_{jt}^{B}=(1-\ell_{2})I_{j,t-1}^{B}+\sum_{i=1}^{N}f_{ijt}-r_{jt},\forall j\in I,t\in T \tag{2.3e}$$

$$I_{jt}^{G}=I_{j,t-1}^{G}+\frac{1}{\gamma}q_{jt}^{B}Y_{j}-\sum_{k=1}^{M}q_{jkt},\forall j\in I,t\in T \tag{2.3f}$$

$$I_{kt}^{M}\geq I_{k,t-1}^{M}+\sum_{j=1}^{N}q_{jkt}-G_{kt},\forall k\in K,t\in T \tag{2.3g}$$

$$\text{Constraints (2.1e),(2.1f).} \tag{2.3h}$$

$$0\leq I_{it}^{S}\leq U_{i}^{S},\forall i\in I,t\in T \tag{2.3i}$$

$$0\leq I_{jt}^{B}\leq U_{j}^{B,B},\forall j\in I,t\in T \tag{2.3j}$$

$$0\leq I_{jt}^{G}\leq U_{j}^{B,G},\forall j\in I,t\in T \tag{2.3k}$$

$$0\leq I_{kt}^{M}\leq U_{k}^{M},\forall k\in K,t\in T \tag{2.3l}$$

$$I_{i,0}^{S}=I_{j,0}^{B,B}=I_{j,0}^{B,G}=I_{k,0}^{M}=0,\forall i,j\in I,k\in K \tag{2.3m}$$

$$f_{ijt}\geq 0,\forall i,j\in I,t\in T \tag{2.3n}$$

$$q_{jkt}\geq 0,\forall j\in I,k\in M,t\in T \tag{2.3o}$$

$$v_{it}\geq 0,\forall i\in I,t\in T \tag{2.3p}$$

$$q_{jt}^{B}\geq 0,\forall j\in I,t\in T \tag{2.3q}$$

$$\delta_{jl}\in\{0,1\},\forall j\in I,l\in L \tag{2.3r}$$

The objective function (2.3a) is to minimize total system costs over all time periods, including biomass transportation cost $\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j=1}^{N}\tau D_{ij}C_{ij}^{S,T}f_{ijt}$, biofuel transportation cost $\sum_{t=1}^{T}\sum_{j=1}^{N}\sum_{k=1}^{M}\tau\gamma D_{jk}C_{jk}^{G,T}q_{jkt}$, biomass collecting and loading cost $\sum_{t=1}^{T}\sum_{i=1}^{N} C^{S,CL} v_{it}$, biofuel transportation cost $\sum_{t=1}^{T}\sum_{j=1}^{N} \frac{1}{\gamma} C_j^{G,C} q_{jt}^{B}$, penalty cost for biofuel demand shortage $\sum_{t=1}^{T}\sum_{k=1}^{M} \lambda_{kt}(G_{kt} - \sum_{j=1}^{N} q_{jkt})_{+}$, and fixed biorefinery facility cost $\sum_{j=1}^{N}\sum_{l=1}^{L} \frac{C_l^B \delta_{jl}}{\frac{(1+r)^H - 1}{r(1+r)^H}}$. Inventory costs for biomass and biofuel over the time periods are also included in the objective function. The inventory costs include biomass inventory cost $\sum_{t=1}^{T}\sum_{i=1}^{N} h_i^S I_{it}^S$ at farm i, biomass inventory cost $\sum_{t=1}^{T}\sum_{j=1}^{N} h_j^{B,B} I_{jt}^{B,B}$ at biorefinery facility j, biofuel inventory cost $\sum_{t=1}^{T}\sum_{j=1}^{N} h_j^{B,G} I_{jt}^{B,G}$ at biorefinery facility j, biofuel inventory cost $\sum_{t=1}^{T}\sum_{k=1}^{M} h_k^M I_{kt}^M$ at MSA k. Constraint (2.3b) shows that for each month, biomass harvest cannot exceed available biomass. Constraint (2.3c) indicates that biorefinery facilities only operate when production reaches a certain level. In this study, both upper and lower bounds for production levels are set for the refinery facilities to operate. Constraints (2.3d)-(2.3g) are biomass and biofuel storage balance constraints for facility j at period t. Decision variables in this model include equation (2.3i)-(2.3r).

2.3 Case study

Iowa has been recognized as one of the leading states for biofuel production [93]. Currently, there are several commercial size biorefinery plants under construction in Iowa. In the computation analysis section, we present a case study in the state of Iowa. Results of both the annual based model and the multi-period operational planning model are presented. Parameters and data sources are listed in Table 2.1.

Corn stover, as the main cellulosic biomass supply in the Midwest, is under consideration in this paper. Corn stover refers to the stalks, leaves, cob, and husk of the maize plants which is harvested together with corn. The moisture content of corn stover is assumed to be 30% in mass, and the ratio of corn stover to corn is assumed to be 1:1 [87] based on the land sustainability and erosion control metrics. The production pathway analyzed in this paper is fast pyrolysis of corn stover with upgrading to drop-in biofuels [60]. The drop-in fuels could be mixture of a range of biofuels including gasoline and diesel range fuel. The percentage varies based on the configuration and conditions [102, 60]. Without loss of generality, for the supply chain design model, we assume gasoline to be the main product under consideration. It should be noted that the supply chain design and operational planning model formulated in this study can also be utilized to analyze a variety of pathways. The pathways is chosen based on data availability. Corn stover will be transported through truck or train based on the vehicle and infrastructure availability. In this study, we assume truck is the only transportation mode for corn stover. Biogasoline is assumed to be the only transportation fuel in this case study. (In real world scenario, multiple products can be produced through corn stover fast pyrolysis. Since bio-gasoline is the major product we are considering here. The profit for other byproducts can be treated to offset the production cost.) Bio-gasoline is assumed to be transported through existing petroleum pipelines. An ideal assumption to assume that pipelines are accessible anywhere within Iowa. In real world problem, it has to be sent to intermediate hubs to be access to the pipelines. Therefore, one more layer of stakeholders will be added to the biofuel supply chain. In this paper, the authors decide to simplify this without comprimising the quality of the solution. Since the simplification is applied to all the biorefinery facilities in the supply chain. Biofuel demand is based on the population in the MSA areas as shown in Figure 2.4 [58].

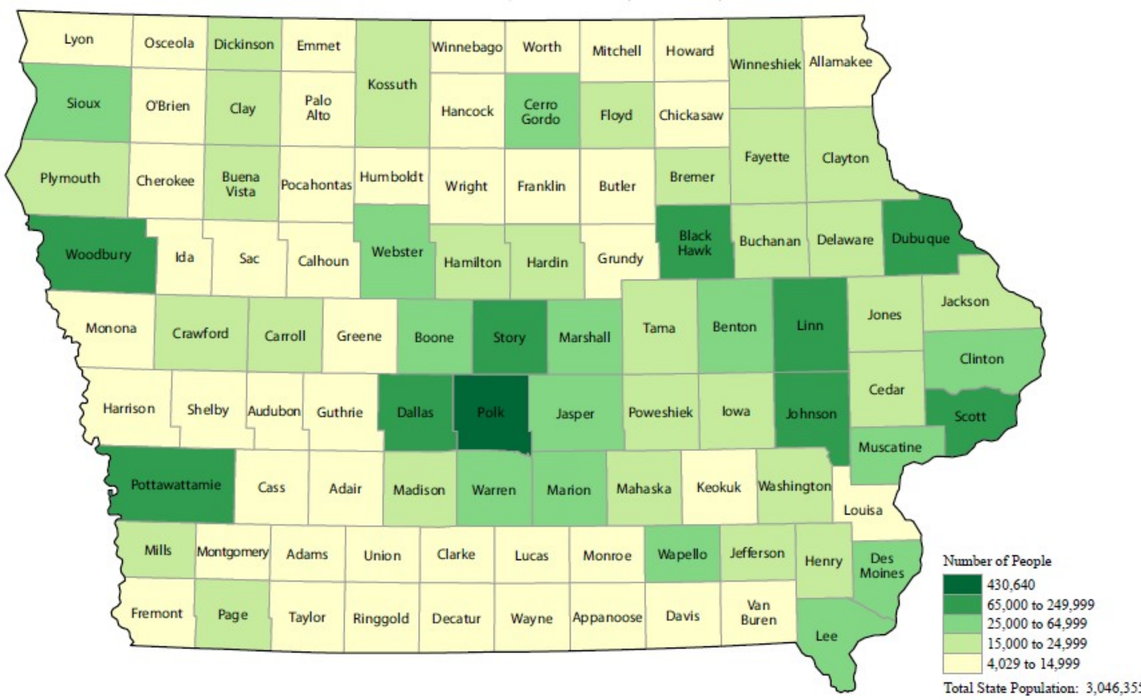

Figure 2.4 Iowa population estimation for 2010 [58]

In the following sections, an example for the state of Iowa (which has 99 counties and 21 MSAs) is presented. The computational results are obtained with CPLEX and ARCGIS.

Table 2.1 Data sources for biofuel supply chain and operational planning models

Parameters	Data	Notes	References
Feedstock parameters			
N	99	Number of counties in Iowa	
A_i		Available feedstock in one year	[3]
S_i	0.718	Sustainability factor	[87]
$C_i^{S,CL}$	\$(24 to 45)/ton	Feedstock collecting and loading cost	[47, 71]
h_i^S	10% of product value	Unit feedstock holding cost	Assumed
U_i^S	1 million ton	Maximum storage capacity	Assumed
ℓ_1	5%	Material loss factor for feedstock	Assumed
D_{ij}		Great circle distance	
τ	1.27	Tortuosity factor	[81]
$C_{ij}^{S,T}$	\$0.19/ton/mile	Unit feedstock transportation cost	[84]
Biorefinery parameters			
γ	$\frac{2.72}{1000}$ton/gal	Unit conversion coefficient of biogasoline from liter to tonne	
U_l^B	400, 1000, 1500, 2000 ton/day	Fixed biorefinery capacity in one year	[101]
C_l^B		Fixed biorefinery cost	[101]
Y_j	0.2180	Biorefinery fuel process yield of feedstock	Assumed
$C_j^{G,C}$	\$2.04/gal	Unit conversion cost of biofuel	[60]
H	30 years	Long term planning horizon in years	Assumed
r	10%	Annual interest for investment	Assumed
$h_j^{B,B}$	20% of product value	Biomass holding cost at biorefinery facility	Assumed
$h_j^{B,G}$	20% of product value	Biofuel holding cost at biorefinery facility	Assumed
$\overline{U}_{lt}^B$		Fixed biorefinery capacity in each time period	
$\underline{U}_{lt}^B$	60% of $\overline{U}_{lt}^B$	Minimum processing quantity per month	
$U_j^{B,B}$	720 thousand ton	Biomass storage capacity at biorefinery facility	Assumed
$U_j^{B,G}$	100 million gal	Biofuel storage capacity at biorefinery facility	Assumed
MSA and biofuel demand parameters			
M	21	Number of MSAs considered	[34]
G_k		Biofuel demand	[34]
G_{kt}		Biofuel demand for month t	
$C_{jk}^{G,T}$	\$0.0176/ton/mile	Biofuel transportation cost per unit	[80]
h_k^M	30% of product value	Unit holding cost for biofuel	Assumed
U_k^M	50 million gal	Biofuel storage level	Assumed

2.3.1 Annual model results and analysis

The annual model has around 12 000 continuous variables, 400 binary variable, and 400 constraints. This problem can be solved within a few seconds.

In this scenario, gasoline shortage penalty λ is set at \$4/gal, the average market price of gasoline. This means that we need to purchase gasoline at \$4/gal at market to fulfill biofuel demand in all MSAs if there is any gasoline shortage.

- If there is no budget limit for biorefinery facility investment, the optimal number of facilities is 23. All gasoline demands are satisfied with the average unit cost for producing gasoline to be \$2.78/gal. The biomass and biofuel allocation as shown in Figure 2.5. The cost components are shown in Figure 2.7.

  From the Figure 2.5, we see that there are 4 biorefinery facilities built in the same location with MSAs, and they are all running 2 000 ton/day. Among all 23 facilities built 10 are running 1 500 ton/day and 13 are running 2 000 ton/day. This allocation of facilities is optimal in minimizing biomass and biofuel transportation distance. Gasoline demand in all MSAs is satisfied.

- If the budget is limited, then the minimum budget to satisfy all gasoline demand is \$ 4 200 million. The optimal number of facilities we is 21. The average unit cost of gasoline is \$2.79/gal. Biomass and biofuel allocations are shown in Figure 2.6. Cost allocation is shown in Figure 2.7.

  If only 21 biorefinery facilities are built, only two facilities will run 1 500 ton/day, and all the others will run 2 000 ton/day. In this scenario, all gasoline demand can still be satisfied. From Figure 2.7, it is observed that gasoline conversion cost, biomass collection cost, and facility building cost are three major cost components for gasoline production. The increase in the unit production cost is mainly due to feedstock transportation.

- If the budget is further reduced thus not enough facilities built to satisfy all demand, then either nearby MSAs or MSAs with higher biofuel shortage penalty λ will receive higher priority to consume the biofuel. For example, if there is only enough budget to build one facility, and penalties for all MSAs are the same, then the optimal location to build this facility is Webster County (see Figure 2.8) which would supply biofuel to three nearby MSAs. If priority is provided to MSA Burlington (the biofuel shortage penalty in Burlington as λ =10 and

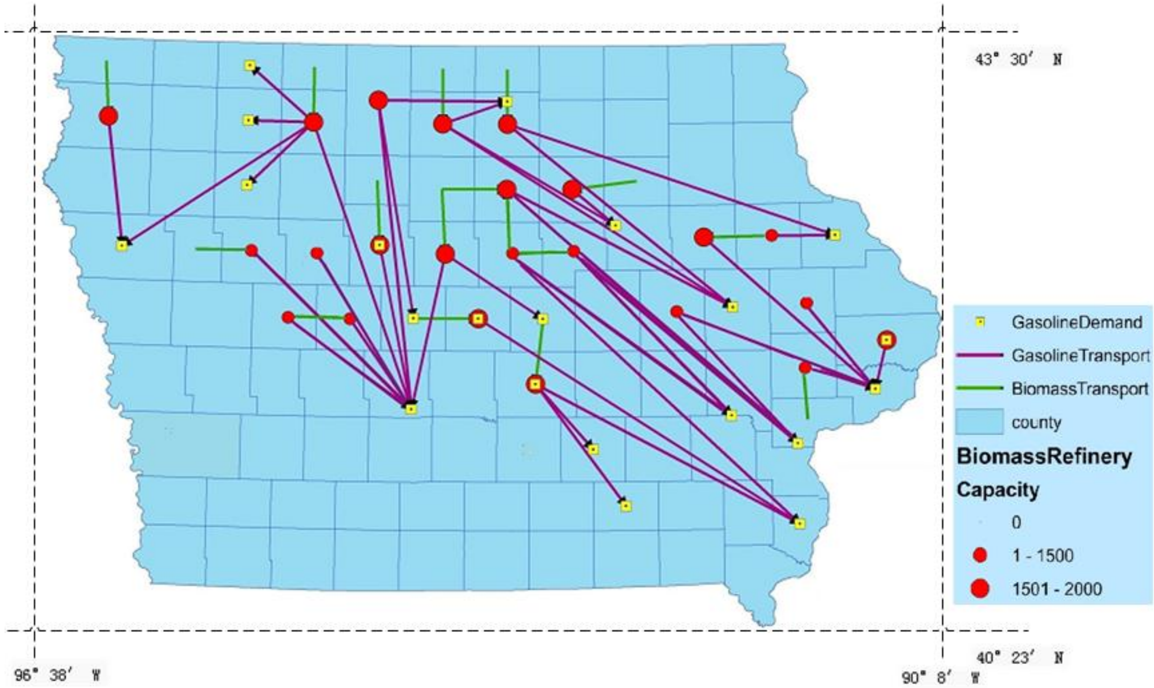

Figure 2.5 Annual model result with no capital budget limit

other MSAs as λ =4), then the optimal location to build a facility is Franklin County (see Figure 2.9), and we can see that gasoline demand in Burlington can still be satisfied even though transportation distance is longer.

2.3.2 Monthly model results and analysis

To better present the detailed allocation, feedstock, and biofuel storage over multiple operational periods, a multi-period model is analyzed and the optimal number of facilities, facility locations, biomass and biofuel allocation, storage levels at each storage facility, and unit production costs for biofuel are investigated.

In this example, we consider scenarios for which there is no budget limit, since cases with a budget limit will get similar results with more facilities built at 2 000 ton/day. For different demand patterns over twelve months, different biorefinery facility numbers, sizes and production level results are shown. The operational planning problem includes around 145 000 continuous variables, 400 binary variables, and 219 000 constraints. The solving time varies for different demand patterns and the average solving time is 30 minutes.

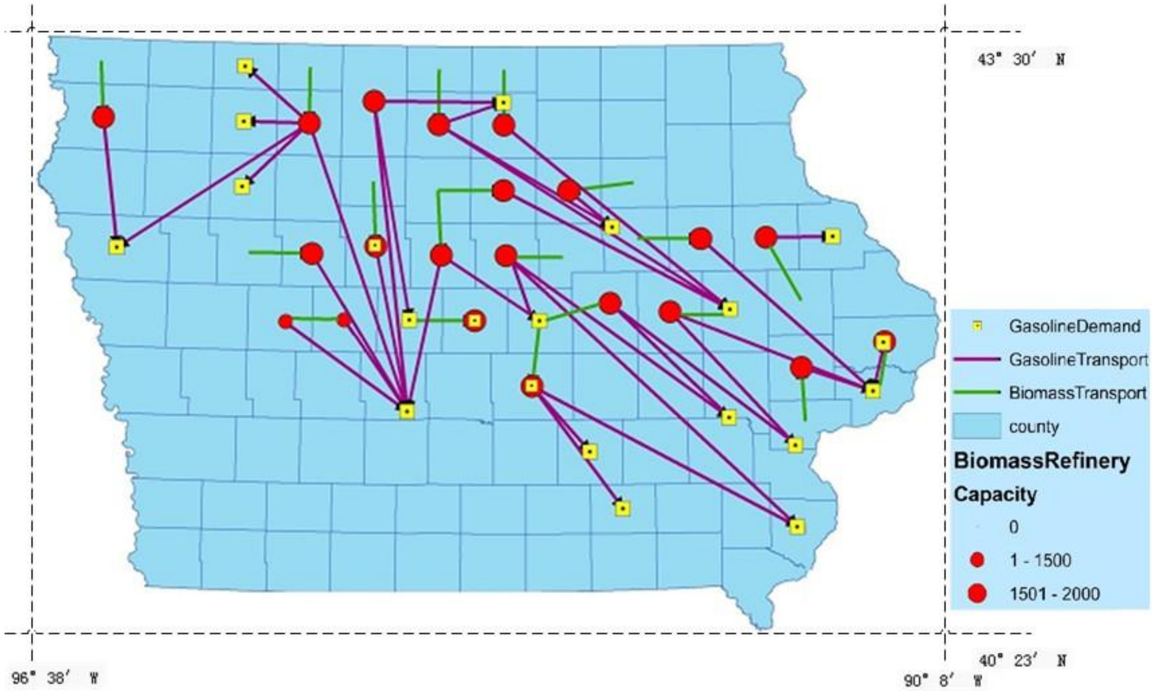

Figure 2.6 Annual model result with capital budget limit

- If the biofuel demand pattern is uniform, then optimal allocation is shown in Figure 2.10, with the optimal number of facilities being 23, including 10 facilities built for 1 500 ton/day. The average unit cost of gasoline is $2.76/gal, and biofuel demands in all MSAs are satisfied. The cost components are presented in Figure 2.12. We see that biofuel conversion cost, fixed facility building cost, and biomass harvesting cost are three major costs in the supply chain of biofuel production. There is no storage cost in this case. Biofuel production distribution over all months is also uniform.

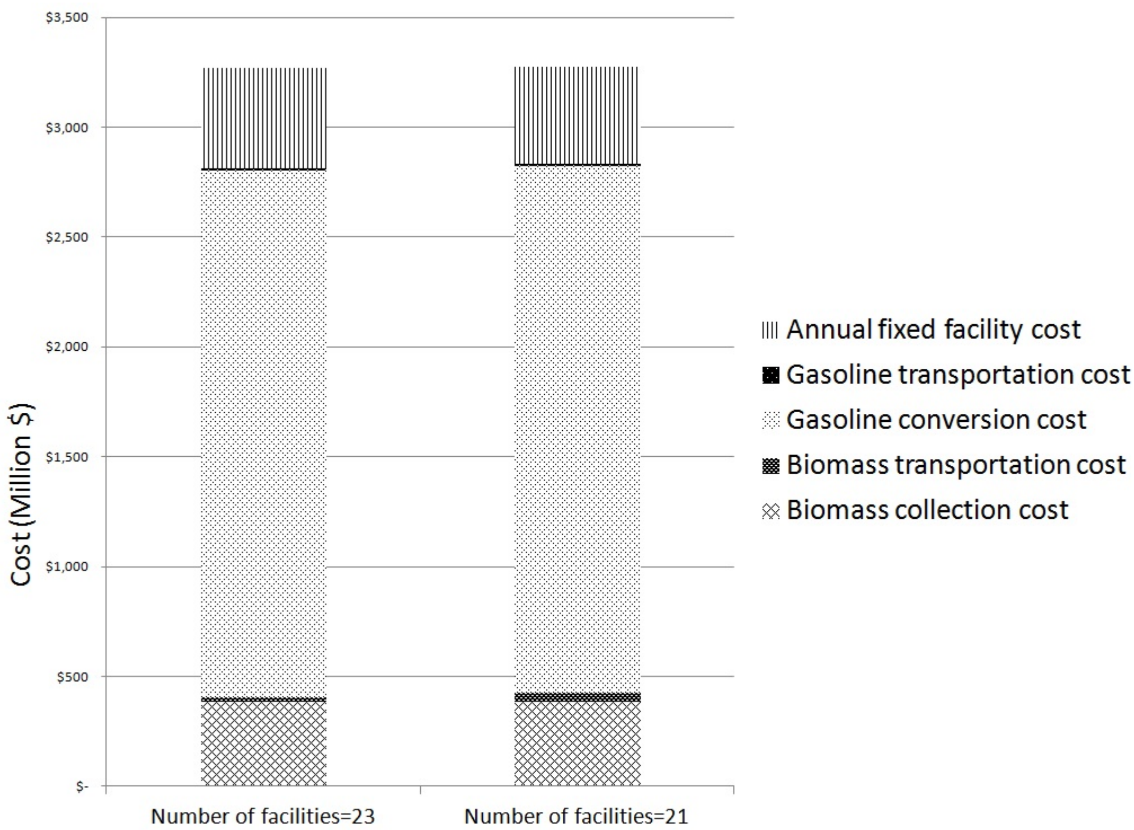

Figure 2.7 Comparison of total annual biogasoline production costs

- For the increasing biofuel demand pattern in Figure 2.11, the optimal number of facilities is 24, with 2 facilities built at 1 500 ton/day and all others built at 2 000 ton/day. The average unit cost of gasoline is $2.98/gal, and all biofuel demands are satisfied. The cost components are shown in Figure 2.12. Biofuel production in all biorefinery facilities follows an nondecreasing distribution, and facilities produce extra biofuel in previous months to satisfy higher biofuel demand in later months.

- For the decreasing pattern in Figure 2.11, if the biofuel shortage penalty is $4/gal, then the optimal number of facilities built is 20, with all 20 facilities built at the 2 000 ton/day level. The average unit cost of gasoline is $3.32/gal including biofuel shortage cost, and $3.10/gal without considering a biofuel shortage cost. In this case, not all biofuel demands are satisfied, and 10 of 21 MSAs' biofuel demands are not satisfied in the first month. Biofuel production in each month follows a non-increasing distribution. Cost components in

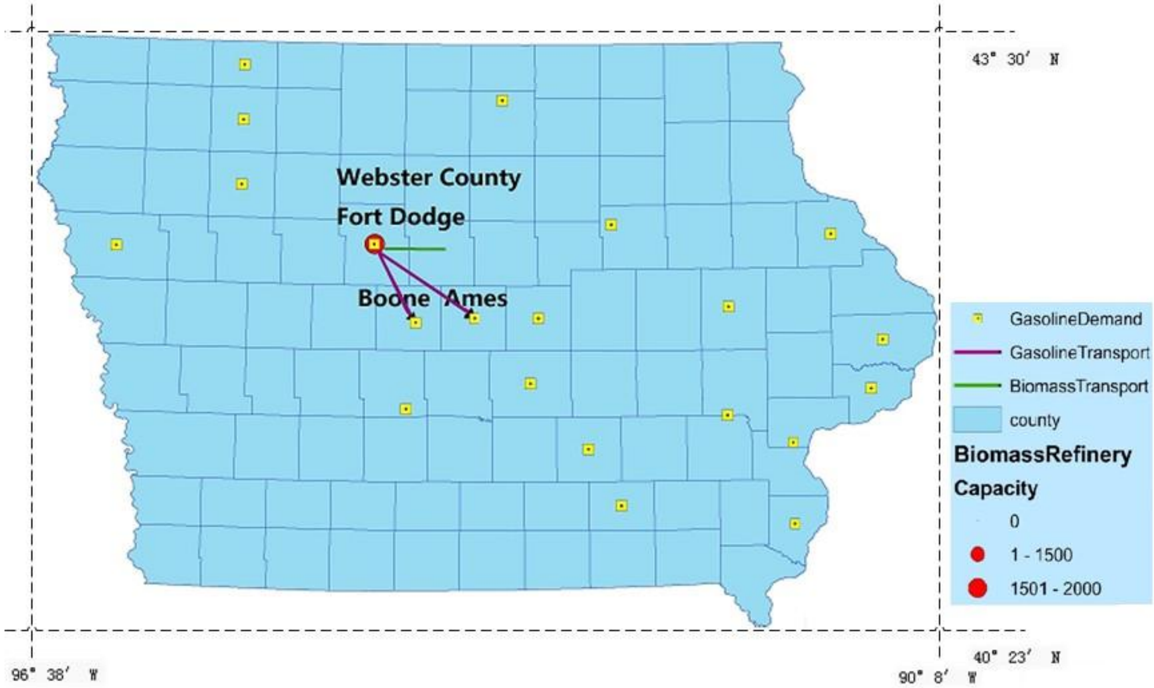

Figure 2.8 Biomass and biofuel distribution under same biofuel shortage penalty

this scenario are seen in Figure 2.12. In this scenario, the biofuel shortage cost is an additional significant component for total cost.

- For the triangle demand pattern illustrated in Figure 2.11, the optimal number of facilities is 21, with 2 facilities built at 1 500 ton/day and all others built at 2 000 ton/day. 8 out of 21 MSAs' biofuel demands are not satisfied. The average unit cost of gasoline is \$2.90/gal including biofuel shortage cost, and \$2.80/gal without biofuel shortage cost. Biofuel demands in eight counties are not satisfied during February and March. The cost components are shown in Figure 2.12. Biofuel production in all biorefinery facilities follows a non-increasing distribution, and facilities produce extra biofuel in the first two months to satisfy higher biofuel demand in February and March.

Figure 2.9 Biomass and biofuel distribution under biofuel shortage penalty with priority for Burlington

2.4 Conclusion

Technology innovation and improvement in advanced biofuel production has made it possible for commercial production of the second generation biofuel. Supply chain design and operational planning represents one of the major challenges to cellulosic biofuel commercialization. The strategic and operational planning decisions for the biorefinery facilities are essential for the successful deployment of the advanced biofuel industry due to the special properties of biomass handling, transportation, biofuel conversion, distribution and consumption. Quantitative models are necessary to assist the decision making for investors, facility manager as well as government agencies to understand the impact of biofuel supply chain design and operational planning.

In this paper, we formulated two models to optimize the number, capacities and locations of biorefinery facilities. Biomass feedstock collection, transportation and biofuel distribution decisions are also investigated. The first model is an annual model for long term strategic planning. It illustrates the feasibility of biofuel production by presenting the facility locations and biofuel unit production cost. Biomass collection cost, biofuel conversion

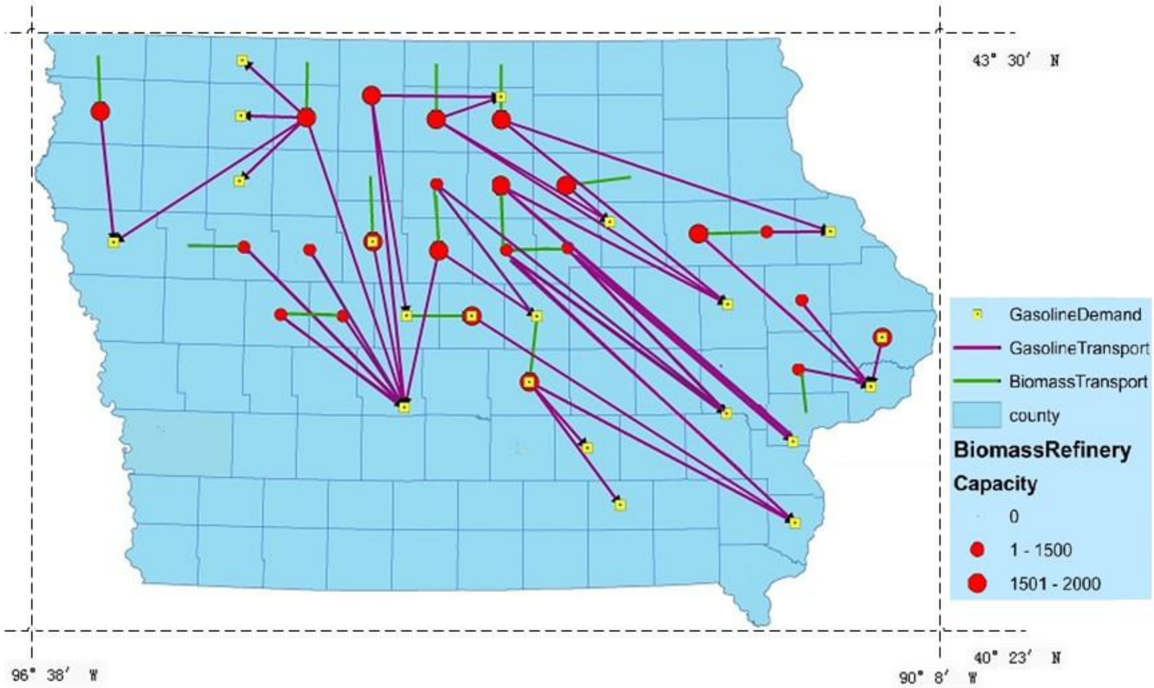

Figure 2.10 Monthly based model results under uniform gasoline demand

cost, and facility capital investment cost are the three major components in the cost model. From the case study in Iowa, it is optimal to build 23 facilities and fulfill the demand from all of the MSAs with flexible budget. If budget is limited, then the number of facilities will be constrained by the available capital budget, with more facilities built at the largest size due to the economies of scale. The effect of a biofuel shortage penalty is analyzed. For MSAs with a higher penalty cost, the demand satisfaction represents the trade-off between biofuel shortage penalties and biofuel transportation costs. Therefore, higher shortage penalty and shorter distance from the facility receive higher priority to satisfy the demand.

The second model analyzes detailed operational planning on feedstock and biofuel allocation, and sensitivity of biofuel demand pattern is also investigated. It is observed that the satisfaction of biofuel depends on the demand patterns over the planning horizon. For uniform and increasing demand patterns, all biofuel demand can be satisfied. However, for decreasing and triangle demand patterns, biofuel demands at the highest demand months will not be fulfilled even with increasing number of facilities. Based on this sensitivity analysis, it can be concluded that the commercialization of advanced biofuel is advantageous if the biofuel demand pattern is steady

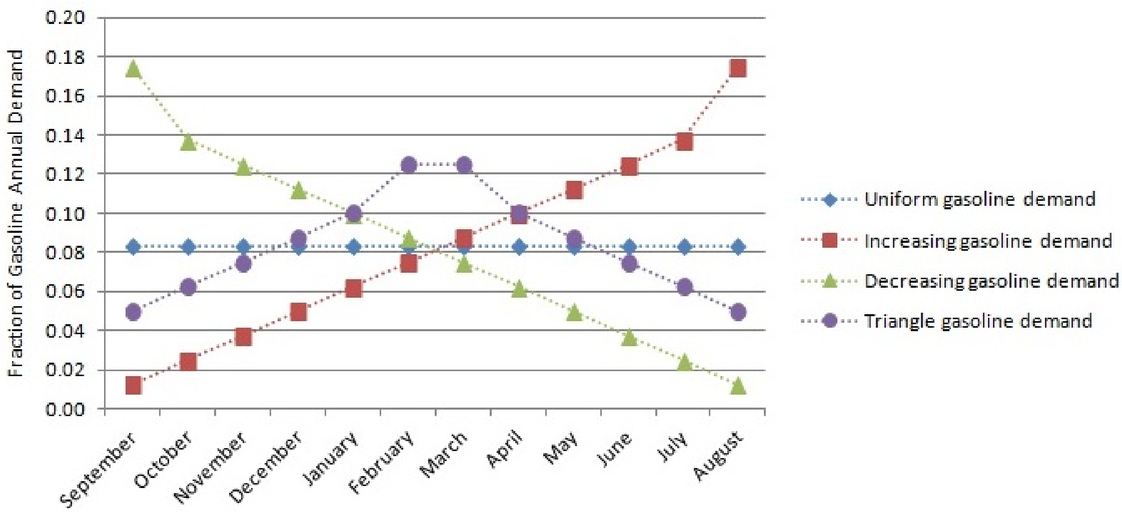

Figure 2.11 The fraction of gasoline annual demand per month

or increasing over the operational horizon.

Assumptions have been made in this study, which suggest the future research directions. One major assumption is that all facilities can be built simultaneously. For future work, a sequential facility sitting problem should be considered in the long term planning model. Parameters are assumed to be deterministic in this study. In the future, uncertainty can be incorporated into the modeling framework. For example, biomass feedstock supply could be uncertain, considering weather conditions, seed quality, soil fertilization, etc. The biofuel demand is estimated based on the population in MSAs. Demand uncertainty could be incorporated to make the model more realistic. The case study in this paper only considered one type of biomass, one pretreatment technology, and one final product category. To better represent the biofuel supply chain, a more comprehensive model with multiple types of biomass, multiple processing technologies and a variety of final products can be analyzed.

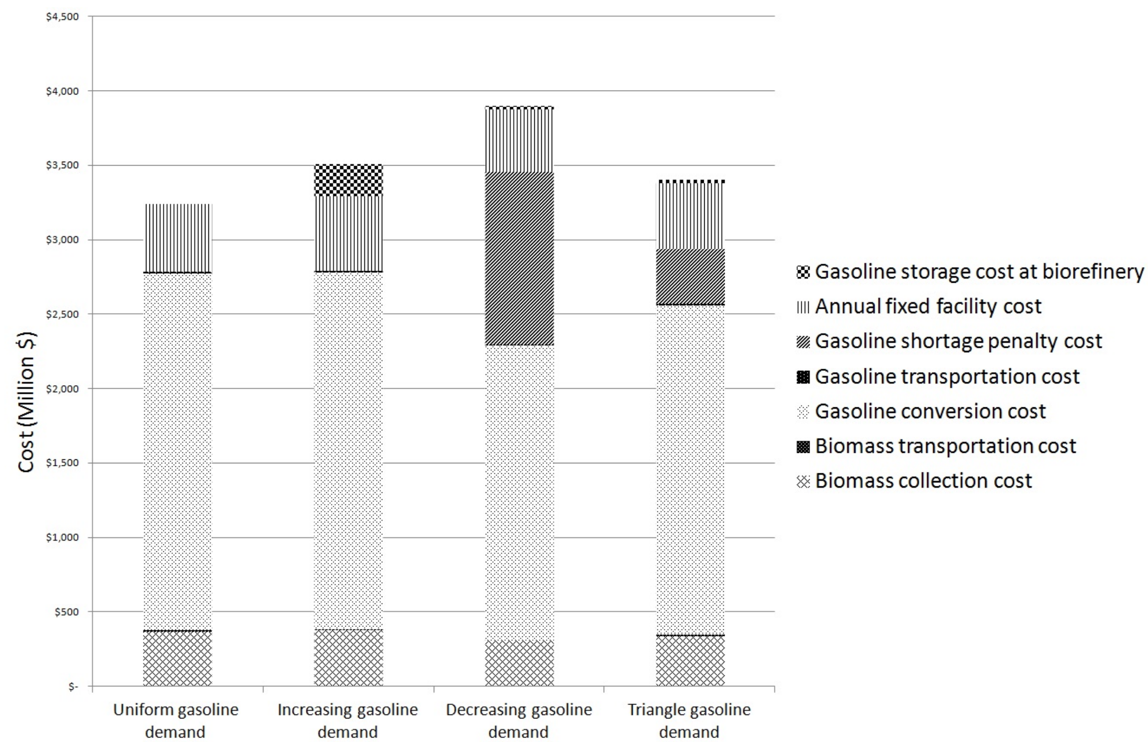

Figure 2.12 Comparison of total annual biogasoline production costs under different biofuel demand patterns

CHAPTER 3. A BOTTOM-UP MARKET EQUILIBRIUM MODEL FOR POLICY ANALYSIS[1]

3.1 Introduction

The US ethanol production increased from 1,630 million gallons in 2000 to 13,900 million gallons in 2011. The number and capacity of ethanol plants also increased from 50 and 1,702 million gallons per year (mgy) in 2000 to 209 and 14,907 mgy in 2012 [76]. The expansion of infrastructure and production is mainly spurred by the increasing oil price, high fuel demand, and various public policies such as tax credit for biofuels blended into conventional gasoline, government subsidy for biofuels produced and consumed in US, and the Renewable Fuels Standards (RFS). The economic argument for favoring these policies is that when firms undertake research and development (R&D) for a new technology they cannot fully retain the economic rent due to the spillover effect. The associated externality of competing technologies, i.e., pollution emitted from producing conventional gasoline, is not fully internalized, and governmental intervention is needed to facilitate its development [89]. These policies differ in their "format," i.e., quantity, price or hybrid instruments, or their points-of-implementation, i.e., farmers, blenders, producers, etc. Typically, a quantity instrument imposes a quota defining either the maximum or minimum quantities that need to be satisfied. For example, in fishery management an individual fishing quota sets a species specific allowable catch for an individual over a period of time. A price instrument defines a tax (subsidy) that collects from (gives to) an entity based on some activities of interest. An example is the Volumetric Ethanol Excise Tax Credit (VEETC), which expired in 2012. A hybrid system is a combination of the previous two instruments, which defines a "percentage" of biofuels required to be blended with conventional fuels. It acts as a subsidy for entities that over-comply with the requirement, and a tax for under-complying entities [42].

[1] **This part of the dissertation is published in Annals of Operations Research [108]**

An example is the renewable portfolio standard that mandates certain percentage of the electricity needs to be produced from renewable sources.

The major legislation promoting biofuels in the United States is the RFS created by the Environmental Protection Agency (EPA) under the Energy Policy Act (EPAct) in 2005. RFS requires that at least 7.5 billion gallons of renewable fuels to be blended into gasoline by 2012, at least 0.25 billion gallons are required to be cellulosic ethanol (E) [85]. The revised RFS (also known as RFS2) was issued in 2007, requiring that by 2022, more than 36 billion gallons of biofuel are produced, including 21 and 16 billions gallons from advanced biofuel and cellulosic biofuel, respectively. RFS or RFS2 is essentially a quantity instrument, and the point-of-implementation is the biofuel blenders. The compliance of RFS2 is determined by assigning each gallon of biofuel produced with a 38-character Renewable Identification Numbers (RINs). The RINs in biofuel are the analog of the emission permits in a cap-and-trade program. Each obligated part, such as biofuel blender can sell its RINs if it exceeds the mandate of renewable biofuel production, while those who cannot meet the mandate must purchase adequate RINs from the market to cover its deficit. Under mild conditions, e.g., competitive markets and perfect information, the marginal compliance cost should be equalized among all blenders, and the aggregate cost is at its minimum for all blenders as a whole. RIN prices are determined by supply and demand conditions of RINs in the market, reflecting their scarcity rent. Another complementary policy is the subsidy to biofuel producers or blenders proposed by the Food, Conservation, Energy Act (FCEA) of 2008. FCEA offers different levels of subsidy for the production of cellulosic feedstocks and for blending biofuels with gasoline. In particular, a $1.01 per gallon of subsidy is provided for cellulosic biofuel produced and consumed in the US. [Act 15321, amending I.R.C. 40(a)]. With a $45 subsidy per tonne of biomass, the Biomass Crop Assistance Program supports farmers for collecting, harvesting, processing, and transporting cellulosic feedstocks [Section 9011]. Meanwhile, a tariff of $0.54 per gallon is levied on the imported sugarcane ethanol from Brazil to the US in order to protect the domestic industry. (This policy expired in 2012.) As seen, those policies differ not only in their *format*, e.g., quantity, price or hybrid, and their *point- of-compliance*, e.g., blenders, producers and farmers. Thus, models to address the impacts of these public policies must entail adequate flexibility to incorporate details.

In this paper, we develop a bottom-up equilibrium optimization model to study the supply chain of the biofuel market, considering farmers, biofuel producers, blenders, and consumers. The model builds on individual's optimization problems and solves for farmers' land allocation, biomass transportation, biofuel production and biofuel blending activities. The prices in the market are determined endogenously by supply-demand conditions of each commodity. The model also allows for consideration of market structure or firms' horizontal and vertical ownership that may arise to oligopoly competition at the different segments of the supply chain, e.g., blenders, biofuel producers, etc. [96]. This might be crucial for the development of the biofuel sector, owing to the fact that transportation constitutes a significant portion of the production costs, and a local monopoly or oligopoly could be possible when new entries are deterred by the limited biomass that can be procured within a reasonable transportation distance. Other factors such as a lengthy permission process and difficulty in accessing technology or capital might also possibly result in less competitive local markets. As experienced in other sectors, the extent to which the cost or subsidy passes on to consumers or producers depends on various factors, such as the elasticity of supply and demand and the market structure [17]. Therefore, models used to analyze public policy impacts on the biofuel sector should allow these factors to be explicitly accounted for in the analysis. The advantage of the bottom-up equilibrium models over optimization models is their flexibility to simulate different scenarios of interest. For example, had there been a single blender dominating the market, a bi-level formulation in which the blender is designated as a leader with other entities, such as producers and farmers, as followers would have been appropriate.

To illustrate the strength of the bottom-up models, we focus on two aspects of market conditions – market structure and choice of regulation or policy entity along the supply chain – and examine their impacts on market outcomes, such as blended fuel market price faced by consumers, consumer surplus change, total social welfare, etc.

The model is then applied to a case study in the state of Iowa. We have three central findings in the paper. First, if a biofuel market is unregulated and allows blenders to exercise market power, then blenders are able to exercise market power and increase their own profits at the cost of social surplus by decreasing biofuel supply quantities to consumers, raising biofuel market prices, and lowering purchase prices of cellulosic biofuel. Second, when a subsidy is given to farmers, producers, or blenders, it stimulates the total production level of biofuels, lower biofuel market prices faced by consumers, and increases consumer surplus and total social welfare. Moreover, the equilibrium outcomes suggest that subsidies would pass on to all the entities in the supply chain, and, thereby, incentivizes more investment in the biofuel industry. Although the subsidy pass-through may differ depending on the points-of-implementation, they are proportional to each entity's earned profit. Third, our model, to our best knowledge, is among the first to endogenously calculate RINs prices from a market equilibrium model.This methods is analogous to the calculation of Renewable Energy Credits (RECs) in electricity market [19].

The rest of the paper is organized as follows. In Section 3.2 some related literatures will be presented. Model introduction, formulation, and some solution techniques will be presented in Section 3.3. In Section 3.4, a small case study will be presented to better illustrate our model and findings. Conclusions and future research will be discussed in Section 3.5.

3.2 Literature review

A number of existing models have been used to address the effects of various policies on the biofuel sectors. For example, the Biofuel and Environmental Policy Analysis Model or BEPAM [20] is a spatial dynamic multi-market model formulated as a nonlinear program solving for prices endogenously. The model has been used to analyze the market impacts under RFS2, subsidies, import tariffs, and a carbon tax policy. The model assumes that the market is perfectly competitive, so the objective is to maximize the social surplus. The FASOM, Forest and Agricultural Sector Optimization Model, similar to BEPAM, is a multiple-period model that includes the forest and agricultural sectors, is formulated as a nonlinear program that maximizes the social surplus [10]. The model assumes perfectly competitive markets. However, some important stakeholders in the biofuel markets are not considered, such as blenders. Another model, FAPRI, developed by the Food and Agricultural Policy Research Institute, is a multi-market *top-down* partial equilibrium model that solves for market outcomes at both domestic and international markets at the macro level [99]. In a sense, the model is solved for a system of equations, each representing the balance of supply and demand conditions for an underlying commodity. The strength of FAPRI is its ability to capture the interaction of multiple markets through its cross-elasticity formulation. Another popular model is BIOBREAK or the Biofuel Breakeven model [66]. The model is a long run breakeven model that represents the feedstock supply system and biofuel refining process. It estimates the breakeven price that biofuel refiners would pay for biomass and that biomass producers would be willing to accept for producing and delivering feedstock to biomass processing plants. Overall, these existing models do not have adequate flexibility to incorporate market and policy details, e.g., market structures and points-of-implementation, that are crucial in determining policy impacts. Therefore, we develop a process-based model to address such limitations.

Process-based models based on bottom-up principles have been used extensively to study the energy sector's response to proposed public policies or emerging markets. For example, models formulated as complementarity problems [2] or mathematical programs with equilibrium constraints have been applied previously to assess possible business partnership scenarios between feedstock suppliers and biofuel manufacturers [7]. In contrast to top-down models [82, 67], process-based models are more flexible in representing optimization problems faced by different entities in the supply chain of energy production, institutional policies that impose on different entities, and market conditions. For example, a recent paper by [18] formulates the electricity sector as complementarity market models to study three proposed emission policies in California, in which each of the proposed policies has a different point of compliance. Process-based models represent supply curves using step functions. Each step corresponds to the marginal production cost of an individual technology or production unit. If production units are arrayed in the order of production costs, their "non-economic" performance, such as the marginal emission rate, likely nonmonotonic and non-differentiable, can be appropriately represented by bottom-up models. There are at least two strengths of process-based modeling: explicitness and flexibility. The explicitness of the process-based approach allows for changes in technology, policies, input prices, and new entities in the supply chain or objectives to be modeled by altering decision variables, objective function coefficients or constraints. The transparency of the formulation and inputs of process-based models facilitates the review of model assumptions, and applies to a wide range of policy design parameters.

Some research has been done in biofuel supply chains to analyze the total production cost and risk for the biofuel industry. [32] proposed a mathematical model to investigate the optimal sizes and locations of biorefinery facilities as well as the short term logistic costs for biofuel production. [104] developed a multi-objective mixed integer linear programming model to optimize economic, environmental, and social benefits of a biofuel supply chain network. A multiperiod stochastic mixed integer linear programming model was built by [46] to optimize

[2] A complementarity problem refers to a mathematical problem that finds a vector x that satisfies $x \geq 0$, $f(x) \geq 0$ and $x^T f(x) = 0$. When $f(x)$ is linear, this problem is known as a linear complementarity problem (LCP). The theoretical properties of LCP concerning the uniqueness and existence of such solutions can be found in references [22, 100, 41]. There are many applications of LCPs for policy analyses in electricity, natural gas markets and other industries, e.g., [38, 63, 18, 44].

the annualized cost and financial risk in the biorefinery supply chain under biomass supply and biofuel demand uncertainty. [95] built a two-stage bioenergy plant location-allocation problem to optimize rural energy planning considering both domestic and commercial energy demands. However, the decision of biorefinery facility locations and sizes based on available biomass in market and existing biofuel demand was not explicitly considered. In this paper, we focus on evaluating the profitability of different entities including farmers, producers, and blenders given that optimal location and size of biorefinery facilities are determined, and farmers have the right to decide their biomass crop allocation and influent the prices.

3.3 Model formulation

We consider four entities in the biofuel supply chain: farmers, biofuel producers, biofuel blenders, and consumers. A general framework of the model is shown in Figure3.1. Farmers grow a variety of biomass crops to be harvested and sell to biofuel producers for biofuel production. We assume that throughout the supply chain, the transportation cost is paid by the downstream entities. For example, biofuel producers will pay for the biomass transportation fee from farmland to their facilities. Biofuel producers purchase crops from farmers through bilateral arrangement, convert different biomass into cellulosic ethanol (E) and biogasoline (BG), and then sell these to blenders, who then blend biofuels with petroleum fuels ready for vehicle use. We assume that the production capacity of each producer is fixed. Prices of cellulosic ethanol and biogasoline are determined by their supply and demand. Ethanol is blended with gasoline into ethanol fuel mixtures such as E10 and E85 for vehicle consumption. Blenders blend cellulosic ethanol with conventional gasoline purchased from the market. Biogasoline as a type of drop-in fuel is not blended, but purchased from producers and sold directly into the market. As a simplified case, we assume each blender exclusively faces its own markets for both ethanol fuel mixture and biogasoline. Thus, other blenders cannot compete in markets besides their own. Therefore, we might overstate the extent of market power. Finally, consumers of both ethanol fuel mixture and biogasoline are not modeled as separate entities but represented by separate inverse demand functions. We do not consider cross-elasticity between different fuel products. However, in reality, a vehicle driver (when re-filling gas) would seek the lowest cost gas station considering convenience cost including distance, availability, etc.

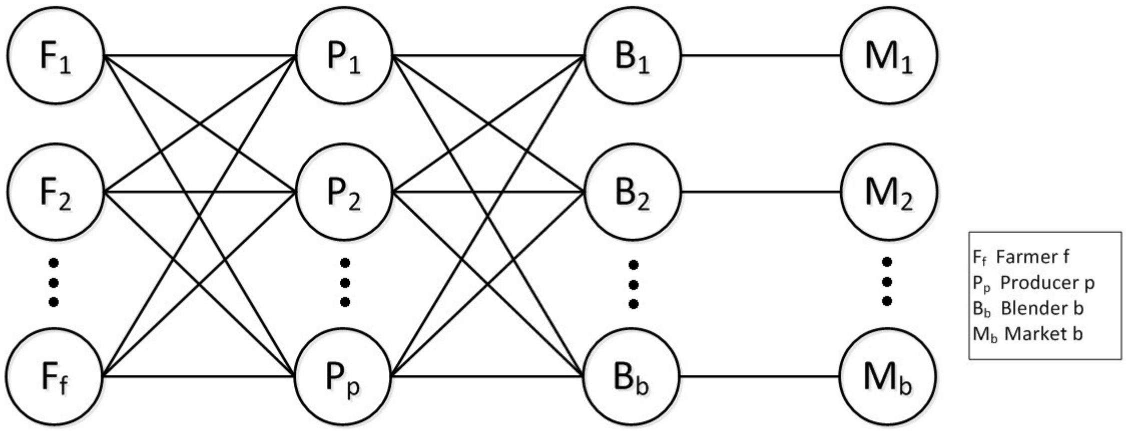

Figure 3.1 Market structure of the biofuel supply chain

In what follows, we first list the notations that we use in the paper. We use lower case for variables and upper case for parameters. The optimization problem faced by each entity will be introduced in Sections 3.3.2-3.3.4, followed by the market equilibrium condition in Section 3.3.5.

3.3.1 Notation

Sets and Indices

F ($f \in$ F)	Set of farmers
P ($p \in$ P)	Set of producers
B ($b \in$ B)	Set of blenders
C ($c \in$ C)	Set of crops
M ($m \in$ M)	Set of biofuels and blended fuels

Decision variables

a_{fc}	Farmer f's area of land used to produce crop c [acre]
x^{FC}_{fpc}	Amount of crop c sold by farmer f to producer p [ton]
x^{PC}_{fpc}	Amount of crop c purchased by producer p from farmer f [ton]
x^{PM}_{pbm}	Amount of cellulosic biofuel m sold by producer p to blender b [gal]
x^{BM}_{pbm}	Amount of biofuel m purchased by blender b from producer p [gal]
t^{P}_{pcm}	Amount of crop c converted to biofuel m for producer p [ton]
$\overline{\pi}^{\text{M}}_{bm}$	Market prices of blended biofuel m for market b [\$/gal]
$\overline{\pi}^{\text{G}}_{b}$	Market prices of conventional gasoline for blender b [\$/gal]

Market clearing variables

π^{C}_{fpc}	Contract price between farmer f and producer p for crop c [\$/ton]
π^{M}_{pbm}	Contract price between producer p and blender b for biofuel m [\$/gal]
π^{RIN}	RIN price for each gallon of biofuel in market [\$/gal]

Dual variables

α_{f0}	Dual variable for land availability constraints
α_{fc}	Dual variable for biomass yield constraints
β_{pc}	Dual variable for biomass process capacity constraints
τ_{pm}	Dual variable for biofuel yield constraints
γ_{pc}	Dual variable for biomass process quantity constraints
κ_{bm}	Dual variable for biofuel blend capacity
ρ^{M}_{bm}	Dual variable for blend fuel inverse demand function
ρ^{G}_{b}	Dual variable for conventional gasoline inverse supply function

Parameters

L_f	Farmer f's total area of land available for biofuel crops [acre]
C^{F}_{fc} (D^{F}_{fc})	Intercept (slope) of farmer f's linear production cost function for crop c
Y^{F}_{fc}	Farmer f's yield of crop c [ton/acre]
S^{F}_{c}	Government subsidy given to farmers for each acre of biomass c planted [$/acre]
T^{C}_{c}	Unit transportation cost of crop c from farmers to producers [$/ton]
τ^{C}_{c}	Tortuosity factor for transporting crop c. (Tortuosity factor is the expected ratio of the actual flow-path length to the great circle distance between any two points on earth.)
D^{FP}_{fp}	Great circle distance from farmer f to producer p [mile]
C^{P}_{pcm} (D^{P}_{pcm})	Intercept (slope) of producer p's linear production cost function for biofuel m from biomass c
Y^{P}_{pcm}	Producer p's conversion rate from crop c to biofuel m [gallon/ton]
U^{P}_{pc}	Producer p's process capacity for crop c [ton/year]
S^{P}_{m}	Government subsidy given to producers for each gallon of cellulosic biofuel m produced [$/gal]
T^{M}_{m}	Unit transportation cost of biofuel m from producers to blenders [$/gal]
τ^{M}_{m}	Tortuosity factor for transporting biofuel m (Different transportation methods have different tortuosity factors)
D^{PB}_{pb}	Great circle distance from producer p to blender b [mile]
A^{G}_{b} (B^{G}_{b})	Intercept (slope) of blender b's inverse supply function for gasoline [$/gal]
A^{M}_{bm} (B^{M}_{bm})	Intercept (slope) of blender b's inverse demand function for blended fuel m [$/gal]
U^{B}_{bm}	Blender b's process capacity for biofuel m [gallon/year]
C^{B}_{bm} (D^{B}_{bm})	Intercept (slope) of blender b's production cost function for each gallon of biofuel m blended [$/gal]
S^{B}_{m}	Government subsidy given to blenders for each gallon of cellulosic biofuel m blended [$/gal]
T^{REQ}_{b}	Total biofuel production mandate faced by blender b [gal]
θ_m	The percentage of biofuel m in blended gasoline.

Ton here means short ton.
1 acre=4046.86 m^2, 1 gallon=3.7854 liter, 1 mile=1.6093 km, 1 short ton= 0.9072 tonne.

3.3.2 Farmer f's profit maximization model

We assume that biomass can only be used for biofuel production but not sold into other markets. It is also assumed that farmers do not have market power in the supply chain. Unlike biofuel producers, decisions such as how much and which crop to plant are typically critical and need to be determined months ahead of harvest. The ability of farmers to behave strategically is limited by this "lead-time" effect. For profit, we only consider here the farmers' profit for producing and selling biomass. Profits for selling food, livestock products, and other byproducts are not included. This underestimates the ability of farmers to optimize their output to maximize the profit. The profit maximization model for farmer f is

$$\max_{a,x} \quad \sum_{pc} \pi^{\mathrm{C}}_{fpc} x^{\mathrm{FC}}_{fpc} - \sum_{c} \left(C^{\mathrm{F}}_{fc} a_{fc} + \frac{1}{2} D^{\mathrm{F}}_{fc} a^2_{fc} \right) \tag{3.1}$$

$$s.t. \quad \sum_{c} a_{fc} \leq L_f \qquad (\alpha_{f0}) \tag{3.2}$$

$$\sum_{p} x^{\mathrm{FC}}_{fpc} \leq Y^{\mathrm{F}}_{fc} a_{fc} \qquad (\alpha_{fc}) \qquad \forall c \in \mathrm{C} \tag{3.3}$$

$$a_{fc}, x^{\mathrm{FC}}_{fpc} \geq 0 \qquad \forall p \in \mathrm{P}, c \in \mathrm{C}. \tag{3.4}$$

Here $\sum_{pc} \pi^{\mathrm{C}}_{fpc} x^{\mathrm{FC}}_{fpc}$ is farmer f's revenue from selling biomass. The second summation in equation (3.1) is the total cost for biomass production. Land availability constraints are shown in constraint (3.2). Constraint (3.3) implies that the sold biomass should not exceed the available biomass produced in the farm. The dual variables for the constraints are included in the parentheses. This also applies for producers and blenders submodel in Section 3.3.3 and 3.3.4.

3.3.3 Producer p's profit maximization model

In this model we consider two biofuel products: cellulosic ethanol and biogasoline. An assumption for the producers is that they have no market power, and biofuel selling prices are market clearing prices determined by the supply and demand of biofuels.The profit maximization model for producer p is

$$\max_{x,t} \quad \sum_{bm} \pi^{\mathrm{M}}_{pbm} x^{\mathrm{PM}}_{pbm} - \sum_{fc} \left(\pi^{\mathrm{C}}_{fpc} + T^{\mathrm{C}}_c \tau^{\mathrm{C}}_c D^{\mathrm{FP}}_{fp} \right) x^{\mathrm{PC}}_{fpc} - \sum_{cm} \left[C^{\mathrm{P}}_{pcm} Y^{\mathrm{P}}_{pcm} t^{\mathrm{P}}_{pcm} + \frac{1}{2} D^{\mathrm{P}}_{pcm} (Y^{\mathrm{P}}_{pcm} t^{\mathrm{P}}_{pcm})^2 \right] \tag{3.5}$$

$$s.t. \quad \sum_f x^{\mathrm{PC}}_{fpc} \le U^{\mathrm{P}}_{pc} \qquad (\beta_{pc}) \quad \forall c \in \mathrm{C} \tag{3.6}$$

$$\sum_b x^{\mathrm{PM}}_{pbm} \le \sum_c Y^{\mathrm{P}}_{pcm} t^{\mathrm{P}}_{pcm} \qquad (\tau_{pm}) \quad \forall m \in \mathrm{M} \tag{3.7}$$

$$\sum_m t^{\mathrm{P}}_{pcm} \le \sum_f x^{\mathrm{PC}}_{fpc} \qquad (\gamma_{pc}) \quad \forall c \in \mathrm{C} \tag{3.8}$$

$$x^{\mathrm{PM}}_{pbm}, t^{\mathrm{P}}_{pcm} \ge 0 \qquad \forall b \in \mathrm{B}, c \in \mathrm{C}, m \in \mathrm{M}. \tag{3.9}$$

In this model, equation (3.5) is the producer p's profit function. Producer p's revenue from selling biofuels is $\sum_{bm} \pi^{\mathrm{M}}_{pbm} x^{\mathrm{PM}}_{pbm}$. Producer p's total cost for producing biofuels includes its production cost for biofuels $\left(\sum_{cm}\left[C^{\mathrm{P}}_{pcm} Y^{\mathrm{P}}_{pcm} t^{\mathrm{P}}_{pcm} + \frac{1}{2} D^{\mathrm{P}}_{pcm} (Y^{\mathrm{P}}_{pcm} t^{\mathrm{P}}_{pcm})^2\right]\right)$, purchasing, and transportation cost for biomass $\left(\sum_{fc}\left(\pi^{\mathrm{C}}_{fpc} + T^{\mathrm{C}}_c \tau^{\mathrm{C}}_c D^{\mathrm{FP}}_{fp}\right) x^{\mathrm{PC}}_{fpc}\right)$. Turning to constraints, constraint (3.6) implies that total amount of biomass purchased by producer p is limited by its biorefinery facility capacity. Constraint (3.7) shows that biofuels sold to blenders are no more than biofuels produced in biorefinery facilities. Constraint (3.8) implies that the biomass used in biofuel production is no more than the total biomass purchased from farmers.

3.3.4 Blender b's profit maximization model

We assume that blenders purchase cellulosic ethanol from producers and conventional gasoline from the market, and then blend at a percentage θ into the ethanol fuel mixture for consumers' end use. Biogasoline is purchased from producers and sold at market without blending. Here, we assume that each blender faces its own market for both products. Therefore, each blender b has market prices $\overline{p}^{\mathrm{M}}_{bm}$ for each blended fuel $m \in \mathrm{M}$. If blenders are under perfect competition (defined as PC), which means that no blender has market power, then blended ethanol and biogasoline market prices are exogenous variables for the models. Blender b's profit optimization model is

$$\begin{aligned} \max_x \quad & \sum_m \overline{\pi}^{\mathrm{M}}_{bm} \Big(\sum_p x^{\mathrm{BM}}_{pbm}\Big) - \overline{\pi}^{\mathrm{G}}_b \sum_m (1-\theta_m) \Big(\sum_p x^{\mathrm{BM}}_{pbm}\Big) \\ & - \sum_{pm} \left[(T^{\mathrm{M}}_m \tau^{\mathrm{M}}_m D^{\mathrm{PB}}_{pb} + \pi^{\mathrm{M}}_{pbm}) \theta_m x^{\mathrm{BM}}_{pbm}\right] - \sum_m \left[C^{\mathrm{B}}_{bm} \theta_m \sum_p x^{\mathrm{BM}}_{pbm} + \frac{1}{2} D^{\mathrm{B}}_{bm} \Big(\theta_m \sum_p x^{\mathrm{BM}}_{pbm}\Big)^2\right] \end{aligned} \tag{3.10}$$

$$s.t. \quad \theta_m \sum_p x^{\text{BM}}_{pbm} \leq U^{\text{B}}_{bm} \qquad (\kappa_{bm}) \quad \forall m \in \text{M} \tag{3.11}$$

$$x^{\text{BM}}_{pbm} \geq 0 \qquad \forall p \in \text{P}, m \in \text{M}. \tag{3.12}$$

Equation (3.10) is blender b's profit function. The two summations in the first line of Equation (3.10) correspond to the blender b's revenue from selling blended fuels and the cost of purchasing conventional gasoline from market, respectively. The second line presents the cost of purchasing and transporting cellulosic biofuels $\left(\sum_{pm}\left[(T^{\text{M}}_m \tau^{\text{M}}_m D^{\text{PB}}_{pb} + \pi^{\text{M}}_{pbm})\theta_m x^{\text{BM}}_{pbm}\right]\right)$. Blender b's total cost for blending cellulosic biofuel with conventional gasoline is represented by the last summation in Equation (3.10). Constraints (3.11) are capacity constraints for cellulosic biofuel blending.

If all blenders possess market power (defined as MP), then the objective function of this profit maximization model only differs from equation (3.10) in the first line. Instead of taking exogenous prices $\overline{\pi}^{\text{M}}_{bm}$, and $\overline{\pi}^{\text{G}}_{b}$ from market, blenders are able to influence ethanol fuel mixture and biogasoline prices $\overline{\pi}^{\text{M}}_{bm}$ by deciding its output level. We elaborate on their difference when introducing their Karush-Kuhn-Tucker (KKT) conditions in the next section.

3.3.5 Market equilibrium conditions

We present the market equilibrium conditions of the profit maximization models to solve the farmer, producer, and blender individual profit maximization model simultaneously. The operator $\perp$ refers to the complementarity condition: $0 \leq x \perp y \geq 0$ implies that $x \geq 0$, $y \geq 0$, and $x^T y = 0$.

- The KKT conditions for the farmer f's profit maximization model (3.1)-(3.4) under both market structures, PC and MP, are as follows

$$0 \leq a_{fc} \perp \qquad -Y^{\text{F}}_{fc}\alpha_{fc} + \alpha_{f0} + C^{\text{F}}_{fc} + D^{\text{F}}_{fc}a_{fc} \geq 0 \quad \forall f \in \text{F}, c \in \text{C} \tag{3.13}$$

$$0 \leq x^{\text{FC}}_{fpc} \perp \qquad \alpha_{fc} - \pi^{\text{C}}_{fpc} \geq 0 \quad \forall f \in \text{F}, p \in \text{P}, c \in \text{C} \tag{3.14}$$

$$0 \leq \alpha_{f0} \perp \qquad L_f - \sum_c a_{fc} \geq 0 \quad \forall f \in \text{F} \tag{3.15}$$

$$0 \leq \alpha_{fc} \perp \qquad Y^{\text{F}}_{fc}a_{fc} - \sum_p x^{\text{FC}}_{fpc} \geq 0 \quad \forall f \in \text{F}, c \in \text{C}. \tag{3.16}$$

- The KKT conditions for the producer p's profit maximization model (3.5)-(3.9) under both market structures, PC and MP, are as follows

$$0 \le x^{\mathrm{PM}}_{pbm} \perp \quad \tau_{pm} - \pi^{\mathrm{M}}_{pbm} \ge 0 \quad \forall p \in \mathrm{P}, b \in \mathrm{B}, m \in \mathrm{M} \tag{3.17}$$

$$0 \le x^{\mathrm{PC}}_{fpc} \perp \quad -\gamma_{pc} + \beta_{pc} + \pi^{\mathrm{C}}_{fpc} + T^{\mathrm{C}}_{c}\tau^{\mathrm{C}}_{c} D^{\mathrm{FP}}_{fp} \ge 0 \quad \forall f \in \mathrm{F}, p \in \mathrm{P}, c \in \mathrm{C} \tag{3.18}$$

$$0 \le t^{\mathrm{P}}_{pcm} \perp \quad \gamma_{pc} - Y^{\mathrm{P}}_{pcm}\tau_{pm} + Y^{\mathrm{P}}_{pcm}C^{\mathrm{P}}_{pcm} + D^{\mathrm{P}}_{pcm}(Y^{\mathrm{P}}_{pcm})^2 t^{\mathrm{P}}_{pcm} \ge 0 \quad \forall p \in \mathrm{P}, c \in \mathrm{C}, m \in \mathrm{M} \tag{3.19}$$

$$0 \le \beta_{pc} \perp \quad U^{\mathrm{C}}_{pc} - \sum_{f} x^{\mathrm{PC}}_{fpc} \ge 0 \quad \forall p \in \mathrm{P}, c \in \mathrm{C} \tag{3.20}$$

$$0 \le \tau_{pm} \perp \quad \sum_{c} Y^{\mathrm{P}}_{pcm} t^{\mathrm{P}}_{pcm} - \sum_{b} x^{\mathrm{PM}}_{pbm} \ge 0 \quad \forall p \in \mathrm{P}, m \in \mathrm{M} \tag{3.21}$$

$$0 \le \gamma_{pc} \perp \quad \sum_{f} x^{\mathrm{PC}}_{fpc} - \sum_{m} t^{\mathrm{P}}_{pcm} \ge 0 \quad \forall p \in \mathrm{P}, c \in \mathrm{C}. \tag{3.22}$$

- The KKT conditions for blender b's profit maximization model (3.10)-(3.12) under market structures PC and MP are as follows.

  If blenders are under perfect competition, the KKT conditions are

$$\begin{aligned} 0 \le x^{\mathrm{BM}}_{pbm} \perp \quad & -\overline{\pi}^{\mathrm{M}}_{bm} + (1-\theta_m)\overline{\pi}^{\mathrm{G}}_{b} \\ & + \theta_m \kappa_{bm} + \theta_m \pi^{\mathrm{M}}_{pbm} + \theta_m T^{\mathrm{M}}_{m} \tau^{\mathrm{M}}_{m} D^{\mathrm{PB}}_{pb} + \theta_m C^{\mathrm{B}}_{bm} + D^{\mathrm{B}}_{bm}\theta_m^2 \sum_{p} x^{\mathrm{BM}}_{pbm} \ge 0 \quad \forall p \in \mathrm{P}, b \in \mathrm{B} \end{aligned} \tag{3.23}$$

$$0 \le \kappa_{bm} \perp \quad U^{\mathrm{B}}_{bm} - \theta_m \sum_{p} x^{\mathrm{BM}}_{pbm} \ge 0 \quad \forall b \in \mathrm{B} \tag{3.24}$$

  When the market power of blenders is considered, the constraints (3.23) need to be replaced with

$$\begin{aligned} 0 \le x^{\mathrm{BM}}_{pbm} \perp \quad & -\overline{\pi}^{\mathrm{M}}_{bm} + B^{\mathrm{M}}_{bm} \sum_{p} x^{\mathrm{BM}}_{pbm} + (1-\theta_m)\overline{\pi}^{\mathrm{G}}_{b} + (1-\theta_m) B^{\mathrm{G}}_{b} \sum_{m} (1-\theta_m) \sum_{p} x^{\mathrm{BM}}_{pbm} \\ & + \theta_m \kappa_{bm} + \theta_m \pi^{\mathrm{M}}_{pbm} + \theta_m T^{\mathrm{M}}_{m} \tau^{\mathrm{M}}_{m} D^{\mathrm{PB}}_{pb} + \theta_m C^{\mathrm{B}}_{bm} + D^{\mathrm{B}}_{bm}\theta_m^2 \sum_{p} x^{\mathrm{BM}}_{pbm} \ge 0 \quad \forall p \in \mathrm{P}, b \in \mathrm{B}. \end{aligned} \tag{3.25}$$

- Market clearing conditions

Biomass prices π^{C}_{fpc} between farmers and producers are obtained from the market clearing conditions of biomass supply equaling to biomass demand. Similar market clearing conditions also exist for cellulosic biofuel prices π^{M}_{pbm} between producers and blenders:

$$\pi^{\mathrm{C}}_{fpc} \text{ free} \perp \quad x^{\mathrm{FC}}_{fpc} = x^{\mathrm{PC}}_{fpc} \quad \forall f \in \mathrm{F}, p \in \mathrm{P}, c \in \mathrm{C} \tag{3.26}$$

$$\pi^{\mathrm{M}}_{pbm} \text{ free} \perp \quad x^{\mathrm{PM}}_{pbm} = \theta_m x^{\mathrm{BM}}_{pbm} \quad \forall p \in \mathrm{P}, b \in \mathrm{B}, m \in \mathrm{M}. \tag{3.27}$$

Constraints (3.28) and (3.29) are the exogenous constraints for the blender's optimization model (3.10)-(3.12) to determine market prices for blended biofuels under blenders' perfect competition. If blenders possess market power, then they are endogenous constraints for model (3.10)-(3.12).

$$\rho^{\mathrm{M}}_{bm} \text{ free} \perp \qquad \overline{\pi}^{\mathrm{M}}_{bm} = A^{\mathrm{M}}_{bm} - B^{\mathrm{M}}_{bm} \sum_p x^{\mathrm{BM}}_{pbm} \qquad \forall b \in \mathrm{B}, m \in \mathrm{M} \tag{3.28}$$

$$\rho^{\mathrm{G}}_{b} \text{ free} \perp \qquad \overline{\pi}^{\mathrm{G}}_{b} = A^{\mathrm{G}}_{b} + B^{\mathrm{G}}_{b} \sum_m (1-\theta_m)(\sum_p x^{\mathrm{BM}}_{pbm}) \qquad \forall b \in \mathrm{B} \tag{3.29}$$

In summary, if no blender has market power, the equivalent complementarity model to solve profit maximization models of farmers, producers and blenders simultaneously includes (3.13)-(3.24), (3.26)-(3.29). If the blenders all have market power, then the equilibrium model consists of equations (3.13)-(3.22), (3.24)-(3.29).

3.3.6 Formulations under various policies

Various policies have been implemented by the government to promote biofuel production. [3] Four policies corresponding to RFS2, biofuel subsidy and RINs are considered in this section, including subsidy on blenders, on producers, on farmers, and both subsidy and biofuel mandate on blenders. The RIN is an endogenously determined quantity when blenders are allowed to meet their mandate by purchasing RINs from the market. These policies can be incorporated in the models as shown in Sections 3.3.2-3.3.4.

(a) If the subsidy is given to the blenders for each gallon of cellulosic biofuels blended and consumed in U.S., the term $\sum_m S^{\mathrm{B}}_m \theta_m \sum_p x^{\mathrm{BM}}_{pbm}$ needs to be inserted into objective function (3.10). In a sense, the subsidy will be used to offset the production cost.

(b) If the subsidy is given to producers for each gallon of cellulosic biofuel m produced, then the objective (3.5) needs to include the subsidy term $\sum_m S^{\mathrm{P}}_m \sum_p (Y^{\mathrm{P}}_{pcm} t^{\mathrm{P}}_{pcm})$.

(c) If the subsidy is handed out to farmers for growing each acre of biomass, objective (3.1) of farmers' problem needs to include the subsidy term $\sum_c S^{\mathrm{F}}_c a_{fc}$.

[3] RFS2 proposed by EPA requires that at least 16 billion gallons of cellulosic biofuels will be consumed by the year 2022 [79]. FCEA offers \$1.01 per gallon of subsidy for cellulosic biofuel produced and consumed in US [40]. The policies that importers have to pay \$0.54/gal tariff on imported ethanol, and US ethanol producers get \$0.45/gal tax credit expired on January, 2012.

(d) If a mandate T_b^{REQ} [4] is imposed on blender b, then in addition to (a), the term $\pi^{\text{RIN}}\left[\sum_{pm}\theta_m x_{pbm}^{\text{BM}} - T_b^{\text{REQ}}\right]$ needs to be added to (3.10), which may be a revenue (if positive) or a cost (if negative). The variable π^{RIN} is the RINs market price that will be determined by the following complementarity condition.

$$0 \leq \pi^{\text{RIN}} \perp \sum_b \left[\sum_{pm}\theta_m x_{pbm}^{\text{BM}} - T_b^{\text{REQ}}\right] \geq 0. \tag{3.30}$$

3.3.7 Consumer surplus and social welfare

ω =Consumer surplus.

$$\omega = \frac{1}{2}\sum_{bm} B_{bm}^{\text{M}}(\sum_p x_{pbm}^{\text{BM}})^2 \tag{3.31}$$

ϕ =Subsidy expense.

$$\phi = \sum_c S_c^{\text{F}} a_{fc} + \sum_m S_m^{\text{P}} \sum_p Y_{pcm}^{\text{P}} t_{pcm}^{\text{P}} + \sum_m S_m^{\text{B}} \theta_m \sum_p x_{pbm}^{\text{BM}} \tag{3.32}$$

σ =Total social surplus.

If blenders behave competitively (PC), then

$$\begin{aligned}
\sigma = &\sum_m \overline{\pi}_{bm}^{\text{M}} \sum_p x_{pbm}^{\text{BM}} + \pi^{\text{RIN}}\left[\sum_{pm}\theta_m x_{pbm}^{\text{BM}} - T_b^{\text{REQ}}\right] \\
&- \sum_c \left[C_{fc}^{\text{F}} a_{fc} + \frac{1}{2} D_{fc}^{\text{F}} a_{fc}^2\right] - \sum_{cm}\left[C_{pcm}^{\text{P}} Y_{pcm}^{\text{P}} t_{pcm}^{\text{P}} + \frac{1}{2} D_{pcm}^{\text{P}} (Y_{pcm}^{\text{P}} t_{pcm}^{\text{P}})^2\right] \\
&- \sum_m \left[C_{bm}^{\text{B}} \theta_m \sum_p x_{pbm}^{\text{BM}} + \frac{1}{2} D_{bm}^{\text{B}} (\theta_m \sum_p x_{pbm}^{\text{BM}})^2\right] - \overline{\pi}_b^{\text{G}} \sum_m (1-\theta_m) \sum_p x_{pbm}^{\text{BM}} \\
&- \sum_{fc} T_c^{\text{C}} \tau_c^{\text{C}} D_{fp}^{\text{FP}} x_{fpc}^{\text{PC}} - \sum_{pm} T_m^{\text{M}} \tau_m^{\text{M}} D_{pb}^{\text{PB}} \theta_m x_{pbm}^{\text{BM}} + \omega - \phi
\end{aligned} \tag{3.33}$$

If blenders have market power, then in total social surplus the term $\overline{\pi}_{bm}^{\text{M}}$ will be replace by equation (3.28), and $\overline{\pi}_b^{\text{G}}$ will be replaced by equation (3.29).

3.4 Case study

We apply the model in Section 3.3 to a case study in Iowa. We focus on the effect of various policies and different market assumptions on the equilibrium market outcomes. The purpose is to illustrate the capacity of the proposed models.

[4] In fact, for setting a biofuel target, the regulatory body in US, Environmental Protection Agency (EPA), applied a uniform percentage to each blender based on either projected or its historical production level. Therefore, T_b^{REQ} is treated as an exogenous parameter in the paper.

Our analysis is based on 10 scenarios, a combination of policy choices and market structures. We denote policies B, P, and F for the cases that government subsidies are given to the blenders, producers and farmers, respectively. Policy P0 is the case that no subsidy is provided. Additionally, policy B&M represents the case in which RFS and subsidy are jointly implemented through the blenders. In terms of market assumptions, PC and MP correspond to the case of blenders behaving competitively and strategically (market power), respectively. A combination of market and policies assumptions is referred to as {PC, MP}-{P0, B, P, F, B&M}, 10 scenarios in total.

The main data source is summarized in Section 3.4.1. The results are presented in Section 3.4.2. The model is implemented on an Intel(R) Pentium(R) D CPU, Memory 4.00GB, 64-bit Operating System using interface GAMS and solver PATHNLP. Our model of Section 3.4.1 can be solved in a few seconds.

3.4.1 Data source

We rely upon the data from a previous study that examines optimal facility locations, capacities, and biomass and biofuel allocations by [107]. We choose three counties (F1-F3) Franklin, Kossuth, and Webster as farmers, four counties (P1-P4) Cerro Gordo, Hamilton, Jasper, and Palo Alto as producers, and five cities (B1-B5) Cedar Rapids, Davenport-Moline-Rock Island, Des Moines, Iowa City, and Waterloo-Cedar Falls as blenders. The farmers (blenders) are the first three (five) leading counties (cities) with most biomass supply (biofuel demand) from [91] and [35]. The producers are four of the biggest biorefinery facilities in numerical results in the same report. The locations of the above counties and cities are displayed in Figure 3.2. The biomass species we consider in this study are corn stover and switchgrass. Producers are assumed to produce only cellulosic ethanol and biogasoline. Blenders are assumed to blend cellulosic ethanol and conventional gasoline into E10 (with 10% of cellulosic ethanol and 90% of biogasoline). Data sources for all parameters in this model are listed in Table 3.1.

3.4.2 Numerical results

In this section, we present the results of a variety of scenarios. Section 3.4.2.1 presents base case results for the biofuel market. Farmers' optimal land allocation strategy, producers' biofuel production plan, blenders' optimal biofuel blend, biomass prices between farmers and producers, cellulosic biofuel prices between producers and blenders, and blended biofuel market prices faced by consumers are presented to provide a general picture of the biofuel market under the current parameter set and market structure assumptions. The effect of the blenders' market power will be illustrated in Section 3.4.2.2. Two scenarios are compared: the scenario that no blender has market power and that in which blenders have market power. The purpose is to investigate the impacts of the blenders' market power on various outcomes that are presented in Section 3.4.2.1. Section 3.4.2.3 presents the effects of different policies under the scenario that blenders have no market power. Insights and suggestions will be provided on government policy-making to encourage biofuel industry investment while preventing market power.

3.4.2.1 Base scenario

The base scenario is the case in which all stakeholders take the price as given and compete in markets (i.e. PC scenario). Figure 3.2 shows selected results under the market structure PC. In this figure, the solid arrows are biomass flows sold from the farmers to producers, and dash arrows are biofuel flows sold from the producers to blenders. Detailed transportation quantities for biomass and biofuels are shown in Tables 3.2 and 3.3, respectively. The pie-charts of farmers F1-F3 illustrate farmers' percentage production for corn stover and switchgrass. Similarly, the pie-charts for producers P1-P4 illustrate producers' production quantity in percentage for cellulosic ethanol and biogasoline. Note that land use of corn stover is more than switchgrass for both scenarios. This is because the average cost of corn stover ($36.67/ton) is less than switchgrass ($51.60/ton). Table 3.5 shows that the general ethanol production level is lower than the biogasoline production level. The reason is that for each ton of biomass purchased from farmers, the conversion cost for biogasoline ($2.55/gal) is higher than that of cellulosic ethanol ($2.15/gal for corn stover and $ 1.87/gal for switchgrass), and the selling prices of biogasoline are even higher than cellulosic biogasoline. (Selling prices of biogasoline are $4.40/gal for producers P1, P2, and P3 and $4.39/gal for P4, while the selling prices for cellulosic ethanol are $2.97/gal for P1 and P2, $3.00 and $2.94/gal for P3 and P4 respectively.) Overall, biogasoline is more profitable than cellulosic ethanol. Additionally, less corn stover is used to produce cellulosic ethanol, because the corn stover unit conversion cost is higher than that of switchgrass, and the ethanol conversion yield for corn stover is lower than that of switchgrass. However, for biogasoline, unit conversion costs are the same, and switchgrass has a higher biofuel yield. Hence, more corn stover is used to produce biogasoline than switchgrass.

Table 3.2 shows the quantities of biomass shipped from farmers to producers. For instance, the corn stover transportation quantity from farmer F1 to producer P1 is 128 k tons. The corn stover prices for farmers F1, F2, and F3 are $59.61, $53.89, and $58.63/ton, respectively. The switchgrass prices for farmers F1, F2, and F3 are $67.00, $62.89, and $66.02/ton, respectively. The price differences of corn stover and switchgrass reflect their relative yields and production costs. In this model, biomass shipment cost is paid by the producers. Recall that these prices do not include transportation costs. Had the transportation costs been included, the pair of farmers and producers with a positive shipment quantity would have the same total gate prices. This is because shipping capacity is not limited, and any price differential will be arbitraged away. Any zero shipment implies a higher gate price. For example, producer P3 purchases corn stover from farmers F1 and F3, since the corn stover gate price for F1 and F3 are equivalent: F1: $59.61+$19.07=$78.68/ton, and F3: $58.63+$20.05=$78.68/ton in which $19.07 and $20.05 are transportation costs to producer P3 from farmers F1 and F3, respectively. However the gate price from F2 is $53.89+$30.55=$84.44/ton, which is much higher than that of F1 and F3. Thereby no biomass was transported from F2 to P3.

Table 3.3 shows the quantities of ethanol and biogasoline from producers to blenders. For instance, ethanol transportation quantity from producer P1 to blender B1 is 1,275 k gallons. The ethanol selling price from producers P1 and P2 equals to $2.97, and $3.00 and $2.94/gal for P3 and P4. The biogasoline selling price from producers P1, P2, and P3 is $4.40, and $4.39/gal for P4. Analogous to the situation between farmers and producers, the biofuel shipment cost is also paid by downstream blenders. Similarly, from the perspective of each blender, we observe that they tend to purchase biofuel from producers with cheaper gate prices. Take blender B1, for example, if blender B1 decides to purchase cellulosic ethanol from producers P1-P4, respectively, it leads to gate prices for P1 and P2 equal to $2.97+ $0.066=$3.036/gal, $3.00+ $0.048=$3.048/gal for P3 and $2.94+ $0.103=$3.043/gal for P4, respectively. Blender B1 would prefer to purchase cellulosic ethanol from P1 and P2 first if they can provide adequate biofuel. If the producer with the lowest gate price cannot provide sufficient biofuel, blenders would choose to purchase from producers with the second lowest gate price. Likewise, blender B2 would choose to purchase 1,918 k gallons of cellulosic ethanol (Table 3.3) from producer P2 first with the lowest price \$2.97+ \$0.109=\$3.079/gal. However because producer P2 cannot provide enough ethanol, the blender B2 would have to purchase an additional 107 k gallons from the producer P3 with a price \$3.082/gal(=\$3.00+ \$0.082).

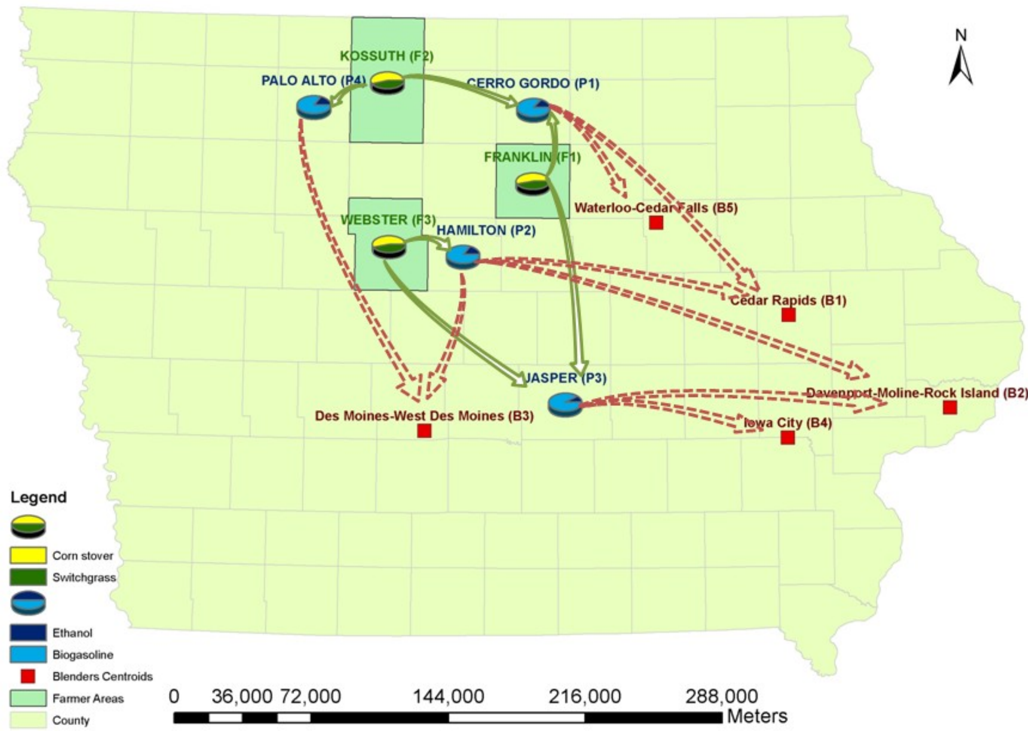

Figure 3.2 Supply chain results for base scenario case study

3.4.2.2 Effects of blenders' market power

This section reports the results from comparing the market structure that allows blenders to exercise market power to the case which blenders behave competitively as in Section 3.4.2.1. These results are summarized in Tables 3.4-3.10 for scenarios PC-P0 and MP-P0.

Blenders play a crucial role in the supply chain of the biofuel industry. A blender can exercise "monopsony" power by reducing cellulosic biofuel purchased quantities in order to lower the payment to producers. On the other hand, they can act as a seller to sell ethanol fuel mixtures to consumers, thereby exercising "monopsony" power by restricting their sales to raise the price. For example, Table 3.9 suggests that blender B1 can effectively reduce its procurement quantities of cellulosic ethanol from producers by 49.82% (from 1,371 k gallons in PC, to 688 k gallons in MP) and reduce cellulosic biofuel purchasing prices (Table 3.7) by 5.93% (from \$2.97+\$0.066=\$3.036/gal in PC, to \$2.79+\$0.066=\$2.856/gal in MP). At the same time, blenders can exercise monopoly power by withholding its sales to consumers by 6,830 k gal (ten times of cellulosic ethanol purchasing quantities because of the blending percentage of E10), and push up the market price of E10 from \$3.37/gal in PC to \$10.80/gal in MP (Table 3.8). Overall, profits of the blenders are increased by \$105.61, \$155.75, \$230.52, \$62.89, and \$ 68.12 million for blenders B1-B5, respectively (Table 3.10). The increase in their profits is at the expense of both biofuel producers and consumers. The consumer surplus drops by \$888.52 million. As a result of lower biofuel consumption, producers will decrease biofuel production level (Table 3.5), and hence farmers reduce their biomass production, as alluded to in Table 3.4.

Turning to the social surplus in Table 3.10 under PC, in which blenders behave competitively, this leads to a higher total social surplus (=consumers' surplus + blenders' surplus + biofuel producers' surplus + farmers' surplus) of \$300.19 million. (Recall that payment between farmers and biofuel producers, between biofuel producers and blenders, and between blenders and consumers, all represent internal wealth transfer between entities in the market, and these payments will cancel out in total surplus calculation.) Comparing these two market structures that blenders behave competitively and when blenders are allowed to exercise market power, the blenders' total profits increase by \$622.91 million at the expenses of other entities: farmers (-\$6.63 million), producers (-\$27.91 million), and consumers (-\$888.52 million) (see Figure 3.3).

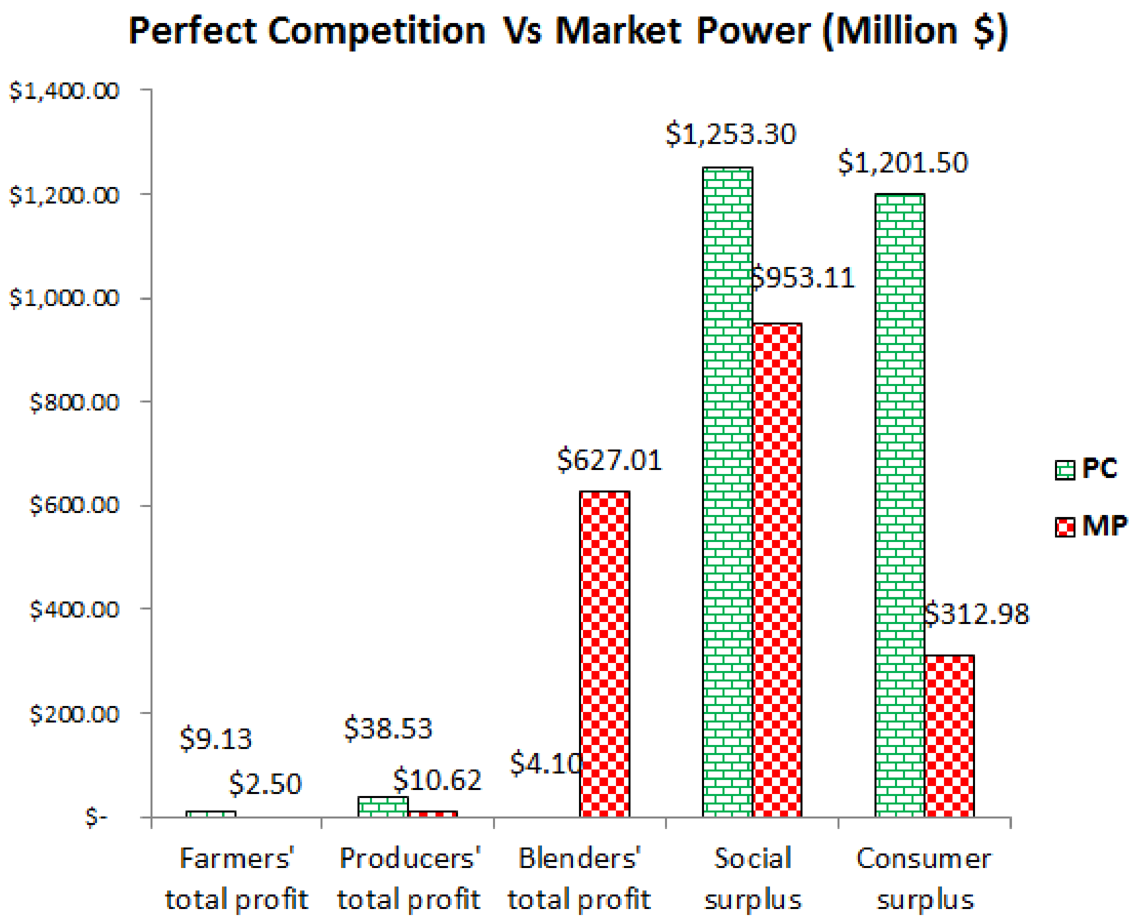

Figure 3.3 Blenders' market power effect on profit and surplus

3.4.2.3 Effects of different policies and points-of-implementation on market outcome

This section focuses on comparing the results of perfect competition when the recipients of the biofuel subsidy are different: no policy PC-P0, biofuel blenders PC-B, biofuel producers PC-P, farmers PC-F, and subsidy and biofuel mandate are both imposed on blenders PC-B&M under the structure that all blenders behave competitively. To make the comparison meaningful, the aggregated subsidy is equivalent across the three scenarios (PC-B, PC-P, and PC-F). The two key questions are: (1) whether policies with different points of implementation lead to different market outcomes, and (2) what the distributional effects are on any of the market participants. The main results are displayed in Tables 3.4-3.10 labeled as PC-B, PC-P, PC-F, and PC-B&M, respectively.

Several observations emerge from Tables 3.4-3.10. First, market outcomes under the scenarios when the government subsidy is provided to blenders and producers (PC-B and PC-P) are equivalent. For example, market prices for five demand areas for E10 are \$3.27, \$3.30, \$3.35, \$3.24, and \$3.24/gal, respectively (Table 3.8) if government subsidy is given to blenders, which is lower than the scenario when no policy is imposed on the biofuel supply chain (PC-P0) which are \$3.27, \$3.40, \$3.44, \$3.34, and \$3.34/gal for the five demand areas (see Figure 3.4). Another way to look at the impacts of government subsidy on market outcomes is to inspect the KKT conditions (3.23). If blenders are subsidized, an extra term $-S^{\mathrm{B}}_{m}\theta_{m}$ is added to the right of the sign $\perp$. This term effectively offsets the production cost of blenders, leading to an increase in biofuel blending quantity, and therefore, an increase in the biofuel purchasing quantity from producers and increase in biomass production for farmers. The increase in biomass and biofuel production quantities is driven by higher selling prices for biomass and biofuels. Second, while the prices of cellulosic ethanol and biogasoline are different when the producers sell to blenders, they become equivalent if incorporating transportation cost. Similar results have been discussed in Section 3.4.2.1 for blenders' biofuel gate prices. Third, when the farmers are the recipients of the subsidies, they would expand their land use because the subsidy is based on per acre. For example, when subsidy is given to farmer F1, the land use for corn stover grows from 93 k acres to 140 k acres (Table 3.4). The expansion of land use leads to an increase in biomass production and so is the cellulosic biofuel production (Table 3.5). Fourth, under the scenario that blenders receive subsidies, the blenders will raise the cellulosic biofuel prices π^{M}_{pbm} to increase biofuel quantities purchased and blended because the subsidy they receive depends on the quantities of blended fuel. For instance, producer P1 increases cellulosic ethanol prices between producers and blenders from \$2.97/gal to \$2.98/gal, and raises biogasoline prices between producers and blenders from \$4.40/gal to \$4.47/gal. On the other hand, if the subsidy to biofuel producers is implemented, the selling prices (to blenders) would be lower owing to the fact that the subsidy is based on the total biofuel that is converted by producers. If subsidy is given to producers, then the right hand side of constraints (3.19) would have an extra term $S^{\mathrm{P}}_{m}Y^{\mathrm{P}}_{pcm}$. This offsets producers' cost and leads to the increase of biofuel production level t^{P}_{pcm} and biomass purchase quantity x^{PC}_{fpc}. This, in turn, increases biomass price π^{C}_{fpc}. For producer P1, the cellulosic ethanol selling price declines from \$2.97/gal to \$1.97/gal, and the biogasoline selling price lowers from \$4.40/gal to \$3.46/gal. In either case, the gate price for consumers will be equivalently lower than the case with subsidy. In other words, consumers will experience the pass-through of the subsidy, regardless of the points-of-implementation of policies. Finally, when farmers receive the subsidy, this leads to higher consumer prices. For example, market price of E10 for blender

B1 is $3.37/gal if no subsidy is imposed on the biofuel market. If subsidy is given to producers (or blenders) and farmers, market prices are $3.27 and $3.30/gal respectively.

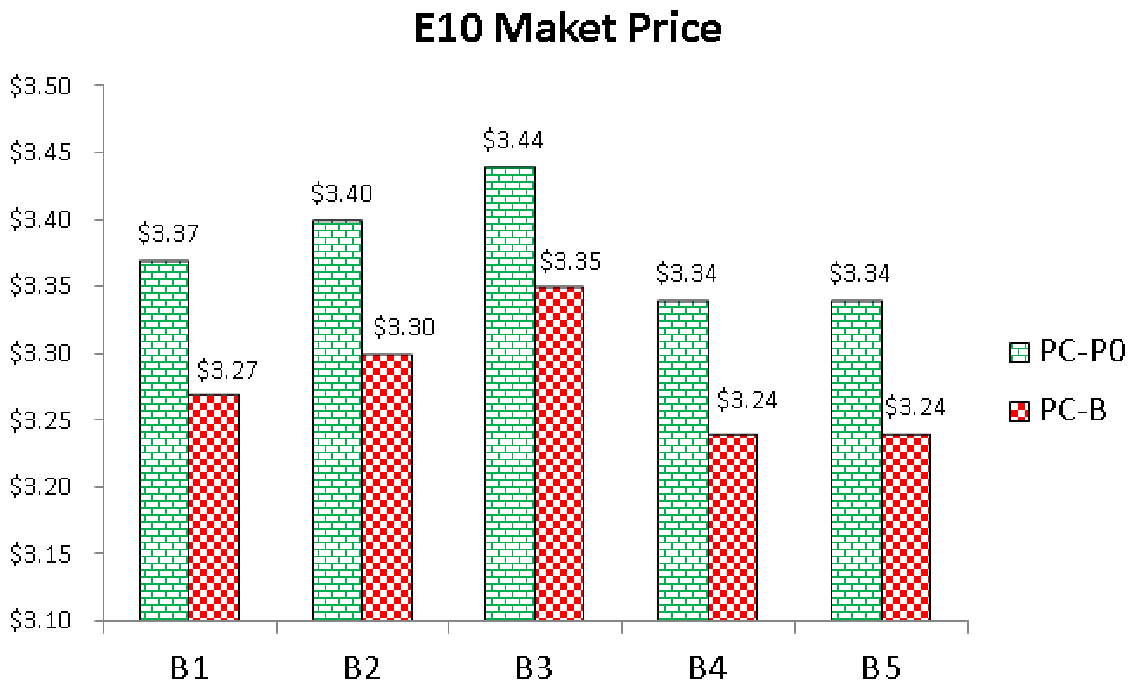

Figure 3.4 E10 market price change with policy PC-B

Next, we examine the pass-through of the subsidy of various entities under different points-of-implementation. The pass-through of subsidy is by the increase of total biofuel production quantity and the change of an equilibrium price for biomass and biofuels. For instance, if a subsidy is given to biofuel producers, then producers will have an incentive to increase the production of biofuels by elevating the purchasing prices of biomass and decrease the selling price of biofuels. As discussed earlier, PC-B and PC-P lead to the same market outcomes. Overall, both upstream and downstream entities benefit from the subsidy. The corresponding profit increases are $1.04, $4.70, $0.06, and $82.90 million for farmers, producers, blenders, and consumer surplus compared to PC-P0, respectively. The profit share for farmers, producers, and blenders are 17.64%, 74.43%, and 7.93%, respectively. Therefore, consumers receive most benefits from the subsidy. On the other hand, when the subsidy is given to the farmers, they are able to retain a significant share of the benefit, increasing their profit from $9.13 to

$18.53 million. As in the scenarios PC-B and PC-P, both producers and blenders only benefit marginally. Figure 3.5 shows the proportion of subsidy obtained by each entity under different policy scenarios. The consumers remain receiving most benefit as its surplus increments to $1259.50 million compared to PC-P0. Finally, when the subsidy is given to the farmers, the market price of E10 and biogasoline is higher than when the subsidy is offered to producers or blenders. The reason is that high subsidies on farmers lead to an expansion of land for growing corn stover and switchgrass. However there is unsold biomass in the market even their prices are zero. This is because the marginal cost of producing biofuel is upward sloping, and the profit margin declines as producers' output increases. At the equilibrium, the profit margin of further output expansion cannot be justified due to the incurred transportation and conversion costs.

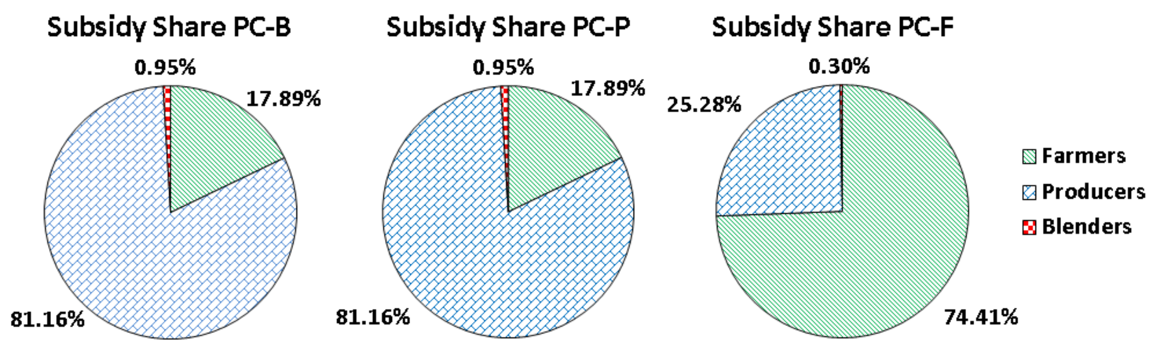

Figure 3.5 Pass-through of government subsidy

If blenders have market power (MP), similar results as in Section 3.4.2.3 can be seen. Different policies have similar effects on the biofuel supply chain under both market structure PC and MP. For each policy, a similar effect as presented in Section 3.4.2.2 can be seen in Tables 3.4-3.10. If blenders have market power, then they can increase their profits greatly by exercising market power and their total profit will take a relatively larger percentage in the total profits as shown in Table 3.10. For example, if subsidy is given to blenders under market structure MP, then the blenders' total profit will be $ 671.32 million out of $ 685.99 million for the whole biofuel market. For completeness, we also present the effect of various policies under market structure MP.

3.4.3 Effect of combined policy

If both subsidies and biofuel mandate are imposed on blenders, then compared with scenario PC-B, a larger government subsidy will be given to the biofuel market since the subsidy per gallon of biofuel stays the same while a higher biofuel production level is observed. Therefore, more cellulosic biofuels are blended and sold into market, and hence market price of E10 and biogasoline will be lower relative to the scenario in which only a subsidy is imposed on blenders. For example, the biogasoline market price for blender B5 decreases from \$3.46/gal to \$3.45/gal, which leads to higher demand from blenders, and therefore increasing production level of cellulosic biofuels as shown in Table 3.5. (i.e. Producer P1 produces biogasoline from 134.89 k gallons under scenario PC-P to 134.96 k gallons under scenario PC-B&M). Farmers will expand land use for biofuel crops to meet a higher biomass demand (i.e. Farmer F1 will expand its land use for corn stover from 97.40 under scenario PC-P to 97.45 k acres under scenario PC-B&M). If blenders are under perfect competition, then the RINs price for cellulosic biofuels in market is \$0.01/gal. This price goes up when a higher biofuel mandate from government is implemented. Low RINs price is observed here because we assume that blended fuels and conventional fuels are not substitutable. We suspect a higher RINs price for cellulosic biofuels if this assumption is relaxed. This will be addressed in future research efforts. The impact of market power on RINs price depends on how mandate is imposed. In our case, because mandate is an exogenous parameter, the market power will lead to a higher RINs price.

3.5 Conclusion

Although still subject to debates, the biofuel sector is expected to play a crucial role in reducing greenhouse gas emission in the transportation sector. One emerging concern that has received little attention by the academic or government community is a lack of tools with adequate details and flexibility to examine the implication of various policy designs or market competitions in biofuel supply chain. In particular, policies with different points-of-implementation or interactions of various concurrent policies in the presence of an oligopoly market structure might lead to suboptimal market outcomes that discourage biofuel production.

In this paper, we have developed a bottom-up equilibrium optimization model to study the supply chain of the biofuel market, considering farmers, biofuel producers, blenders and consumers. The model is built on individual's optimization problem and is solved for farmers' land allocation, biomass transportation, biofuel production and biofuel blending activities. The prices in the market are determined endogenously through supply-demand conditions. The model also allows for the consideration of market structure or firms' horizontal and vertical ownership that may arise to oligopoly competition at different segments of the supply chain. We applied the models to a case study in the state of Iowa, considering scenarios with a combination of policies with different points-of-implementation and market structures.

There are several findings in this paper. First, policies with different points-of-implementation could lead to different market outcomes. In particular, when subsidies are given to the farmers, they would choose to expand crop land, and produce more biomass, leading to a drop in biomass and biofuel selling prices. Therefore, biofuel producers also benefit from the policy due to the pass-through of subsidies that reduces biomass selling prices.[5] Perhaps surprisingly, it results in higher fuel prices. Because aggregate subsidy is the same across policies, excessive biomass produced by farmers means that less per-unit pass-through that the producers can benefit from. This results in a lower production of biofuel, and higher biofuel prices. While all biomass purchased by producers is used for biofuel production, not all biomass produced by farmers is sold to producers. There is unsold biomass as indicated by the solutions in the equilibrium. (Even surplus biomass implied that farmers would provide biomass for free, there is still cost associated with transportation paid by producers). On the other hand, when subsidies are given to either blender or producer, it could yield the same market equilibrium. In all cases, consumers will benefit from lower fuel prices, owing to the passthrough of the subsidies. This suggests that to whom the subsidies were given by the government has important market and policy implications that go beyond simply distribution of economic rent or fairness considerations. Therefore a careful examination should be given when government determines subsidy policies. Second, when the blenders in the supply chain are allowed to exercise monopsony power to upstream producers and monopoly power to the downstream consumers, they can earn substantial profits at expense of other entities in the markets. This is specifically critical as the biofuel sector is still at early stage of development. Any distortion of market outcomes when blenders exercise market power might discourage the investment of biofuel infrastructure in the long run. Thus, a strong government oversight of

[5] So pass-through is a measurement of the incidence of a proposed policy. In case of taxes, the pass-through measures the "cost" of a regulation to different entities in the market.

the market is necessary to prevent biofuel blenders from exercising market power. Third, on the methodological side, our model allows for endogenously determining the RINs price for cellulosic biofuels by explicitly modeling the RINs price in the equilibrium model. This would provide a useful tool as the industry or government would be interested in understanding the underlying factors that derive RINs prices.

Our study is subject to a number of limitations. First, our model assumes that all biomass produced is sold to producers for biofuel production. In the real world, farmers have options to sell it to the biofuel market or other markets for heating or electricity generation, which we did not consider. Second, only two biofuel products are considered in the model (ethanol fuel mixture and biogasoline). They are assumed to be not substitutable, and, therefore, each biofuel has its own market. Third, in our model, we assume that each blender serves its own local biofuel market instead of competing with all other blenders. For future work we could consider that each blender can supply different biofuel markets and each market can be supplied by different blenders. Fourth, our model assumes that biomass yield is known beforehand, which is not the case in reality. If biomass yield is uncertain in the model, then the farmers' decision on land allocation and the whole biofuel supply chain could be different. Fifth, the biofuel industry is a long term investment, therefore instead of evaluating one year profitability, a long term planning under policy uncertainty would be more realistic. Regardless of these limitations, we believe that our model has advanced tools which are sufficiently flexible to address important policy questions in the biofuel sector. We shall address these limitations in our future research.

Table 3.1 Data sources for biofuel bottom-up equilibrium model

Parameters	Data	Data source	
L_f	Total area of land available	F1: 372,460.8 acres	[91]
		F2: 622,540.8 acres	
		F3: 457,996.8 acres	
C^{F}_{fc}	Intercept of farm production cost	Corn stover: $74.07/acre	[57]
		Switchgrass: $133.14/acre	
D^{F}_{fc}	Slope of farm production cost	5×10^{-4}	Assumed
Y^{F}_{fc}	Crop c yield	Corn stover: 2.02 ton/acre	[57]
		Switchgrass: 2.58 ton/acre	
S^{F}_{c}	Subsidy for biomass c	$155.69/acre for PC	Aggregated
		$145.44/acre for MP	Aggregated
T^{C}_{c}	Unit transportation cost of crop c	$0.19/ton/mile	[84]
$C^{\mathrm{P}}_{pc,E}$	Intercept of ethanol production cost	Corn stover: $2.15/gal	[70]
		Switchgrass: $1.87/gal	[51]
$D^{\mathrm{P}}_{pc,E}$	Slope of ethanol production cost	1×10^{-7}	Assumed
$C^{\mathrm{P}}_{pc,BG}$	Intercept of biogasoline production cost	$2.55/gal	[60]
$D^{\mathrm{P}}_{pc,BG}$	Slope of biogasoline production cost	1×10^{-7}	Assumed
$Y^{\mathrm{P}}_{pc,E}$	Ethanol conversion rate from	Corn stover: 79 gal/ton	[70]
		Switchgrass: 83 gal/ton	[51]
$Y^{\mathrm{P}}_{pc,BG}$	Biogasoline conversion rate from	Corn stover: 79 gal/ton	[60]
		Switchgrass: 83 gal/ton	[60]
U^{P}_{pc}	Producer capacity	2200 ton/day	[69]
S^{P}_{E}	Subsidy for ethanol	$1.01/gal	[40]
S^{P}_{BG}	Subsidy for biogasoline	$1.01/gal	[40]
T^{M}_{E}	Unit transportation cost of ethanol	$0.1654/ton.mile	[80]
T^{M}_{BG}	Unit transportation cost of biogasoline	$0.0176/ton.mile	[80]
$\overline{p}^{\mathrm{G}}_{b}$	Inverse supply function of gasoline	$3.315/gal	[34]
$\overline{p}^{\mathrm{M}}_{b,E}$	Inverse demand function of E10	B1: $18.2857 - 0.1088 \times 10^{-5} q^E_1$	[64, 35]
		B2: $18.2857 - 0.0735 \times 10^{-5} q^E_2$	
		B3: $18.2857 - 0.0495 \times 10^{-5} q^E_3$	
		B4: $18.2857 - 0.1831 \times 10^{-5} q^E_4$	
		B5: $18.2857 - 0.1691 \times 10^{-5} q^E_5$	
$\overline{p}^{\mathrm{M}}_{b,BG}$	Inverse demand function of biogasoline	B1: $19.8857 - 0.1183 \times 10^{-5} q^{BG}_1$	[64, 35]
		B2: $19.8857 - 0.0800 \times 10^{-5} q^{BG}_2$	
		B3: $19.8857 - 0.0539 \times 10^{-5} q^{BG}_3$	
		B4: $19.8857 - 0.1991 \times 10^{-5} q^{BG}_4$	
		B5: $19.8857 - 0.1838 \times 10^{-5} q^{BG}_5$	
$U^{\mathrm{B}}_{b,E}$	Blender ethanol capacity	5×10^{8} gal/year	Assumed
$U^{\mathrm{B}}_{b,BG}$	Blender biogasoline capacity	5×10^{8} gal/year	
$C^{\mathrm{B}}_{b,E}$	Intercept of ethanol blending cost	$0.1/gal	Assumed
$D^{\mathrm{B}}_{b,E}$	Slope of ethanol blending cost	5×10^{-7}	Assumed
S^{B}_{E}	Subsidy for cellulosic ethanol blended	$1.01/gal	[40]
S^{B}_{BG}	Subsidy for biogasoline sold	$1.01/gal	[40]
T^{REQ}_{b}	Total biofuel production mandate	Assumed	

Table 3.2 Biomass shipment under PC market structure (in k tons)

	Corn stover				Switchgrass			
	P1	P2	P3	P4	P1	P2	P3	P4
F1	128	0	59	0	142	0	63	0
F2	0	0	0	141	0	0	0	150
F3	0	131	49	0	0	146	46	0

Table 3.3 Biofuel shipment under PC market structure (in k gallons)

	Cellulosic ethanol					Biogasoline				
	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
P1	1,275	0	0	0	884	11,283	0	0	0	8,425
P2	96	1,918	357	0	0	1,805	10,468	7,799	0	0
P3	0	107	0	816	0	0	8,881	0	7,776	0
P4	0	0	2,641	0	0	0	0	20,932	0	0

Table 3.4 Biomass land use (in k acres)

	Corn stover			Switchgrass		
	F1	F2	F3	F1	F2	F3
PC-P0	93	70	89	79	58	74
PC-B	97	74	93	84	61	79
PC-P	97	74	93	84	61	79
PC-F	140	140	140	79	58	74
PC-B&M	97	74	93	84	61	79
MP-P0	51	38	47	40	30	35
MP-B	54	40	50	42	31	37
MP-P	54	40	50	42	31	37
MP-F	95	95	95	40	29	35
MP-B&M	59	44	55	46	34	41

Table 3.5 Biomass processed for ethanol and biogasoline production (in k ton)

		Cellulosic ethanol				Biogasoline			
		P1	P2	P3	P4	P1	P2	P3	P4
PC-P0	Corn stover	0	0	0	4	128	130	108	137
	Switchgrass	26	28	11	28	116	118	98	122
PC-B	Corn stover	0	0	0	3	135	137	115	144
	Switchgrass	26	28	11	29	123	125	105	129
PC-P	Corn stover	0	0	0	3	135	137	115	0
	Switchgrass	26	28	11	29	123	125	105	129
PC-F	Corn stover	5	7	0	2	139	140	120	139
	Switchgrass	23	26	9	26	117	119	99	123
PC-B&M	Corn stover	0	0	0	3	135	137	115	144
	Switchgrass	26	28	11	29	123	125	105	129
MP-P0	Corn stover	0	0	0	0	72	74	52	77
	Switchgrass	15	18	1	15	58	60	40	61
MP-B	Corn stover	0	0	0	0	76	78	56	81
	Switchgrass	15	18	1	15	62	64	44	65
MP-P	Corn stover	0	0	0	0	76	78	56	81
	Switchgrass	15	18	1	15	62	64	44	65
MP-F	Corn stover	0	0	0	0	79	80	59	79
	Switchgrass	15	18	1	15	58	60	40	61
MP-B&M	Corn stover	0	0	0	0	83	85	63	89
	Switchgrass	15	18	1	16	69	71	51	73

Table 3.6 Sales weighted biomass prices between farmers and producers (in $/ton)

	Corn stover			Switchgrass		
	F1	F2	F3	F1	F2	F3
PC-P0	59.61	53.89	58.63	67.00	62.89	66.02
PC-B	60.78	54.97	59.79	67.85	63.50	66.86
PC-P	60.78	54.97	59.79	67.85	63.50	66.86
PC-F	0.00	0.00	0.00	11.00	6.92	10.02
PC-B&M	60.79	54.98	59.81	67.86	63.51	66.87
MP-P0	49.35	46.14	48.37	59.35	57.33	58.36
MP-B	50.01	46.62	49.03	59.78	57.64	58.79
MP-P	50.01	46.62	49.03	59.78	57.64	58.79
MP-F	0.00	0.00	0.00	12.23	10.23	11.25
MP-B&M	51.26	47.52	50.28	60.60	58.24	59.61

Sales weighted price is the price calculated by $\frac{\sum_p \text{Price}_p \times \text{quantity}_p}{\sum_p \text{quantity}_p}$

Table 3.7 Sales weighted ethanol and biogasoline prices between producers and blenders (in \$/gal)

	Cellulosic ethanol				Biogasoline			
	P1	P2	P3	P4	P1	P2	P3	P4
PC-P0	2.97	2.97	3.00	2.94	4.40	4.40	4.40	4.39
PC-B	2.98	2.98	3.01	2.95	4.47	4.47	4.47	4.47
PC-P	1.97	1.97	2.00	1.94	3.46	3.46	3.46	3.46
PC-F	2.28	2.28	2.31	2.25	3.73	3.73	3.74	3.73
PC-B&M	2.98	2.98	3.01	2.95	4.47	4.47	4.47	4.47
MP-P0	2.79	2.79	2.82	2.76	3.83	3.83	3.83	3.82
MP-B	2.80	2.80	2.83	2.77	3.86	3.86	3.87	3.86
MP-P	1.79	1.79	1.82	1.76	2.85	2.85	2.86	2.85
MP-F	2.22	2.23	2.26	2.19	3.26	3.26	3.26	3.25
MP-B&M	2.81	2.81	2.84	2.78	3.93	3.93	3.94	3.93

Table 3.8 E10 and biogasoline market prices (in \$/gal)

	E10					Biogasoline				
	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
PC-P0	3.37	3.40	3.44	3.34	3.34	4.40	4.41	4.40	4.40	4.40
PC-B	3.27	3.30	3.35	3.24	3.24	3.46	3.47	3.46	3.46	3.46
PC-P	3.27	3.30	3.35	3.24	3.24	3.46	3.47	3.46	3.46	3.46
PC-F	3.30	3.33	3.38	3.27	3.27	3.74	3.74	3.74	3.74	3.74
PC-B&M	3.27	3.30	3.34	3.24	3.24	3.45	3.46	3.45	3.46	3.45
MP-P0	10.80	10.81	10.82	10.79	10.79	11.86	11.86	11.86	11.86	11.86
MP-B	10.75	10.76	10.77	10.74	10.74	11.37	11.38	11.37	11.37	11.37
MP-P	10.75	10.76	10.77	10.74	10.74	11.37	11.38	11.37	11.37	11.37
MP-F	10.77	10.78	10.79	10.77	10.76	11.57	11.58	11.57	11.57	11.57
MP-B&M	10.65	10.67	10.67	10.65	10.65	10.45	10.45	10.45	10.45	10.45

Table 3.9 Blender *b*'s cellulosic ethanol and biogasoline purchasing quantities (in k gallons)

	Cellulosic ethanol					Biogasoline				
	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
PC-P0	1,371	2,025	2,998	816	884	13,088	19,349	28,731	7,776	8,425
PC-B	1,380	2,038	3,018	822	890	13,882	20,523	30,473	8,248	8,936
PC-P	1,380	2,038	3,018	822	890	13,882	20,523	30,473	8,248	8,936
PC-F	1,378	2,034	3,012	820	888	13,648	20,177	29,960	8,109	8,786
PC-B&M	1,381	2,039	3,018	822	890	13,890	20,534	30,489	8,253	8,941
MP-P0	688	1,017	1,509	409	443	6,785	10,031	14,893	4,031	4,368
MP-B	693	1,024	1,519	412	446	7,196	10,639	15,796	4,276	4,632
MP-P	693	1,024	1,519	412	446	7,196	10,639	15,796	4,276	4,632
MP-F	691	1,021	1,514	411	445	7,026	10,388	15,424	4,175	4,523
MP-B&M	701	1,037	1,538	417	452	7,976	11,792	17,509	4,739	5,135

Table 3.10 Profit of market entities under various policies (in $ million)

Profit	PC-P0	PC-B	PC-P	PC-F	PC-B&M	MP-P0	MP-B	MP-P	MP-F	MP-B&M
F1	3.73	4.13	4.13	6.48	4.13	1.06	1.17	1.17	2.64	1.41
F2	2.06	2.31	2.31	5.76	2.31	0.58	0.65	0.65	2.46	0.77
F3	3.35	3.73	3.73	6.29	3.74	0.86	0.97	0.97	2.54	1.18
Total	9.13	10.17	10.17	18.53	10.18	2.50	2.79	2.79	7.64	3.36
P1	9.95	11.13	11.13	11.00	11.14	2.87	3.20	3.20	3.17	3.86
P2	10.35	11.56	11.56	11.29	11.57	3.10	3.43	3.43	3.32	4.11
P3	6.98	7.99	7.99	7.90	8.00	1.42	1.65	1.65	1.64	2.14
P4	11.25	12.55	12.55	11.54	12.56	3.23	3.60	3.60	3.29	4.35
Total	38.53	43.23	43.23	41.72	43.27	10.62	11.88	11.88	11.42	14.46
B1	0.47	0.48	0.48	0.47	0.33	106.08	113.58	113.58	110.42	112.29
B2	1.03	1.04	1.04	1.03	0.82	156.78	167.86	167.86	163.19	165.96
B3	2.25	2.28	2.28	2.27	1.95	232.77	249.22	249.22	242.29	246.39
B4	0.17	0.17	0.17	0.17	0.08	63.06	67.51	67.51	65.63	66.74
B5	0.20	0.20	0.20	0.20	0.10	68.32	73.15	73.15	71.11	72.32
Total	4.10	4.16	4.16	4.14	3.29	627.01	671.32	671.32	652.65	663.70
ω	1,201.50	1,284.40	1,284.40	1,259.50	1,285.20	312.98	335.14	335.14	325.80	380.43
ϕ	0.00	91.11	91.11	91.11	91.16	0.00	47.10	47.10	47.10	51.81
σ	1,253.30	1,250.90	1,250.90	1,232.70	1,250.80	953.11	1,021.10	1,021.10	997.52	1,061.90

CHAPTER 4. IMPACTS OF FLEXIBLE FUEL VEHICLES IN IMPERFECTLY COMPETITIVE BIOFUEL MARKETS

4.1 Introduction

Nowadays most of the United States transportation system is fueled by gasoline and diesel. US transportation fuel has mainly relied on petroleum imported from foreign countries or produced domestically. To improve the national energy independency and reduce greenhouse gas emissions from transportation sector, two different strategies are being explored: improving vehicle fuel efficiency and incorporating renewable transportation fuels. Vehicle technology has significantly improved vehicle fuel efficiency over years. However, US is still far from reducing petroleum dependence. Incorporating renewable fuel into the transportation sector has been brought to the forefront of the discussion in academic, industry, and government entities. Different alternative fuels are being studied, such as biodiesel, electricity, ethanol, hydrogen, natural gas, and propane [28]. Among the alternative fuels vehicles, Flexible Fuel Vehicles(FFVs), which can run on gasoline-ethanol blends with up to 85% ethanol blended into gasoline, is one of the promising alternative fuel vehicles.

Ethanol has been the main renewable fuel used in the transportation sector. Modern vehicle could run on fuel with up to 10%-15% of ethanol blended in to gasoline without making any modification to the vehicle. Now almost all gasoline sold in US is blended with up to 10% ethanol (E10) [77]. E10 and gasoline are perfectly substitutable since no vehicle engine modification is needed.

To reduce greenhouse gas emission and the fuel dependency on gasoline, US government and different automakers have turned their attentions to FFVs, which can be fueled with ethanol fuel mixture up to E85 [78, 27]. Over the past years, the number of FFVs in US has been increasing steadily from 87,570 in year 2000 to 862,840 in year 2011 [29], and the number of E85 fuel stations has been growing quickly [30].

There are, however, still obstacles to the wide adoption of FFVs in the market. Consumers' awareness and willingness to switch to FFVs [23], limited accessibility of flexible fuels stations [30], and relative higher price of E85 in terms of energy content [31] are among the major reasons for the current low penetration in the market. With the limited accessibility of ethanol in the flexible fuel market also rises the issue of imperfectly competitive cellulosic biofuel markets, as explained in [52]. In the advanced biofuel markets, it is possible for stakeholders to possess the ability to manipulate prices instead of as price takers of ethanol products. With the increasing of FFVs penetration levels, it is of interest to develop models to address the following questions: how the ethanol fuel mixture market prices change, how different stakeholders interact in the imperfectly competitive markets, whether it is profitable to invest in the cellulosic biofuel industry, etc.

There has been an emerging literature on the penetration of alternative fuel vehicles in the markets. Studies have been done on the consumers' willingness to pay for E85 and E10 [2, 59, 72], as well as economic sustainability of E85 as transportation fuel [88, 74]. A number of approaches have been proposed to study the penetration of alternative fuel vehicles in the markets. For example, Chen et al. [21] considered ethanol and gasoline competition based on vehicle kilometers traveled, assuming perfect substitution of ethanol and gasoline on energy equivalent basis in perfectly competitive markets. Eppstein et al. [36] proposed an agent-based vehicle consumer model to investigate the penetration of plug-in hybrid vehicle in market. Beresteanu et al. [11] simulated the demand for hybrid vehicles and the overall market outcomes under different gasoline price and federal support schemes. Gallagher et al. [45] built Generalized Linear Models to find factors impacting the adoption of alternative fuel vehicles. In this chapter, we aim to investigate the impacts of FFVs on the biofuel markets in a bottom-up equilibrium model framework considering imperfectly competitive biofuel markets. The constant elasticity demand functions are applied to representing the penetration level of FFVs in transportation vehicle markets.

More specifically, the constant price elasticity of demand function for E10 and E85 takes the form of

$$q_{E10} = a_{E10} p_{E10}^{e_{E10,E10}} p_{E85}^{e_{E10,E85}}, \text{ and} \tag{4.1}$$

$$q_{E85} = a_{E85} p_{E10}^{e_{E85,E10}} p_{E85}^{e_{E85,E85}} \tag{4.2}$$

where $(p_{E10}, q_{E10}), (p_{E85}, q_{E85})$ indicate the price and quantity pairs for E10 and E85; $e_{E10,E10}$ ($e_{E85,E85}$) represents the own price elasticity of demand for E10 (E85) as shown in Equation 4.3, while $e_{E10,E85}(e_{E85,E10})$ measures the demand change of E10 (E85) in response to the price change of E85 (E10) as shown in Equation (4.4), i.e., cross price elasticity of demand. Cross price elasticity of demand could be used as a measure of the penetration of FFVs in the conventional fuel markets. For instance, with higher penetration of FFVs in the markets, we expect more FFVs in the market, and more consumers could switch between E10 and E85. If the price of E10 increases, consumers would find it economically desirable to consume more E85 instead of E10. Reversely, an increase of E85 market price could lead to more consumption of E10. This concept of FFVs penetration could be explained by cross price elasticity $e_{E10,E85}, e_{E85,E10}$. By the definition of $e_{E10,E85}$, 1% of increase in E85 market price would lead to $e_{E10,E85}$% of increase in E10 consumption. With the increase of $e_{E10,E85}$, we expect more consumers would switch to consume E10 when E85 price increases. Therefore, constant elasticity of demand functions could be used to represent the penetration of FFVs in the markets. Note that $e_{E10,E85}$ is small as theory suggests that the market equilibrium only exists when the market is imperfectly competitive (see Appendix B for more detail).

$$e_{E10,E10} = \frac{\frac{\partial q_{E10}}{q_{E10}}}{\frac{\partial p_{E10}}{p_{E10}}} \tag{4.3}$$

$$e_{E10,E85} = \frac{\frac{\partial q_{E10}}{q_{E10}}}{\frac{\partial p_{E85}}{p_{E85}}} \tag{4.4}$$

This chapter aims to answer the following research questions: What are the impacts of blenders' market power on the emerging biofuel market outcomes? How could FFVs penetration on the transportation vehicle markets affect the market outcomes in imperfectly competitive biofuel markets? Which stakeholder would benefit most from the increasing of FFVs penetration (fuel substitution)?

The rest of the chapter is organized as follows. In Section 4.2 the model formulation is introduced. Solution techniques for the complementarity problem are presented in Section 4.3. A case study in the state of California and some preliminary results are shown in Section 4.4. Model summary and some future research directions are summarized in Section 4.5.

4.2 Model formulation

We consider four main stakeholders in the biofuel supply chain: farmers (or biomass supplier), biofuel producers, biofuel blenders, and blended fuel consumers in this study. The framework of the model is shown in Figure 4.1. It is assumed that farmers supply biomass to biofuel producers based on a bilateral agreement. Biofuel producers convert biomass into cellulosic ethanol. Cellulosic ethanol is then purchased by biofuel blenders to be blended with conventional gasoline into ethanol fuel mixtures for vehicle consumption. Transportation cost for biomass is assumed to be paid by biofuel producers, transportation cost for produced biofuel and blended fuels are both at the expense of biofuel blenders. Each stakeholder has its own profit maximization model, and the stakeholders (farmers, biofuel producers, and biofuel blenders) are endogenously connected by supply and demand relationship. For instance, the biomass supply from the farmers should be equal to the demand for biomass from biofuel producers, the supply of biofuel from biofuel producers should match biofuel demand from biofuel blenders. Note that blenders sell blended fuels to various markets, and consumer markets are represented by demand functions with constant elasticity of demand.

In this section, we will first show the notations of the model using lower case for variables and upper case for parameters in Section 4.2.1. The optimization models for the stakeholders are shown in Section 4.2.2-4.2.5.

4.2.1 Notation

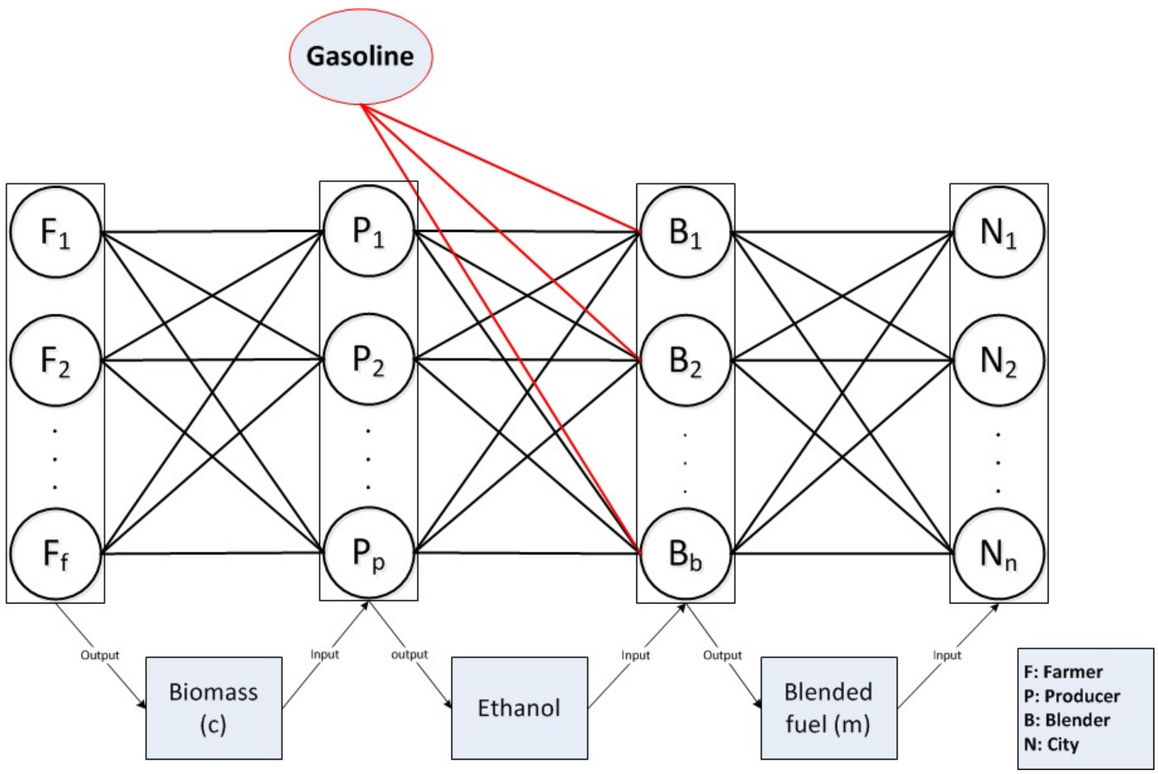

Figure 4.1 Market structure of the biofuel supply chain

Sets and indices

F ($f \in$ F)	Set of farmers
P ($p \in$ P)	Set of producers
B ($b \in$ B)	Set of blenders
C ($c \in$ C)	Set of crops
M ($m \in$ M)	Set of blended fuels ((e,g), e for E85, g for E10)
N ($n \in$ N)	Set of biofuel consumption cities

Decision variables

a_{cf}	Area of land used by farmer f for crop c [acre]
x^{FC}_{cfp}	Amount of crop c sold by farmer f to producer p [dry ton]
x^{PC}_{cfp}	Amount of crop c purchased by producer p from farmer f [dry ton]
x^{PE}_{pb}	Amount of cellulosic ethanol sold by producer p to blender b [gal]
x^{BE}_{pb}	Amount of cellulosic ethanol purchased by blender b from producer p [gal]
x^{BM}_{mbn}	Amount of biofuel m sold from blender b to city n [gallon]

Market clearing variables

π^{C}_{cfp}	Equilibrium price of biomass between farmers and producers [$/dry ton]
π^{E}_{pb}	Equilibrium price of ethanol between producers and blenders [$/gal]
π^{M}_{mn}	Equilibrium price of biofuel m in city n [$/gal]
π^{G}_{b}	Equilibrium price of conventional gasoline for blender b [$/gal]

Dual variables

τ_{f0}	Dual variable for land availability constraints
τ_{cf}	Dual variable for biomass yield constraints
α_p	Dual variable for producer capacity constraints
β_p	Dual variable for ethanol convertion constraints
κ_b	Dual variable for ethanol balance constraints

Parameters

L_f	Farmer f's total area of land available for biofuel crops [acre]
Y^{F}_{cf}	Farmer f crop c yield [ton/acre]
C^{F}_{cf} (D^{F}_{cf})	Intercept (slope) of farmer f's linear production cost function from biomass c
T^{C}_{cfp}	Transportation cost for biomass c from farmer f to producer p [\$/wet ton]
$Moist_c$	Moisture content for biomass c
D^{FP}_{cfp}	Distance from farmer f to producer p [mile]
C^{P}_{c} (D^{P}_{c})	Intercept (slope) of producer p's linear production cost function from biomass c
Y^{P}_{c}	Producer p's conversion rate from crop c to ethanol [gal/dry ton]
T^{M}_{pb}	Transportation cost of ethanol from producers to blenders [\$/gal]
D^{PB}_{pb}	Distance from producer p to blender b [mile]
U^{P}_{p}	Producer p's process capacity [gal/year]
θ_m	The percentage of ethanol in blended fuel m, (e with 85%, g with 10%).
C^{B}_{m} (D^{B}_{m})	Intercept (slope) of blender b's production cost function for each gallon of ethanol blended into biofuel m [\$/gal]
A^{G} (B^{G})	Intercept (slope) of blender b's inverse supply function for conventional gasoline [\$/gal]
D^{BN}_{bn}	Distance from blender b to city n [mile]
A^{M}_{m}	Coefficient of city n inverse demand function for blended fuel m [\$]
B^{ME}_{m}	Coefficient of city n inverse demand function for E85, e, g coefficients [\$/gal]
B^{MG}_{m}	Coefficient of city n inverse demand function for E10, e, g coefficients [\$/gal]
$e_{m_1 m_2}$	Own /cross price elasticity of biofuel m_1 to m_2 (where $m_1, m_2 \in \mathrm{M}$)

4.2.2 Farmer f's profit maximization model

In this model we assume that farmers can produce different types of biomass and sell to cellulosic biofuel producers. The profit maximization model for farmer f is as follows.

$$\max_{a,x} \quad \sum_{cp} \pi^{\mathrm{C}}_{cfp} x^{\mathrm{FC}}_{cfp} - \sum_{c} \left(C^{\mathrm{F}}_{cf} a_{cf} + \frac{1}{2} D^{\mathrm{F}}_{cf} a^2_{cf} \right) \tag{4.5}$$

$$s.t. \quad \sum_{c} a_{cf} \leq L_f \qquad (\tau_{f0}) \tag{4.6}$$

$$\sum_{p} x^{\mathrm{FC}}_{cfp} \leq Y^{\mathrm{F}}_{cf} a_{cf} \qquad (\tau_{cf}) \tag{4.7}$$

$$a_{cf}, x^{\mathrm{FC}}_{cfp} \geq 0 \tag{4.8}$$

Here $\sum_{cp} \pi^{\mathrm{C}}_{cfp} x^{\mathrm{FC}}_{cfp}$ is farmer f's revenue from selling biomass. The second summation in equation (4.5) is the total cost for biomass production. Land availability constraints are shown in constraint (4.6). Constraint (4.7) implies that the sold biomass should not exceed the available biomass produced in the farm.

4.2.3 Producer p's profit maximization model

In this model we assume that producers purchase different types of biomass from farmers and produce cellulosic ethanol from the biomass. Produced ethanol is then sold to blenders at market prices endogenously determined in the model. Producer p's profit maximization model is as follows.

$$\max \quad \sum_{b} \pi^{\mathrm{E}}_{pb} x^{\mathrm{PE}}_{pb} - \sum_{cf} \pi^{\mathrm{C}}_{cfp} x^{\mathrm{PC}}_{cfp} - \sum_{cf} T^{\mathrm{C}}_{cfp} x^{\mathrm{PC}}_{cfp} / (1 - Moist_c) - \sum_{c} \left[C^{\mathrm{P}}_{c} Y^{\mathrm{P}}_{c} \sum_{f} x^{\mathrm{PC}}_{cfp} + \frac{1}{2} D^{\mathrm{P}}_{c} (Y^{\mathrm{P}}_{c} \sum_{f} x^{\mathrm{PC}}_{cfp})^2 \right] \tag{4.9}$$

$$s.t. \quad \sum_{c} Y^{\mathrm{P}}_{c} \sum_{f} x^{\mathrm{PC}}_{cfp} \leq U^{\mathrm{P}}_{p} \qquad (\alpha_p) \tag{4.10}$$

$$\sum_{b} x^{\mathrm{PE}}_{pb} \leq \sum_{c} Y^{\mathrm{P}}_{c} \sum_{f} x^{\mathrm{PC}}_{cfp} \qquad (\beta_p) \tag{4.11}$$

$$x^{\mathrm{PC}}_{cfp}, x^{\mathrm{PE}}_{pb} \geq 0 \tag{4.12}$$

Here $\sum_{b} \pi^{\mathrm{E}}_{pb} x^{\mathrm{PE}}_{pb}$ is producer p's revenue for selling cellulosic ethanol. $\sum_{cf} \pi^{\mathrm{C}}_{cfp} x^{\mathrm{PC}}_{cfp}$ is biomass purchasing cost. $\sum_{cf} T^{\mathrm{C}}_{cfp} x^{\mathrm{PC}}_{cfp} / (1 - Moist_c)$ is biomass transportation cost. The moisture content is considered here to account for the transportation of biomass in wet ton. The last summation in equation (4.9) is the total cost for ethanol production. Ethanol plant capacity is reflected in constraint (4.10). Constraint (4.11) states that total ethanol sold to blenders should be no more than ethanol produced from biomass.

4.2.4 Blender b's profit maximization model

Blenders purchase conventional gasoline from gasoline wholesale market, and purchase cellulosic ethanol from ethanol producers. Different ethanol fuel mixtures are defined by the percentage of ethanol blended with gasoline, denoted as θ. Produced ethanol fuel mixtures are then sold to different biofuel markets for vehicle consumption. Blender b's profit maximization model is as follows.

$$\begin{aligned}
\max \quad & \sum_{mn} \pi^{\mathrm{M}}_{mn} x^{\mathrm{BM}}_{mbn} - \pi^{\mathrm{G}}_{b} \sum_{m} (1-\theta_m) \sum_{n} x^{\mathrm{BM}}_{mbn} - \sum_{p} \pi^{\mathrm{E}}_{pb} x^{\mathrm{BE}}_{pb} - \sum_{p} T^{\mathrm{M}}_{pb} x^{\mathrm{BE}}_{pb} - \sum_{mn} T^{\mathrm{N}}_{bn} x^{\mathrm{BM}}_{mbn} \\
& - \sum_{m} \left[C^{\mathrm{B}}_{m} \theta_m \sum_{n} x^{\mathrm{BM}}_{mbn} + \frac{1}{2} D^{\mathrm{B}}_{m} (\theta_m \sum_{n} x^{\mathrm{BM}}_{mbn})^2 \right] \qquad (4.13) \\
s.t. \quad & \sum_{mn} \theta_m x^{\mathrm{BM}}_{mbn} \leq \sum_{p} x^{\mathrm{BE}}_{pb} \qquad (\kappa_b) \qquad (4.14) \\
& x^{\mathrm{BE}}_{pb}, x^{\mathrm{BM}}_{mbn} \geq 0 \qquad (4.15)
\end{aligned}$$

Blender b's profit in equation (4.13) includes revenue for selling blended fuels $\sum_{mn} \pi^{\mathrm{M}}_{mn} x^{\mathrm{BM}}_{mbn}$, conventional gasoline purchase cost $\pi^{\mathrm{G}}_{b} \sum_{m} (1-\theta_m) \sum_{n} x^{\mathrm{BM}}_{mbn}$, ethanol purchase cost $\sum_{p} \pi^{\mathrm{E}}_{pb} x^{\mathrm{BE}}_{pb}$, ethanol and blended fuel transportation cost $\sum_{p} T^{\mathrm{M}}_{pb} x^{\mathrm{BE}}_{pb} + \sum_{mn} T^{\mathrm{N}}_{bn} x^{\mathrm{BM}}_{mbn}$, and blending cost $\sum_{m} \left[C^{\mathrm{B}}_{m} \theta_m \sum_{n} x^{\mathrm{BM}}_{mbn} + \frac{1}{2} D^{\mathrm{B}}_{m} (\theta_m \sum_{n} x^{\mathrm{BM}}_{mbn})^2 \right]$. Constraint (4.14) indicates that ethanol sold to markets should be no more than ethanol purchased.

Note that if blenders are under perfect competition, they are price takers, and variables π^{M}_{mn} and π^{G}_{b} are both taken as exogenous variables for blenders' model. If blenders have market power with respect to downstream blended fuel markets, they are able to influence blended fuel market price π^{M}_{mn} by making decisions on blended fuel sold amount x^{BM}_{mbn}. That is π^{M}_{mn} is represented in Equation (4.13) as a function of x^{BM}_{mbn} as shown in Equation (4.34) and (4.35). If blenders have market power to both upstream ethanol producers and downstream blended fuel markets, then both blended fuel and conventional gasoline prices, π^{M}_{mn} and π^{G}_{b}, can be included in blender b's decision making. A similar treatment can be applied to expressing prices π^{M}_{mn} and π^{G}_{b} respectively.

4.2.5 Market equilibrium conditions

In this section, we rewrite each entity's profit maximization problem with equivalent KKT conditions. The market equilibrium conditions are equivalent to solving each individual's profit maximization model simultaneously. The resulting problem is a complementarity problem.

- The KKT conditions for the farmer f's profit maximization model (4.5)-(4.8) are as follows.

$$0 \le \tau_{f0} \perp \qquad L_f - \sum_c a_{cf} \ge 0 \tag{4.16}$$

$$0 \le \tau_{cf} \perp \qquad Y^{\mathrm{F}}_{cf} a_{cf} - \sum_p x^{\mathrm{FC}}_{cfp} \ge 0 \tag{4.17}$$

$$0 \le a_{cf} \perp \qquad -Y^{\mathrm{F}}_{cf}\tau_{cf} + \tau_{f0} + C^{\mathrm{F}}_{cf} + D^{\mathrm{F}}_{cf} a_{cf} \ge 0 \tag{4.18}$$

$$0 \le x^{\mathrm{FC}}_{cfp} \perp \qquad \tau_{cf} - \pi^{\mathrm{C}}_{cfp} \ge 0 \tag{4.19}$$

- The KKT conditions for the producer p's profit maximization model (4.9)-(4.12) are as follows

$$0 \le \alpha_p \perp \qquad U^{\mathrm{P}}_p - \sum_c Y^{\mathrm{P}}_c \sum_f x^{\mathrm{PC}}_{cfp} \ge 0 \tag{4.20}$$

$$0 \le \beta_p \perp \qquad \sum_c Y^{\mathrm{P}}_c \sum_f x^{\mathrm{PC}}_{cfp} - \sum_b x^{\mathrm{PE}}_{pb} \ge 0 \tag{4.21}$$

$$0 \le x^{\mathrm{PC}}_{cfp} \perp \qquad \pi^{\mathrm{C}}_{cfp} + T^{\mathrm{C}}_{cfp}/(1 - Moist_c) + C^{\mathrm{P}}_c Y^{\mathrm{P}}_c + D^{\mathrm{P}}_c (Y^{\mathrm{P}}_c)^2 \sum_f x^{\mathrm{PC}}_{cfp} + Y^{\mathrm{P}}_c \alpha_p - Y^{\mathrm{P}}_c \beta_p \ge 0 \tag{4.22}$$

$$0 \le x^{\mathrm{PE}}_{pb} \perp \qquad -\pi^{\mathrm{E}}_{pb} + \beta_p \ge 0 \tag{4.23}$$

- The KKT conditions for blender b's profit maximization model (4.13)-(4.15) are as follows.

If blenders are under perfect competition (PC), the KKT conditions are

$$0 \le \kappa_b \perp \qquad \sum_p x^{\mathrm{BE}}_{pb} - \sum_{mn} \theta_m x^{\mathrm{BM}}_{mbn} \ge 0 \tag{4.24}$$

$$0 \le x^{\mathrm{BE}}_{pb} \perp \qquad \pi^{\mathrm{E}}_{pb} + T^{\mathrm{M}}_{pb} - \kappa_b \ge 0 \tag{4.25}$$

$$0 \le x^{\mathrm{BM}}_{mbn} \perp \qquad -\pi^{\mathrm{M}}_{mn} + \pi^{\mathrm{G}}_b (1 - \theta_m) + T^{\mathrm{N}}_{bn} + C^{\mathrm{B}}_m \theta_m + D^{\mathrm{B}}_m \theta_m^2 \sum_n x^{\mathrm{BM}}_{mbn} + \theta_m \kappa_b \ge 0 \tag{4.26}$$

If blenders have market power to only downstream stakeholders (MPD), then the constraint (4.26) can be replaced by

$$0 \leq x^{\text{BM}}_{ebn} \perp \quad -\pi^{\text{M}}_{en} + \pi^{\text{G}}_{b}(1-\theta_e) + T^{\text{N}}_{bn} + C^{\text{B}}_{e}\theta_e + D^{\text{B}}_{e}\theta_e^2 \sum_{n} x^{\text{BM}}_{ebn} + \theta_e \kappa_b$$
$$-x^{\text{BM}}_{ebn}\frac{\partial \pi^{\text{M}}_{en}}{\partial x^{\text{BM}}_{ebn}} - x^{\text{BM}}_{gbn}\frac{\partial \pi^{\text{M}}_{gn}}{\partial x^{\text{BM}}_{ebn}} \geq 0 \qquad (4.27)$$

$$0 \leq x^{\text{BM}}_{gbn} \perp \quad -\pi^{\text{M}}_{gn} + \pi^{\text{G}}_{b}(1-\theta_g) + T^{\text{N}}_{bn} + C^{\text{B}}_{g}\theta_g + D^{\text{B}}_{g}\theta_g^2 \sum_{n} x^{\text{BM}}_{gbn} + \theta_g \kappa_b$$
$$-x^{\text{BM}}_{ebn}\frac{\partial \pi^{\text{M}}_{en}}{\partial x^{\text{BM}}_{gbn}} - x^{\text{BM}}_{gbn}\frac{\partial \pi^{\text{M}}_{gn}}{\partial x^{\text{BM}}_{gbn}} \geq 0 \qquad (4.28)$$

If blenders have market power to both up and downstream stakeholders (MPUD), then the constraint (4.26) can be replaced by

$$0 \leq x^{\text{BM}}_{ebn} \perp \quad -\pi^{\text{M}}_{en} + \pi^{\text{G}}_{b}(1-\theta_e) + T^{\text{N}}_{bn} + C^{\text{B}}_{e}\theta_e + D^{\text{B}}_{e}\theta_e^2 \sum_{n} x^{\text{BM}}_{ebn} + \theta_e \kappa_b$$
$$-x^{\text{BM}}_{ebn}\frac{\partial \pi^{\text{M}}_{en}}{\partial x^{\text{BM}}_{ebn}} - x^{\text{BM}}_{gbn}\frac{\partial \pi^{\text{M}}_{gn}}{\partial x^{\text{BM}}_{ebn}} + B^{\text{G}}(1-\theta_e)\sum_{mn}(1-\theta_m)x^{\text{BM}}_{mbn} \geq 0 \qquad (4.29)$$

$$0 \leq x^{\text{BM}}_{gbn} \perp \quad -\pi^{\text{M}}_{gn} + \pi^{\text{G}}_{b}(1-\theta_g) + T^{\text{N}}_{bn} + C^{\text{B}}_{g}\theta_g + D^{\text{B}}_{g}\theta_g^2 \sum_{n} x^{\text{BM}}_{gbn} + \theta_g \kappa_b$$
$$-x^{\text{BM}}_{ebn}\frac{\partial \pi^{\text{M}}_{en}}{\partial x^{\text{BM}}_{gbn}} - x^{\text{BM}}_{gbn}\frac{\partial \pi^{\text{M}}_{gn}}{\partial x^{\text{BM}}_{gbn}} + B^{\text{G}}(1-\theta_g)\sum_{mn}(1-\theta_m)x^{\text{BM}}_{mbn} \geq 0 \qquad (4.30)$$

- Market clearing conditions

The market clearing prices of biomass π^{C}_{cfp} and cellulosic ethanol π^{E}_{pb} are defined as market clearing conditions of biomass and ethanol supply equating demand as shown in Equation (4.31 - 4.32). The conventional gasoline supply is represented by linear marginal supply function as in Equation (4.33). The inverse demand functions of the blended fuels are presented in Equation (4.34 - 4.35).

$$\pi^{\mathrm{C}}_{cfp} \text{ free} \perp \qquad x^{\mathrm{FC}}_{cfp} = x^{\mathrm{PC}}_{cfp} \tag{4.31}$$

$$\pi^{\mathrm{E}}_{pb} \text{ free} \perp \qquad x^{\mathrm{PE}}_{pb} = x^{\mathrm{BE}}_{pb} \tag{4.32}$$

$$\pi^{\mathrm{G}}_{b} = A^{\mathrm{G}} + B^{\mathrm{G}} \sum_{m} (1-\theta_m) \sum_{n} x^{\mathrm{BM}}_{mbn} \tag{4.33}$$

$$\pi^{\mathrm{M}}_{en} = (\sum_{b} x^{\mathrm{BM}}_{ebn})^{\frac{e_{gg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (\sum_{b} x^{\mathrm{BM}}_{gbn})^{-\frac{e_{eg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A^{\mathrm{M}}_{en})^{-\frac{e_{gg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A^{\mathrm{M}}_{gn})^{\frac{e_{eg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} \tag{4.34}$$

$$\pi^{\mathrm{M}}_{gn} = (\sum_{b} x^{\mathrm{BM}}_{ebn})^{-\frac{e_{ge}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (\sum_{b} x^{\mathrm{BM}}_{gbn})^{\frac{e_{ee}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A^{\mathrm{M}}_{en})^{\frac{e_{ge}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A^{\mathrm{M}}_{gn})^{-\frac{e_{ee}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} \tag{4.35}$$

Note that the inverse demand function (4.34,4.35) are derived from constant elasticity demand function (4.36,4.37). Detail information can be found in Appendix A. Table 4.1 summarizes the scenarios as well as their corresponding equations.

$$\sum_{b} x^{\mathrm{BM}}_{ebn} = A^{\mathrm{M}}_{en} (\pi^{\mathrm{M}}_{en})^{e_{ee}} (\pi^{\mathrm{M}}_{gn})^{e_{eg}} \tag{4.36}$$

$$\sum_{b} x^{\mathrm{BM}}_{gbn} = A^{\mathrm{M}}_{gn} (\pi^{\mathrm{M}}_{en})^{e_{ge}} (\pi^{\mathrm{M}}_{gn})^{e_{gg}} \tag{4.37}$$

Table 4.1 Model and market equilibrium constraints summary

Model abbreviation	Model description	Model equations
PC	Blenders are price takers in perfectly competitive markets	(4.18-4.26), (4.31-4.35)
MPD	Blenders can excise market power to only downstream stakeholders	(4.18-4.25), (4.27-4.28), (4.31-4.35)
MPUD	Blenders have market power to both upstream and downstream stakeholders	(4.18-4.25), (4.29-4.30), (4.31-4.35)

For models under imperfectly competitive scenario, the market equilibrium only exists when blenders sell both E10 and E85 and for only a limited range of the levels of cross price elasticities. See Appendix B for the discussion of the conditions of the existence of market equilibrium. When blenders sell only E10, the profit maximization model can be simplified as a single commodity profit maximization model. The marginal revenue (see Appendix B for the formulation) for this model is negative when blenders face imperfectly competitive markets. Therefore, blenders would not excise market power when E10 is the only commodity they sell.

4.3 Solution techniques

The complementarity problem for the cases of imperfect competition (such as MPD and MPUD cases) are difficult to solve due to the high nonlinearity caused by the inverse demand function for blended fuels and $\frac{\partial \pi_{mn}^{\mathrm{M}}}{\partial x_{mbn}^{\mathrm{BM}}}$. In this chapter, a recursive Taylor expansion procedure is developed to approximately solve the resulting highly nonlinear complementarity problem. For each iteration of the recursive method based on Taylor expansion, we approximate the nonlinear demand function with a linear function, such that the cross price elasticity in the neighborhood around last iteration is constant. Thus, in each iteration we solve a linear complementarity problem, of which rich literature has been developed to guarantee it solution properties [22]. Recursive Taylor expansion method have been widely applied to nonlinear programs [13, 68]. However, due to highly nonlinearlity in the objective function, the global optimality is not guaranteed.

4.3.1 Recursive Taylor expansion procedure

Assume we already have constant elasticity demand function (4.36, 4.37). The procedure for recursively solving the complementarity problem is as follows. Graphical illustration of the procedure is shown in Figure 4.2.

1. Start with a initial equilibrium point $(\pi_{en}^0, q_{en}^0), (\pi_{gn}^0, q_{gn}^0)$ (here we choose the market equilibrium for PC as the initial equilibrium point, the interaction of linear supply function and nonlinear demand function as shown in Figure 4.2). In a case, we start with this point, and allow high-dimension demand curve to "rotate" dependently on levels of cross price elasticities.

2. For each iteration $k \geq 1$

   (a) Record current equilibrium point as $(\pi_{en}^{k-1}, q_{en}^{k-1}), (\pi_{gn}^{k-1}, q_{gn}^{k-1})$.

   (b) Take Taylor expansion of inverse demand function (4.34, 4.35), and linearized inverse demand functions become

$$\pi_{en}^{\text{M}} = A_{en}^{\text{M}} - B_{en}^{\text{ME}} \sum_b x_{ebn}^{\text{BM}} - B_{gn}^{\text{ME}} \sum_b x_{gbn}^{\text{BM}}, \text{ and}$$

$$\pi_{gn}^{\text{M}} = A_{gn}^{\text{M}} - B_{en}^{\text{MG}} \sum_b x_{ebn}^{\text{BM}} - B_{gn}^{\text{MG}} \sum_b x_{gbn}^{\text{BM}}.$$

See the downward slope dash lines in Figure 4.2 for the linearized demand function at each equilibrium point.

(c) Solve the linear complementarity problem with constraints (4.27, 4.28) or constraints (4.29, 4.30) by setting $\frac{\partial \pi_{en}^{\text{M}}}{\partial x_{ebn}^{\text{BM}}} = -B_{en}^{\text{ME}}$, $\frac{\partial \pi_{en}^{\text{M}}}{\partial x_{gbn}^{\text{BM}}} = -B_{gn}^{\text{ME}}$, $\frac{\partial \pi_{gn}^{\text{M}}}{\partial x_{ebn}^{\text{BM}}} = -B_{en}^{\text{MG}}$, and $\frac{\partial \pi_{gn}^{\text{M}}}{\partial x_{gbn}^{\text{BM}}} = -B_{gn}^{\text{MG}}$. The new optimal solution is $(\pi_{en}^k, q_{en}^k), (\pi_{gn}^k, q_{gn}^k)$ (as the interaction of the dash lines in each step in Figure 4.2).

(d) If the new solution $(\pi_{en}^k, q_{en}^k), (\pi_{gn}^k, q_{gn}^k)$ is sufficiently close to the previous solution $(\pi_{en}^{k-1}, q_{en}^{k-1}), (\pi_{gn}^{k-1}, q_{gn}^{k-1})$ (within tolerance τ), then stop and report equilibrium solution $(\pi_{en}^k, q_{en}^k), (\pi_{gn}^k, q_{gn}^k)$. Otherwise, fix q_{en}^k, q_{gn}^k, and obtain new solution on the constant elasticity demand function by constraints(4.34, 4.35). Let $(\pi_{en}^k, q_{en}^k), (\pi_{gn}^k, q_{gn}^k)$ be equal to the updated solution

$$((q_{en}^k)^{\frac{e_{gg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (q_{gn}^k)^{-\frac{e_{eg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A_{en}^{\text{M}})^{-\frac{e_{gg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A_{gn}^{\text{M}})^{\frac{e_{eg}}{e_{ee}e_{gg}-e_{eg}e_{ge}}}, q_{en}^k),$$

and

$$((q_{en}^k)^{-\frac{e_{ge}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (q_{gn}^k)^{\frac{e_{ee}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A_{en}^{\text{M}})^{\frac{e_{ge}}{e_{ee}e_{gg}-e_{eg}e_{ge}}} (A_{gn}^{\text{M}})^{-\frac{e_{ee}}{e_{ee}e_{gg}-e_{eg}e_{ge}}}, q_{gn}^k).$$

Go back to Step (2a), and recursively solve the problem.

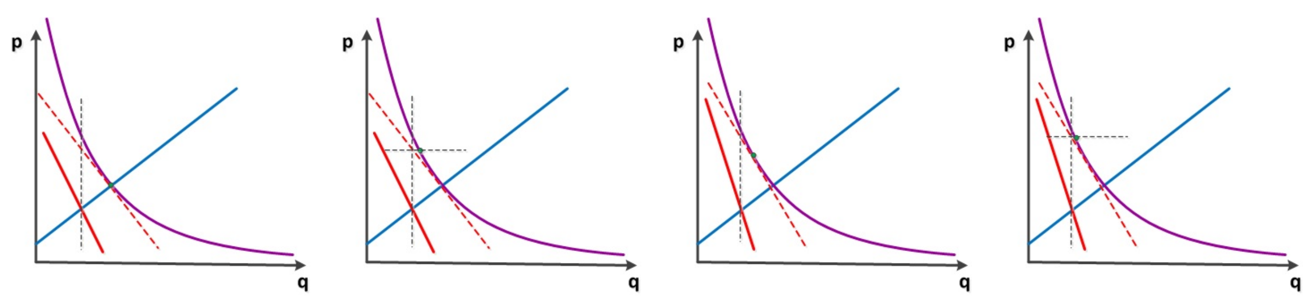

Figure 4.2 Recursive Taylor expansion

4.4 Numerical results

We apply the model to a California case study. The detailed data on facility locations and capacities can be found in [52]. Two types of biomass are considered: forest residue (47) and corn stover (27), with the number in the parenthesis represents the number of suppliers (farmers). Farmer's optimization model is simplified as linear supply curve. Moreover, four cellulosic ethanol producers (P4, P7, P21, P27) and four biofuel blenders (T4, T7, T11, T18) are assumed to be operating in California (see Figure 4.3). Blenders are assumed to produce two ethanol fuel mixtures, E10 and E85, and sell to 143 different cities for vehicle consumption.

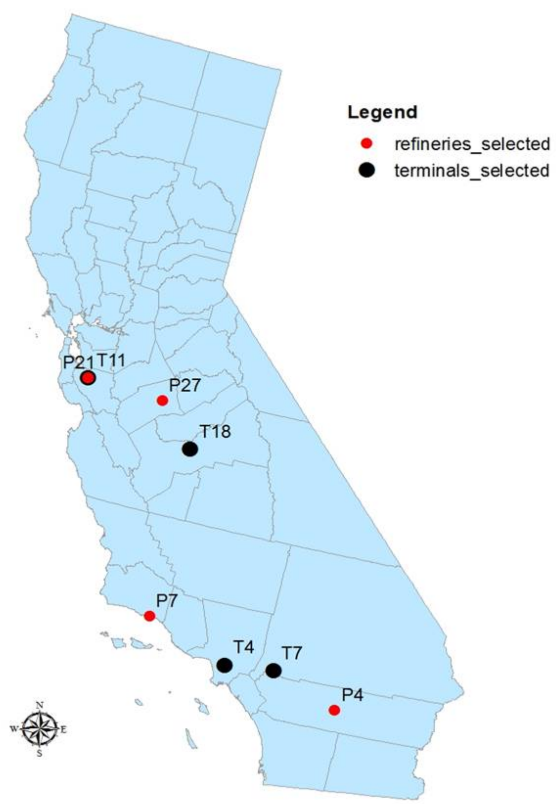

Figure 4.3 Map locations of biofuel producers (P) and blenders (T) [52]

It is assumed that the own price elasticities of demand for E10 and E85 are -0.4 and -1.4 respectively [37, 48, 54], and different cross price elasticities indicate various penetration levels of FFVs. As explained in Section 4.1, with higher penetration of FFVs, we expect to see higher cross price elasticity of demand in the constant elasticity of demand functions. While own price elasticities are broadly consistent with empirical studies, cross price elasticity is subject to further sensitivity analysis.

In the following subsections we first present base scenario with blended fuels under perfect competition markets in Section 4.4.1. In Section 4.4.2 different competition assumptions of biofuel markets are compared to show the impacts of market power possessed by blenders. Sensitivity analysis on different levels of cross price elasticities for MPD cases are presented to investigate the impacts of cross price elasticities on biofuel markets and conventional fuel markets in Section 4.4.3.

4.4.1 Base scenario

For the purpose of comparison between different scenarios, we assume the same perfect competition market equilibrium points for various cross price elasticities. Here we call it the base scenario, as the reference point for all cross price elasticities. The sales weighted average prices for E10 and E85 are \$3.43/gal and \$2.55/gal respectively for the 143 cities in California.

Ethanol selling prices and quantities per year from producers to blenders are shown in Table 4.2. For instance, blender T4 purchases 64.10 (25.61) million gallons (MG) of ethanol from producer P7 (P27) with prices of \$2.14/gal (\$2.09/gal). The reported gate price of ethanol for T4 is the same across two producers P7 and P27 (\$2.19/gal), in spite of the difference in their transportation costs. In equilibrium, the ethanol gate prices for blenders is the same if producers' capacity is not reached. Had one producer raised to a higher ethanol price, it would be immediately arbitraged away by increasing in sales from other producers. However, if one producer's capacity is bounded, blenders would turn to other producers that provide second lowest gate price. E10 and E85 production level for all blenders are shown in Table 4.2. Since E10 and conventional gasoline are perfect substitutes in the markets, and E10 are widely accessible now in the markets, we could observe high demand and small elasticity of demand. The quantity demanded by E85, however, is constrained by limited amount of FFVs in use in the markets. The profits of producers and blenders are shown in Table 4.2. With the current parameter setting, we could observe that producers and blenders earn significant profits around M\$20 to M\$40 with exception of T18 (making M\$9.04), partially due to the fact that the market it serves is relatively small. Our later analysis will be compared to the base scenario results.

Table 4.2 Base scenario results

Panel A: Ethanol price and quantity between producers and blenders

	Ethanol price (in $/gal)				Ethanol quantity (in MG)			
	T4	T7	T11	T18	T4	T7	T11	T18
P4	NA	2.16	NA	NA	0	55.69	0	0
P7	2.14	NA	NA	NA	64.10	0	0	0
P21	NA	2.08	2.08	NA	0	10.40	68.04	0
P27	2.09	2.09	NA	2.09	25.61	16.29	0	44.86

Note that 'NA' indicates no transaction between producer (row) and blender (column), thereby sales quantity is by definition zero.

Panel B: E10 and E85 production level for all blenders (in MG)

Blender	E10	E85
T4	856.89	5.35
T7	796.64	3.63
T11	641.97	5.13
T18	424.50	3.21

Panel C: Producer and blender's profit (in M$)

Producer	Profit	Blender	Profit
P4	27.20	T4	36.79
P7	24.37	T7	31.77
P21	31.57	T11	20.68
P27	31.54	T18	9.04

4.4.2 Effects of blenders' market power

This section reports the outcomes under 3 different scenarios, i.e., PC, MPD, MPUD, when the cross-elasticity is assumed to be 0.0005 and 0.001 for $e_{E10,E85}$ and $e_{E85,E10}$ respectively. The level of "cross-elasticity" is assumed to be small as only limited number of FFVs are on the road.

Face upstream and downstream entities, blenders can exercise market power in two distinct ways. On one hand, they reduce downstream sales, effectively pushing up E10 and E85 prices. On the other hand, blenders could suppress the ethanol procurement price by reducing the amount of ethanol purchased from producers under MPUD case. As a result, substantial profits can be earned from these strategies, even "upstream" market power (MPUD) only increase their profit marginally. (Implied supply elasticity of upstream producers is relatively large, so it limits the ability of blenders to manipulate procurement costs.) As two scenarios (MPD and MPUD) produce very similar results, we therefore focus on our discussions on MPD, while listing MPUD's results in Table 4.3 for completeness.

Under MPD, the E10 and E85 sales weighted average price, total consumption quantities, and revenue for selling E10 and E85 are shown in Table 4.3. Ethanol sales weighted average price between producers and blenders, ethanol total consumption, and profits for both producers and blenders are shown in Table 4.3 as well. Compared to PC case, blenders can effectively raise the sales weighted average market price of E10 from \$3.34/gal to \$9.10/gal, resulting in a drop of E10 overall demand from 2720.00 MG to 1841.98 MG. E85 sales weighted average market prices, however, only increased marginally by \$0.67/gal from \$2.55/gal, with E85 consumption quantity decreased from 44.14 MG to 40.25 MG. This relatively minor impact of E85 can be attributed to its relatively elastic demand. (The impacts on cross-elasticities will be further studied by sensitivity analysis on a latter section). With the increase of market power to the downstream entities in the biofuel supply chain, blenders' revenue for selling E10 increases from M\$9339.06 to M\$16763.07, while that for selling E85 decreases from M\$17.31 to M\$12.49 as shown in Table 4.3. This is due to highly elastic demand of E85. With 1% increase in E85 price, we expect to see a 1.4% of E85 quantity decrease, therefore the E85 revenue decreases with increase of E85 market price. As of "upstream", blenders could also reduce the purchasing price of ethanol by suppressing the ethanol purchasing quantities. For example, Table 4.3 reports that producer P4's ethanol price drops by \$0.31/gal (from \$2.16/gal to \$1.85/gal) as blender T7 reduced its procurement from 55.69 MG in MPD to 47.44 MG in MPD. This leads a sizable gain in profit by blenders at expenses of producers. For instance, T7's profit increases by M$2604.11 (from M$31.77 to M$2635.88) while P4's profit decreases by more than half from M$ 27.20 to M$11.20. With constant elasticity of demand functions, the demand curve asymptotically gets close to y-axis when reducing quantities in x-axis, the consumer surplus is infinity by construction. As maximal willingness to pay (WTP) of consumers for gasoline is infinity.

Table 4.3 Effects of blenders' market power

Panel A: Market price, quantity, and revenue for E10, E85, and cellulosic ethanol

	E10			E85			Ethanol		
	PC	MPD	MPUD	PC	MPD	MPUD	PC	MPD	MPUD
sales weighted average Price (in $/gal)	3.34	9.10	9.11	2.55	3.22	3.22	2.11	1.81	1.81
Quantity (in MG)	2720.00	1841.98	1841.19	44.14	40.25	40.24	284.98	193.57	193.49
Revenue (in M$)	9339.06	16763.07	16773.96	17.31	12.50	12.49	602.55	350.01	349.82

Panel B: Ethanol contract price and quantity between producers and blender T7

Ethanol	Price (in $/gal)			Quantity (in MG)		
	PC	MPD	MPUD	PC	MPD	MPUD
P4	2.16	1.85	1.85	55.69	47.44	47.42
P7	NA	NA	NA	0	0	0
P21	2.08	NA	1.77	10.40	0	0.88
P27	2.09	1.789	NA	16.29	0.88	0

Panel C: Ethanol producers and blenders profits (in M$)

	Ethanol producers				Blenders			
	P4	P7	P21	P27	T4	T7	T11	T18
PC	27.20	24.37	31.57	31.54	36.79	31.77	20.68	9.04
MPD	11.20	8.28	10.50	9.37	2642.70	2635.88	2621.87	2630.28
MPUD	11.20	8.27	10.50	9.36	2646.11	2639.29	2625.29	2633.69

4.4.3 Sensitivity analysis on $e_{E10,E85}$ and $e_{E85,E10}$ for imperfectly competitive markets

In this section we explores the impacts of cross price elasticities ($e_{E10,E85}$ and $e_{E85,E10}$) on biofuel market outcomes for imperfectly competitive markets. As alluded to earlier, we will focus on MPD as the scenario MPUD produces quantitatively similar outcomes.

Since E85 is newly introduced to fuel markets with a limited supply while E10 remains the main fuel in the market, the impact of increasing $e_{E85,E10}$ on the market outcomes is therefore limited. Therefore, we focus our attentions on the impacts of $e_{E10,E85}$ on the fuel markets. In other words, our analysis will mainly concentrate on the demand change of E10 in response to the price change of E85. By the definition of cross price elasticity in Equation (4.4), the parameter $e_{E10,E85}$ means that with 1% raise of E85 market price, E10 demand can raise by $e_{E10,E85}\%$. $e_{E10,E85}$ is usually small due to much larger E10 demand than E85, we therefore expect a smaller percentage change observed in E10 demand.

Fix $e_{E85,E10}$ as 0.001, with the increase of $e_{E10,E85}$ from 0 to 0.001, we expect to see the consumers are more willing to switch to E10, thereby demand of E10 becomes less elastic. As a result, blenders' market power is enhanced as the potential of market power is reversely related to elasticity. In a way, the effect of market power in E85 is "spilled over" to E10. The results of sensitivity analysis on cross price elasticities are shown in Table 4.4. Since the market prices of E10 and E85 change only at a small scale, we show the market price results with 5 significant digits. The focus is on their qualitative impacts. Table 4.4 indicates that with the increase of $e_{E10,E85}$ from 0 to 0.001, blenders can increase the market price of E85 by 31% from \$2.8632/gal to \$3.7517/gal. Accompanied with the increase of $e_{E10,E85}$ is an increase of E10 demand by 0.86 MG from 1841.68 MG to 1842.54 MG as shown in Table 4.4. E10 sales weighted average market price drops only marginally from \$9.1016/gal to \$9.0998/gal. Blenders could also suppress the demand of ethanol from upstream biofuel producers (from 195.22 MG to 191.82 MG) as well as ethanol prices (from 1.8123 to \$1.8053/gal) as reported in Table 4.4. As a result, blenders' profits increase in commensurate with a decline of producers' profits. For instance, blender T7 profit increases by M\$2.35 (from M\$2634.93 to M\$2637.28), while producer P4 profit decreases from M\$11.40 to M\$11.06.

4.5 Conclusion

FFVs have been considered by government as one of the strategies to reduce transportation fuel reliability on petroleum oil, since they can consume fuels up to 85% of ethanol blended into gasoline. However, the widely adoption of FFVs is not yet realized due to social and infrastructural obstacles as alluded to in Section 4.1. Many research projects have been focusing on studying the obstacles that prevent wide adoption of E85. However, little research focuses on the early stage development of the E85 markets and its impacts on both conventional fuel and E85 markets.

This chapter extended Chapter 3 by incorporating constant elasticity of demand functions in the bottom-up equilibrium model to study the penetration of FFVs considering imperfectly competitive fuel markets. The highly nonlinear model, owning to constant elasticity of demand functions, is solved using a recursive approach based on Taylor expansion to linearize demand functions locally in each iteration. The model is applied to a case study in California considering scenarios varied by 1) levels of competitions 2) magnitude of cross price elasticities. We have following findings for this chapter. First, when blenders are modeled as a local monopoly, the outcomes show that blenders can effectively exercise market power with respect to upstream and downstream of the supply chain, and distort markets by reducing the amount of blended fuels sold to downstream consumers to raise their market prices and suppressing the ethanol purchasing prices and quantities from upstream biofuel producers. They can benefit significantly at the expense of producers' profitability.

Second, an increase of FFVs penetration to the market would vender blenders with more market power sine consumers are more willing to switch between E10 and E85 when one commodity market price increases. This might affect the industry negatively as investors (ethanol producers) might be discouraged from additional investments. This implies that the development of a biofuel industry hinge upon strong government oversight, at least at the early stage, to minimize the distortion that might be introduced by strategic behavior.

The framework we developed is subject to a number of limitations. First, we assume that E10 and E85 are both produced from cellulosic ethanol, and blended fuels produced from cellulosic ethanol have demand functions independent of first generation ethanol. However, most E85 stations are selling ethanol fuel mixtures from first generation ethanol. Thus ignore this dependence might lead to over estimation of blenders' market power on E85. One way to improve is to consider first generation ethanol as a perfect substitute of cellulosic ethanol in the markets, and investigate the impacts of cellulosic ethanol on the biofuel market outcomes. Second, the current cellulosic ethanol production cost is relatively high comparing to first generation ethanol. The government have been promoting subsidies, tax credit, and mandate policies to offset the production cost of cellulosic ethanol and to promote its development. Unlike other regulatory mandates, RINs is a market-based instrument, and its value depends on supply-demand of RINs market. As RINs price is an important and complicated factor that could greatly impacts the development of cellulosic biofuel markets, we would incorporate RINs market in this framework. Third, the constant elasticity of demand function currently in use is a simplified case of the general constant elasticity of demand. The general constant elasticity of demand function considers the income effect in the demand. Taking the income effect into consideration might have effects on the blended fuel demand. The constant elasticity of demand function is valid only in a limited range of prices and quantities. Modifications to the demand functions might be needed to simulate the blended fuel markets. These directions should be explored to better model the emerging biofuel markets.

Table 4.4 Cross price elasticity sensitivity analysis

Panel A: E10, E85 market price (in $/gal)

	E10			E85		
$e_{E10,E85}$ | $e_{E85,E10}$	0	0.001	0.002	0	0.001	0.002
0	9.1016	9.1016	9.1017	2.8631	2.8632	2.8632
0.0005	9.1005	9.1006	9.1006	3.2204	3.2200	3.2197
0.001	9.0998	9.0998	9.0999	3.7529	3.7517	3.7504

Panel B: E10, E85 market quantity (in MG)

	E10			E85		
$e_{E10,E85}$ | $e_{E85,E10}$	0	0.001	0.002	0	0.001	0.002
0	1841.69	1841.68	1841.68	14.72	14.73	14.75
0.0005	1841.99	1841.98	1841.98	12.48	12.50	12.51
0.001	1842.55	1842.54	1842.54	10.08	10.09	10.11

Panel C: E10, E85 market revenue (in M$)

	E10			E85		
$e_{E10,E85}$ | $e_{E85,E10}$	0	0.001	0.002	0	0.001	0.002
0	16762.26	16762.29	16762.33	42.14	42.18	42.22
0.0005	16763.02	16763.07	16763.12	40.20	40.25	40.29
0.001	16766.71	16766.77	16766.83	37.82	37.86	37.90

Panel D: Blender profit (in M$)

	T4			T7		
$e_{E10,E85}$ | $e_{E85,E10}$	0	0.001	0.002	0	0.001	0.002
0	2641.73	2641.74	2641.76	2634.92	2634.93	2634.94
0.0005	2642.68	2642.70	2642.72	2635.86	2635.88	2635.90
0.001	2644.08	2644.10	2644.12	2637.26	2637.28	2637.30
	T11			T18		
0	2620.88	2620.89	2620.91	2629.29	2629.31	2629.32
0.0005	2621.85	2621.87	2621.89	2630.26	2630.28	2630.29
0.001	2623.25	2623.27	2623.29	2631.66	2631.68	2631.70

Panel E: Ethanol contract price and quantity

	Price (in $/gal)			Quantity (in MG)		
$e_{E10,E85}$ | $e_{E85,E10}$	0	0.001	0.002	0	0.001	0.002
0	1.8123	1.8123	1.8123	195.21	195.22	195.23
0.0005	1.8081	1.8082	1.8082	193.56	193.57	193.58
0.001	1.8052	1.8053	1.8053	191.81	191.82	191.83

Panel F: Producer profit (in M$)

	P4			P7			P21			P27		
$e_{E85,E10}$	0	0.001	0.002	0	0.001	0.002	0	0.001	0.002	0	0.001	0.002
$e_{E10,E85}$												
0	11.40	11.40	11.40	8.44	8.44	8.44	10.73	10.73	10.73	9.59	9.59	9.59
0.0005	11.20	11.20	11.21	8.28	8.28	8.28	10.50	10.50	10.51	9.37	9.37	9.37
0.001	11.06	11.06	11.07	8.16	8.16	8.17	10.37	10.37	10.37	9.18	9.18	9.18

CHAPTER 5. SUMMARY AND DISCUSSION

In this dissertation, three system analysis and optimization models are formulated for biofuel supply chain, emerging biofuel market and policy analysis, and impacts of FFVs in imperfectly competitive fuel markets to provide managerial insights for stakeholders in the advanced biofuel production industry.

The first piece of the dissertation work focuses on the design of supply chain, and the operational planning for the individual biorefinery facility. The objective of the biofuel supply chain design model is to assist the decision making on facility locations, capacities, and the operational planning to minimize the total system cost. A case study in Iowa is conducted to analyze a variety of scenarios on biofuel production and demand shortage. In addition, the operational planning for various biofuel consumption seasonality patterns are analyzed. The results for the biofuel supply chain indicate that the unit production cost could be lower enough to be commercially feasible. A biofuel market model with the stakeholders along the supply chain will be emerging along the process of commercialization. This also motivates the research for the second piece of work in this dissertation.

A bottom-up equilibrium model is formulated in the second piece of my dissertation for the biofuel market to maximize the profits of all stakeholders (farmers, biofuel producers, and biofuel blenders) simultaneously under different market structures. The impacts of different existing and proposed government policies are analyzed to shed lights on government policy making.

The third part of the dissertation work is to investigate the impacts of FFVs penetration levels on imperfectly competitive fuel markets. The model incorporates constant elasticity of demand functions using cross price elasticity of demand to represent FFVs penetration levels. The impacts of FFVs penetration levels on blended fuel market outcomes (including blended fuel market prices and quantities, cellulosic ethanol prices and quantities, biofuel blenders and producers profitability) in imperfectly competitive markets are analyzed to provide insights for the biofuel investors in their decision makings.

The current model presented in the dissertation, however, are based on a few simplifying assumptions, which point us the future research directions.

For farmers, we assume that their profits are only from selling biomass to produce biofuels, while other profits such as food and byproducts are not included. Additionally, in reality, farm lands with high fertility levels are usually planned to grow commodity crops such as corn and soybean. Marginal lands with lower fertility level, however, may be more appropriate for delicate energy crops such as switchgrass and miscanthus due to the profitability of food products. We plan to include all profits for food, biomass and other byproducts into farmer's model in future. In addition, we assumed the yield and production costs are fixed, while in reality, both of which are uncertain due to the weather and soil condition. Therefore it is important for farmers to make strategic decisions to manage the risk. Mechanisms such as crop insurances and contracts with the biofuel producers should be analyzed. Vertical ownership of farmers and producers may also be emerging in the advanced biofuel market. Furthermore, biomass can be used in various industry sectors such as electricity generation market, animal feeding, soil fertilizer, etc.

For the biofuel producers, the biorefinery facility locations are fixed and production capacity is assumed to be 2200 ton/day as in the literature [102]. As the technology evolves and market matures, it is necessary to integrate the optimal capacity decisions in the supply chain design model in Chapter 2 with the biofuel market model in Chapter 3 and Chapter 4. A number of existing pathways are identified by PNNL as promising pathways to produce biofuels such as gasoline and diesel range fuels. Our current biofuel market model assumes that there are two pathways producing cellulosic ethanol and biogasoline with the same capacity level (2200 ton/day). The choice of pathways and capacity for each pathway should be available for each biofuel producer to maximize its profit. Like farmers, biofuel producers also have the choice of selling biofuels directly into consumer markets or to biofuel blenders in the market or contract prices. Biofuel producers could also be vertically owned by biofuel blenders. In this case, the market structures of the emerging biofuel markets will be different, and its impacts on the biofuel markets are of interest to explore.

Biofuel blenders are currently assumed to face constant elasticity of demand with fuel substitutions. This model formulation, however, are not widely applicable to all quantities in the demand function. In the future we expect to develop more suitable demand function forms reflecting reality of price-demand relationship and uncertainties to better simulate the markets. In this dissertation, blenders are assumed to sell both E10 and E85 to downstream fuel consumers, and blenders can excise monopoly power for both E10 and E85 fuel markets. With the development of alternative fuel vehicles, electricity, natural gas, and other ethanol fuel mixtures will all become substitutes with E85. How to model the impacts of other alternative fuel vehicles on biofuel markets will become a critical problem to study.

Various government policies have been proposed to promote the development of cellulosic biofuel markets. In this dissertation, government subsidy policies on farmers, biofuel producers, and biofuel blenders are investigated, and RINs markets as implementation strategy of volumetric mandate on biofuels are studied. However, there are more policies related to farmers, biofuel producers, biofuel blenders, environmental factors, and RINs banking and RINs market need to be taken into consideration for the better simulation of the emerging biofuel markets. A framework to investigate the biofuel market under federal and local policies could be developed to study the interaction between government policy and the development of emerging biofuel markets, and the interactions between different stakeholders under government policy scenarios.

The market power for farmers, biofuel producers, and biofuel blenders should also be investigated. Different market structures such as centralized structure analogues to electricity market, and bilateral market structure in Chapter 3 and Chapter 4 should be further studied for us to propose a more appropriate structure for future biofuel markets. Further analysis of the biofuel market such as the oligopoly vs. duopoly structure of the market, and the impacts of new entries in biofuel market should also be conducted.

APPENDIX A. DERIVE INVERSE DEMAND FUNCTION FROM CONSTANT ELASTICITY DEMAND FUNCTION

For two products $b1$ and $b2$, the demand functions are given as:

$$q_1 = a_1 p_1^{e_{11}} p_2^{e_{12}} \tag{A.1}$$

$$q_2 = a_2 p_1^{e_{21}} p_2^{e_{22}} \tag{A.2}$$

Then

$$\log(q_1) = \log(a_1) + e_{11}\log(p_1) + e_{12}\log(p_2) \tag{A.3}$$

$$\log(q_2) = \log(a_2) + e_{21}\log(p_1) + e_{22}\log(p_2) \tag{A.4}$$

$$\log(p_1) = \frac{(e_{22}\log(q_1) - e_{12}\log(q_2)) - (e_{22}\log(a_1) - e_{12}\log(a_2))}{e_{11}e_{22} - e_{12}e_{21}} \tag{A.5}$$

$$\log(p_2) = -\frac{(e_{21}\log(q_1) - e_{11}\log(q_2)) - (e_{21}\log(a_1) - e_{11}\log(a_2))}{e_{11}e_{22} - e_{12}e_{21}} \tag{A.6}$$

$$p_1 = q_1^{\frac{e_{22}}{e_{11}e_{22}-e_{12}e_{21}}} q_2^{-\frac{e_{12}}{e_{11}e_{22}-e_{12}e_{21}}} a_1^{-\frac{e_{22}}{e_{11}e_{22}-e_{12}e_{21}}} a_2^{\frac{e_{12}}{e_{11}e_{22}-e_{12}e_{21}}} \tag{A.7}$$

$$p_2 = q_1^{\frac{-e_{21}}{e_{11}e_{22}-e_{12}e_{21}}} q_2^{\frac{e_{11}}{e_{11}e_{22}-e_{12}e_{21}}} a_1^{\frac{e_{21}}{e_{11}e_{22}-e_{12}e_{21}}} a_2^{-\frac{e_{11}}{e_{11}e_{22}-e_{12}e_{21}}} \tag{A.8}$$

The inverse demand function can be written as:

$$p_1 = a_1^{-\alpha_{22}} a_2^{\alpha_{12}} q_1^{\alpha_{22}} q_2^{-\alpha_{12}} \tag{A.9}$$

$$p_2 = a_1^{\alpha_{21}} a_2^{-\alpha_{11}} q_1^{-\alpha_{21}} q_2^{\alpha_{11}} \tag{A.10}$$

$$\alpha_{ij} = \frac{e_{ij}}{e_{11}e_{22} - e_{12}e_{21}} \tag{A.11}$$

APPENDIX B. CONDITIONS FOR THE EXISTENCE OF MARKET EQUILIBRIUM FOR IMPERFECTLY COMPETITIVE MARKETS

For a blender who sells both product $b1$ and $b2$ in imperfectly competitive market (MPD), the profit maximization model is as follows.

$$\max_{q_1,q_2} \quad z = p_{1d}q_1 + p_{2d}q_2 - \int p_{1s}dq_1 - \int p_{2s}dq_2 \tag{B.1}$$

$$s.t. \quad p_{1s} = A_1 + B_1 q_1 \quad \text{Linear supply function of product } b1 \tag{B.2}$$

$$p_{2s} = A_2 + B_2 q_2 \quad \text{Linear supply function of product } b2 \tag{B.3}$$

$$q_1 = a_1 p_{1d}^{e_{11}} q_{2d}^{e_{12}} \quad \text{Constant elasticity of demand function for } b1 \tag{B.4}$$

$$q_2 = a_2 p_{1d}^{e_{21}} q_{2d}^{e_{22}} \quad \text{Constant elasticity of demand function for } b2 \tag{B.5}$$

If market equilibrium exists, then

$$\frac{\partial z}{\partial q_1} = p_{1d} + \frac{\partial p_{1d}}{\partial q_1}q_1 + \frac{\partial p_{2d}}{\partial q_1}q_2 - p_{1s} = 0 \tag{B.6}$$

$$\Rightarrow p_{1d}(1 + \frac{\partial p_{1d}}{\partial q_1}\frac{q_1}{p_{1d}}) + \frac{\partial p_{2d}}{\partial q_1}\frac{q_1}{p_{2d}}\frac{p_{2d}q_2}{q_1} = p_{1s} \tag{B.7}$$

$$\Rightarrow p_{1d}(1 + \frac{1}{e_{11}}) + \frac{1}{e_{12}}\frac{p_{2d}q_2}{q_1} = p_{1s} \tag{B.8}$$

$$\frac{\partial z}{\partial q_2} = p_{2d} + \frac{\partial p_{2d}}{\partial q_2}q_2 + \frac{\partial p_{1d}}{\partial q_2}q_1 - p_{2s} = 0 \tag{B.9}$$

$$\Rightarrow p_{2d}(1 + \frac{\partial p_{2d}}{\partial q_2}\frac{q_2}{p_{2d}}) + \frac{\partial p_{1d}}{\partial q_2}\frac{q_2}{p_{1d}}\frac{p_{1d}q_1}{q_2} = p_{2s} \tag{B.10}$$

$$\Rightarrow p_{2d}(1 + \frac{1}{e_{22}}) + \frac{1}{e_{21}}\frac{p_{1d}q_1}{q_2} = p_{2s} \tag{B.11}$$

The conditions for market equilibrium exist are Equations (B.8) and (B.11). Note that E10 (product 1) and E85 (product 2) have with own price elasticity of demand to be $e_{11} = -0.4$ and $e_{22} = -1.4$ respectively. Cross price elasticities are subject to change. The marginal revenue for E10 is $p_{1d}(1 + \frac{1}{e_{11}}) + \frac{1}{e_{12}}\frac{p_{2d}q_2}{q_1} = p_{1s} > 0$, where

$p_{1d}(1+\frac{1}{e_{11}}) < 0$ is the marginal revenue for blenders if they sell only E10 in imperfectly competitive markets. Therefore, the market equilibrium for imperfectly competitive cases exists when blenders sell both E10 and E85.

Note that if blenders can only sell product E10, then the marginal revenue would be $p_{1d}(1+\frac{1}{e_{11}}) < 0$, therefore the market equilibrium for monopoly case does not exist. This means if blenders can only sell E10, then blenders would not excise market power to reduce E10 quantity and raise market price. Instead, they will only be price takers in the markets.

BIBLIOGRAPHY

[1] A Aden , M Ruth , K Ibsen, et al. (2002). Lignocellulosic biomass to ethanol process design and economic utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL Report No. TP-510-32438. CO: National Renewable Energy Laboratory. 154 p. Report No: TP-510-32438.

[2] ST Anderson. (2012). The demand for ethanol as a gasoline substitute. Journal of Environmental Economics and Management. 63(2), 151-168.

[3] USDA. (2012). United States Department of Agricultrure. Crop production 2011 summary. USDA, National Agriculture Statistics Service. 95 p. ISSN: 1057-7823.

[4] I Awudu, J Zhang. (2012). Uncertainties and sustainability concepts in biofuel supply chain management: A review. Renewable and Sustainable Energy Reviews, Elsevier, 16(2), 13591368.

[5] BV Babu. (2008). Biomass pyrolysis: A state-of-the-art review. Biofuels, Bioproducts and Biorefining, 2 (5), 393-414.

[6] Y Bai, T Hwang, S Kang, Y Ouyang. (2011). Biofuel refinery location and supply chain planning under traffic congestion, Transportation Research Part B: Methodological, 45 (1), 162-175.

[7] Y Bai, Y Ouyang, JS Pang. (2012). Biofuel supply chain design under competitive agricultural land use and feedstock market equilibrium. Energy Economics, Elsevier, 34(5), 1623-1633.

[8] M Balat, M Balat, E Kirtay, H Balat. (2009). Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 1: Pyrolysis systems, Energy Conversion Management, 50 (12), 3147-3157.

[9] GM Barton.(1984). Definition of biomass samples involving wood, bark and foliage. Biomass, 4 (4), 311-314.

[10] RH Beach, BA McCarl. (2010). US agricultural and forestry impacts of the energy independence and security act: FASOM results and model description. Technical report, US Environmental Protection Agency.

[11] A Beresteanu, S Li. (2011). Gasoline prices, government support, and the demand for hybrid vehicles in the United States. International Economic Review, 52(1), 161-182.

[12] IM Bowling,JM Ponce-Ortega, MM El-Halwagi. (2011). Facility location and supply chain optimization for a biorefinery. Industrial & Engineering Chemistry Research, 50 (10), 6276-6286.

[13] SP Bradley, AC Hax, TL Magnanti. (1977). Applied mathematical programming. Addison-Wesley.

[14] CE Brewer, R Unger, K Schmidt-Rohr, RC Brown. (2011). Criteria to select biochars for field studies based on biochar chemical properties. BioEnergy Research, 4 (4), 312-323

[15] RC Brown, C Stevens. (2011). Thermochemical processing of biomass: Conversion into fuels, chemicals and power. Wiley Series In Renewable Resource, Ch.5-7: 124-231.

[16] Y Chen, AL Liu, BF Hobbs. (2011). Economic and emissions implications of load-based, source-based, and first-seller emissions trading programs under California AB32, Operations Research, 59 (3), 696-712.

[17] Y Chen, J Sijm, B Hobbs, W Lise. (2008). Implications of CO2 emissions trading for short-run electricity market outcomes in northwest Europe. Journal of Regulatory Economics, Springer, 34 (3), 251-281.

[18] Y Chen and AL Liu and BF Hobbs. (2011). Economic and emissions implications of load-based, source-based, and first-seller emissions trading programs under California AB32. Operations Research, 59 (3), 696-712.

[19] Y Chen and L Wang. (2013). Renewable Portfolio Standards in the presence of green consumers and emissions trading. Networks and Spatial Economics, 13 (2), 149-181.

[20] X Chen. (2010). A dynamic analysis of US biofuel policy impact on land use, greenhouse gas emission and social welfare. PhD thesis, University of Illinois at Urbana-Champaign.

[21] X Chen, H Onal. (2012). Modeling agricultural supply response using mathematical programming and crop mixes. American Journal of Agricultural Economics, 94 (3), 674-686.

[22] RW Cottle and JS Pang, RE Stone. (1992). The linear complementarity problem. San Diego: Academic Press.

[23] R Daley, J Nangle, G Boeckman, M Miller. (2014). Refueling behavior of flexible fuel vehicle drivers in the federal fleet. Technical report. NREL/TP-5400-61777.

[24] M Dal-Mas, S Giarola, A Zamboni, F Bezzo. (2011). Strategic design and investment capacity planning of the ethanol supply chain under price uncertainty. Biomass and Bioenergy, 35 (5): 2059-2071.

[25] MF Demirbas. (2009). Biorefineries for biofuel upgrading: A critical review. Applied Energy, 86 (0), issue Supplement 1, S151-S161.

[26] DOE, US Department of Energy. (2011). Energy Efficiency & Renewable Energy. Import duty for fuel ethanol. From http://www.afdc.energy.gov/laws/law/US/393.

[27] DOE, US Department of Energy. (2013). Handbook for handling, storing, and dispensing E85 and other ethanol gasoline blends. DOE/GO-102013-3861. From www.afdc.energy.gov/uploads/publication/ethanol_handbook.pdf

[28] DOE, US Department of Energy. (2014). AFV and advanced vehicle history. Energy Efficiency & Renewable Energy. From http://www.afdc.energy.gov/data/10581.

[29] DOE, US Department of Energy. (2014). Alternative fuel vehicles in use. Energy Efficiency & Renewable Energy. From http://www.afdc.energy.gov/data/10300.

[30] DOE, US Department of Energy. (2014). Us alternative fuel stations by fuel type. Energy Efficiency & Renewable Energy. From http://www.afdc.energy.gov/data/10332.

[31] DOE, US Department of Energy. (2014). Average retail fuel prices in US. Energy Efficiency & Renewable Energy. From http://www.afdc.energy.gov/data/10326.

[32] SD Eksioglu, AM Acharya. (2009). Models for supply chain design and logistics management of biorefineries. Transportation Research Board 88th Annual Meeting. Washington, DC, US. Jan. 11-15.

[33] SD Eksioglu, S Li, S Zhang, S Sokhansanj, D Petrolia. (2010). Analyzing impact of intermodal facilities on design and management of biofuel supply chain. Transportation Research Board of the National Academies 2191, 144-151.

[34] EIA, US Energy Information Administration. (2012). US regular gasoline prices, full history. From http://www.eia.gov/petroleum/gasdiesel/

[35] EIA, US Energy Information Administration. (2011). Annual Energy Review 2011. Washington DC:United States: Energy Information Administration, Department of Energy; 390 p. Report No: DOE/EIA-0384(2011).

[36] MJ Eppstein, DK Grover, JS Marshall, DM Rizzo. (2011). An agent-based model to study market penetration of plug-in hybrid electric vehicles. Energy Policy, 39 (6), 3789-3802.

[37] M Espey. (1996). Explaining the variation in elasticity estimates of gasoline demand in the United States: A meta-analysis. The Energy Journal. 17 (3), 49-60.

[38] F Facchinei, C Kanzow. (2010). Generalized Nash Equilibrium problems. Annals of Operations Research, 175, 177-211.

[39] R Fahmi, AV Bridgwater, I Donnison, N Yates, JM Jones. (2008). The effect of lignin and inorganic species in biomass on pyrolysis oil yields, quality and stability, Fuel, 87 (7), 1230-1240.

[40] FCEA, Food, Conservation, and Energy Act. (2008) Food, conservation, and energy act of 2008, section 15321. http://www.finance.senate.gov/legislation/details/?id=2b05ac5a-9dd1-e25d-16dc-23cf01e31cc2. Accessed December 1, 2012.

[41] MC Ferris, JS Pang. (1997). Engineering and economic applications of complementarity problems. SIAM Review, 39, 669-713.

[42] C Fischer. (2010). Renewable Portfolio Standards: When do they lower energy prices? The Energy Journal, International Association for Energy Economics, 0 (1), 101-120.

[43] California Air Resources Board, California Energy Commission. (2007). California State Alternative Fuels Plan.

[44] SA Gabriel, AJ Conejo, JD Fuller, BF Hobbs, C Ruiz. (2012). Complementarity modeling in energy markets. International series in Operations Research & Management Science. Springer. ISBN-13: 978-1441961228.

[45] KS Gallagher, E Muehlegger. (2011). Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology. Journal of Environmental Economics and Management, 61 (1), 1-15.

[46] BH Gebreslassie, Y Yao, F You. (2012). Design under uncertainty of hydrocarbon biorefinery supply chains: multiobjective stochastic programming models, decomposition algorithm, and a comparison between CVaR and downside risk. AIChE Journal, 58 (7), 2155-2179.

[47] RL Graham, R Nelson, J Sheehan, RD Perlack, and LL Wright. (2007). Current and potential US corn stover supplies. Agron, 99 (1), 1-11.

[48] LA Greening, DL Greene, C Difiglio. (2000). Energy efficiency and consumption - the rebound effect - a survey. Energy Policy. 28, 389-401.

[49] JR Hess, K Kenney, P Laney, D Muth, P Prygofle, C Radtke, C Wright. (2006). Feasibility of a producer owned ground-straw feedstock supply system for bioethanol and other products, grant 4-D farms duane grant. Straw Value Add Committee and Idaho National Laboratory, INL/ EXT-06-12000.

[50] J Horner, R Milhollin. (2011). Marketing study for corn stover in Missouri. Technical Report, Missouri Stover Products Commercial Agriculture Program, University of Missouri. 39 p. Technical Report.

[51] HJ Huang, S Ramaswamy, W Al-Dajani, U Tschimer, RA Cairncross. (2009). Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. Biomass and Bioenergy, 33 (2), 234-246.

[52] Y Huang, Y Chen. (2014). Analysis of an imperfectly competitive cellulosic biofuel supply chain. Transportation Research Part E: Logistics and Transportation Review, 72, 1-14.

[53] GW Huber. (2007). Breaking the chemical and engineering barriers to lignocellulosic biofuels: Next generation hydrocarbon biofuel refineries. Workshop. Washington, D.C. June 25-26.

[54] JE Hughes, CR Knittel, D Sperling. (2008). Evidence of a shift in the short-run price elasticity of gasoline demand. The Energy Journal. 29 (1), 113-134.

[55] I Awudu, J Zhang. (2013). Stochastic production planning for a biofuel supply chain under demand and price uncertainties. Applied Energy. 103 (C), 189-196.

[56] KE Ileleji, S Sokhansanj, JS Cundiff. (2010). Farm-gate to plant-gate delivery of lignocellulosic feedstocks from plant biomass for biofuel production. Wiley-Blackwell, Ch.7, 117-159.

[57] University of Illinois. (2007). Corn-based ethanol in Illinois and the US: A report from the Department of Agricultural and Consumer Economics. University of Illinois.

[58] US Census. (2011). US census bureau delivers Iowa's 2010 census population totals, including first look at race and hispanic origin data for legislative redistricting. Report No: CB11-CN24.

[59] KL Jensen, CD Clark, BC English, RJ Menard, DK Skahan, AC Marra. (2010). Willingness to pay for E85 from corn, switchgrass, and wood residues. Energy Economics, 32 (6), 1253-1262.

[60] SB Jones, JE Holladay, C Valkenburg, DJ Stevens, CW Walton, C Kinchin, DC Elliott, S Czernik. (2009). Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: A design case. Technical report, US Department of Energy, PNNL-18284.

[61] E Kiesling, M Günther, C Stummer, LM Wakolbinger. (2009). An agent-based simulation model for the market diffusion of a second generation biofuel. Winter Simulation Conference, Austin, Texas. 1474-1481.

[62] J Kima, MJ Realffa, JH Leeb. (2011). Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty. Computers & Chemical Engineering, Elsevier, (35) 9, 1738-1751.

[63] Z Li and MG Lerapetritou. (2010). A method for solving the general parametric linear complementarity problem. Annals of Operations Research, 181, 485-501.

[64] CY Lin, W Zhang, O Rouhani, L Prince. (2009). The implications of an E10 ethanol-blend policy for California. California State Controller John Chiang Statement of General Fund Cash Receipts and Disbursements, 5 (5), 6-7.

[65] R Milhollin, J Hoehne, J Horner, S Weber. (2011). Feasbility of corn stover in Missouri. University of Missouri: Missouri Stover Products Commercial Agriculture Program. 86 p. Technical Report.

[66] J Miranowski, A Rosburg. (2010). Using cellulosic ethanol to 'Go Green': What price for carbon? In Agricultural & Applied Economics Associations 2010 AAEA, CAES & WAEA Joint Annual Meeting, Denver, Colorado, July 25-27.

[67] T Muller. (2000). Integrating bottom-up and top-down models for energy policy analysis: A dynamic framework. Centre universitaire d'tude des problmes de l'nergie, Universit de Genve, Energy policy. 28 pages.

[68] J Nocedal, SJ Wright. (2006). Numerical optimization, second edition. World Scientific. 664 pages.

[69] JA Satrio, MM Wright, RC Brown. (2010). Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Technical report, Technical Report NREL/TP-6A20-46586, November.

[70] US Government. (2012). Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: Dilute-acid pretreatment and enzymatic hydrolysis of corn stover. General Books LLC, Reference Series. ISBN-13: 978-1234454555.

[71] D Petrolia.(2008). The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota. Biomass and Bioenergy, 32 (7), 603-612.

[72] DR Petrolia, S Bhattacharjee, D Hudson, CW Herndon. (2010). Do Americans want ethanol? A comparative contigent-valuation study of willingness to pay for E10 and E85. Energy Economics, 32 (1), 121-128.

[73] S Phillips, TJ Eggeman. (2007). Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulocis biomass. NREL Technical Report, TP-510-41168. National Renewable Energy Laboratory, Golden(CO).

[74] S Pouliot, BA Babcock. (2014). The demand for E85: Geographical location and retail capacity constraints. Energy Economics, 45, 134-143.

[75] PP Ravula, RD Grisso, JS Cundiff. (2008). Comparison between two policy strategies for scheduling trucks in a biomass logistic system. Bioresource Technology, 99 (13), 5710-5721.

[76] RFA, Renewable Fuels Association. (2012). Historical ethanol prices. From http://www.ethanolrfa.org/pages/statistics.

[77] RFA, Renewable Fuels Association. (2011). Gasoline ethanol blends and the classic auto. From http://ethanolrfa.org/page/-/RFA%20Gas%20Ethanol%20Blends%20and%20Classic%20Auto.pdf?nocdn=1.

[78] RFA, Renewable fuels Association. (2014). Summary of automobile manufacturer fuel recommendations: 2014 model year vehicles.

[79] RFS2, The Revised Renewable Fuels Standards. (2014). Renewable Fuels: Regulations & Standards. From http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm.

[80] RITA, Research and Innovative Technology Administration. (2012). National Transportation Statistics [database on the Internet]. Washington DC: United States: Department of Transportation, Research and Innovative Technology Administration. 2012 - [cited 2013 Jul 23] Publications, RITA, Bureau of Transportation Statistics, National Transportation Statistics. Table 3-21- Average Freight revenue per Ton-Mile (updated April 2012). Available from http://www.rita.dot.gov/bts/ Files updated Annually.

[81] JG Rogers, JG Brammer. (2009). Analysis of transport costs for energy crops for use in biomass pyrolysis plant networks. Biomass and Bioenergy, 33 (10), 1367-1375.

[82] PA Sabatier. (1986). Top-down and Bottom-up approaches to implementation research: A critical analysis and suggested synthesis. Journal of Public Policy, 6 (1), 21-48.

[83] R Schnepf, BD Yacobucci. (2012). Renewable Fuel Standard (RFS): Overview and Issues. CRS Report for Congress. CRS Report for Congress; January 2012. 31 p. Report No: R40155.

[84] E Searcy, P Flynn, E Ghafoori, A Kumar. (2007). The relative cost of biomass energy transport. Applied Biochemistry and Biotechnology, 137-140(1-12): 639-652.

[85] SECO, State Energy Conservation Office. (2012). Energy policy act of 2005 (H.R. 6). From http://www.seco.cpa.state.tx.us/energy-sources/biomass/epact2005.php. Accessed December 1, 2012

[86] Y Shastri, L Rodrguez, A Hansen, KC Ting. (2010). Agent-based analysis of biomass feedstock production dynamics. BioEnergy Research, 4(4), 258-275.

[87] S Sokhansanj, A Turhollow, J Cushman, J Cundiff. (2002). Engineering aspects of collecting corn stover for bioenergy. Biomass and Bioenergy, 23 (5), 347-355.

[88] SW Tatum, SJ Skinner, JD Jackson. (2010). On the economic sustainability of ethanol E85. Energy Economics, 32 (6), 1263-1267.

[89] J Tirole. (1988). The theory of industrial organization, MIT Press.

[90] P Tsiakis, LG Papageorgiou. (2008). Optimal production allocation and distribution supply chain networks. International Journal of Production Economics, 111 (2), 468-483.

[91] US Census. (2011). US Census Bureau, State and County QuickFacts. From http://quickfacts.census.gov/qfd/states/19000.html, Accessed December 1, 2012.

[92] USDA. (2006). Iowa agricultural statistics bulletin. Technical Report, National Agricultural Statistics Service.

[93] USDA, US Department of Agriculture. (2012). Iowa agricultural statistics bulletin. National Agricultural Statistics Service. [cited Oct. 2012] Crops and Plants, Crops, Field Crops, Corn. Available from http://www.nass.usda.gov/ Files updated Annually.

[94] VEETC. (2011). US The Volumetric Ethanol Excise Tax Credit: History and Current Policy, 2011. From http://www.taxpayer.net/images/uploads/downloads/2011_VEETC_Fact_Sheet_April_FINAL.pdf.

[95] HD Venema, PH Calamai. (2003). Bioenergy systems planning using location-allocation and landscapes ecology design principles. Annals of Operations Research, 123, 241-264.

[96] WD Walls, F Rusco, M Kendix. (2011). Biofuels policy and the US market for motor fuels: Empirical analysis of ethanol splashing. Energy Policy, Elsevier, 39(7), 3999-4006.

[97] M Wang, M Wu, H Huo. (2007). Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. Environmental Research Letter 2, 13pp.

[98] C Wang. (2009). Economic analysis of delivering switchgrass to a biorefinery from both the farmers' and processor's perspectives. Thesis (M.S.). University of Tennessee, Knoxville. [cited Oct. 2012] Available from http://etd.utk.edu/2009/May2009Theses/WangChenguang.pdf.

[99] P Westhoff, R Baur, DL Stephens, WH Meyers. (1990). FAPRI US crops model documentation. Technical report, Center for Agricultural and Rural Development, Iowa State University, Technical Report 90-TR 17.

[100] SJ Wight. (1996). A path-following interior-point algorithm for linear and quadratic problems. Annals of Operations Research, 62, 103-130.

[101] M Wright, RC Brown. (2007a). Establishing the optimal sizes of different kinds of biorefineries. Biofuel Bioproducts and Biorefining, 1 (3), 191-207.

[102] M Wright. (2010). Techno-economic, location, and carbon emission analysis of thermochemical biomass to transportation fuels. Graduate Theses and Dissertations. [cited Oct. 2012] Available from http://lib.dr.iastate.edu/etd/11727.

[103] M Wright, RC Brown. (2007b). Comparative economics of biorefineries based on the biochemical and thermochemical platforms. Biofuel Bioproducts and Biorefining, 1 (1), 49-56.

[104] F You, L Tao, DJ Graziano, SW Snyder. (2012). Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and inputoutput analysis, AIChE Journal, 58(4), 1157-1180.

[105] X Zhu, X Li, Q Yao, Y Chen. (2010). Challenges and models in supporting logistics system design for dedicated-biomass-based bioenergy industry. Bioresource Technology, 102 (2), 1344-1351.

[106] X Zhu, Q Yao. (2011). Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. Bioresource Technology, 102 (23), 10936-10945.

[107] L Zhang, G Hu. (2013). Supply chain design and operational planning models for biomass to drop-in fuel production. Biomass and bioenergy, 58, 238-250.

[108] L Zhang, G Hu, L Wang, Y Chen. (2013). A bottom-up biofuel market equilibrium model for policy analysis. Annals of Operations Research, DOI: 10.1007/s10479-013-1497-y.

[109] Zhu X, Yao Q. (2011). Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. Bioresource Technology, 102 (23): 10936-10945.