Biofuel Supply Chain Network Design and Operations

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Abstract The rapidly growing biofuel industry poses considerable challenges to its supply chain network design and operations. In this chapter, we introduce key characteristics of the biofuel supply chain that comprises of feedstock production, biomass logistics, biofuel production and distribution. We then discuss the recent literature on biofuel supply chain models. Using an illustrative biofuel supply chain model to facilitate the understanding of the core trade-offs in this context, we discuss various issues including logistics network optimization, transportation and inventory management, uncertainty management, land use competition, governmental policies, and the resulting environmental and social impacts.

1 Introduction

In 2013, the United States was the largest consumer of crude petroleum oil, accounting for about 21% of worldwide consumption (i.e., 18.5 million barrels per day out of 88.9 million barrels consumed worldwide), more than half of which was imported from about 80 countries [6]. The majority of consumption occurs in the transportation sector, especially the light-duty vehicles Americans drive every day which rely almost exclusively on oil. Such heavy reliance raises two major issues: energy security and environmental sustainability. With increasing oil consumption and dependence on foreign oil imports, the U.S. government has made energy security a key priority. Increasing oil consumption also implies considerable impact on the environment, since transportation-related emissions represent about one third of

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the total greenhouse gas (GHG) emissions in the U.S. and are considered to be a critical contributor to global climate change.

To help alleviate these issues, the U.S. government is firmly supporting the development of biofuel production as one of the ideal alternatives for transportation fuel. Biofuel is converted from renewable resources such as crops or other naturally grown biomass into a form of bioethanol or biodiesel that can be used as a gasoline additive to supplement the petroleum-based fuels. With the great potential that biofuels offer, the U.S. Congress enacted the Energy Independence and Security Act (EISA) in 2007 [7] "to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, vehicles, to promote research on and deploy GHG capture and storage options, and to improve the energy performance of the Federal Government, and for other purpose." Congress further announced the Renewable Fuel Standard (RFS) mandate [1] and its revision (known as RFS2 [2]) as action plans, requiring the annual production of renewable fuel to reach 36 billion gallons by 2022, as shown in Figure 1.

The majority of currently produced renewable fuels are conventional biofuels, also referred to as the first-generation biofuels. The primary feedstocks for conventional biofuels are agricultural crops such as corn and sugarcane. Advanced renewable fuels include cellulosic biofuel, often referred to as the second-generation biofuels. The two main feedstock sources of cellulosic biofuels are dedicated energy crops and non-edible agricultural crop residues. Dedicated energy crops include herbaceous energy crops, such as switchgrass and miscanthus, and woody energy crops, such as fast-growing hardwood trees and hybrid poplars. These are perennial crops that require certain years to reach full productivity. Non-edible agricultural crops include corn stover and wheat straw. In particular, corn stover is likely to be

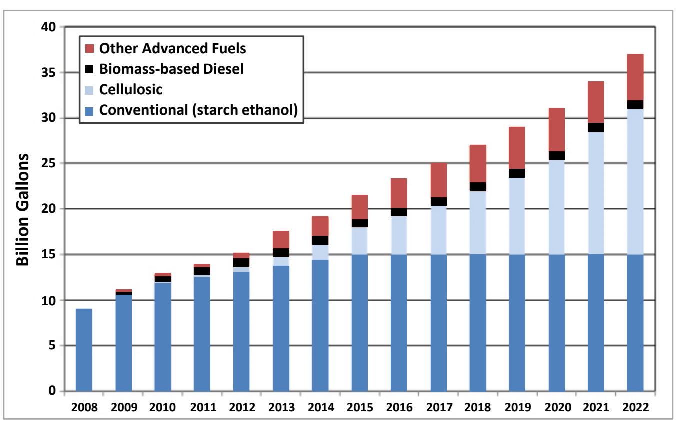

Fig. 1 Renewable fuel volume consumption mandated; Source: United States Department of Energy, Energy Efficiency and Renewable Energy, Alternative Fuels Data Center, URL http://www.afdc.energy.gov/laws/RFS.html

one of the major crop residue feedstocks as approximately 80 million acres of corn are grown in the U.S. On smaller production scales, biodiesel derived from oil seeds of soybeans, canola, and palm is another form of renewable fuel. There are other advanced biofuels derived from various sort of feedstocks including algae and aquatic crops, or any other form of biofuels that may exist in the future.

One important difference between conventional and advanced biofuels is that the raw material (biomass feedstock) for conventional biofuels directly competes against food production whereas advanced biofuels are produced from non-food sources. In addition, advanced biofuels are typically more environmentally-friendly than the typical conventional biofuels. For example, the EPA requires corn-based bioethanol to meet the 20% GHG emission reduction threshold using advanced efficient technologies, compared to the 2005 gasoline baseline; in contrast, cellulosic-based bioethanols or cellulosic-based diesels must comply with the 60% GHG emission reduction threshold [4]. Hence, going forward from 2013, the governmental mandate requires more than 90% of the increase in biofuel production to come from the cellulosic biofuels. In fact, conventional biofuel is considered to play a transition role until the technologies for advanced biofuels mature, eventually leading to a decrease in conventional biofuel production level. For advanced biofuels, one important feature is the high transportation and distribution costs. This is mainly due to the bulky volume (or low energy density) of biomass that result in high/frequent traffic coupled with compatibility issues during transportation. Given that the success of the biofuel industry relies heavily on the reliable supply of high-quality biomass at a reasonable cost, designing a sound *biofuel supply chain network* and establishing efficient operational practices are of utmost importance for the success of this nascent industry.

However, there are many challenges associated with biofuel supply chain design and operations. As an emerging industry, the biofuel industry needs to establish the distribution network spanning different stages of the biofuel production process, while at the same time taking into account high levels of logistics cost and uncertainties resulting from the unique features of biomass feedstocks. The imposed competition for agricultural land also needs to be carefully considered as biomass feedstock will directly and indirectly affect food production and environmental quality. Furthermore, governmental policy instruments such as mandates and subsidies affect the economics (such as supply and demand equilibrium) of the biofuel industry and result in various economic, environmental, and social implications. Therefore, a holistic perspective of biofuel supply chain network design and its operational guidelines is in pressing need in order to achieve sustainable development of the biofuel industry.

The objective of this chapter is twofold. First, in §2, we introduce the *background of this nascent industry and establish key features of the biofuel supply chain*. This will provide a starting point for understanding the industry and the main design and operational issues that rise in the biofuel supply chain. Second, in §3, we introduce the *recent relevant modeling literature on biofuel supply chains*. To facilitate the discussion, we present a simple illustrative biofuel supply chain network design model, and explore specific modeling features by discussing the related issues in each subsection. For broader perspectives of biomass production, biofuel industry, and governmental policies beyond the supply chain, please refer to [3] by the National Research Council and the Billion-Ton studies [1, 2] released by the U.S Department of Energy.

2 Biofuel Supply Chain

A biofuel supply chain encompasses all activities from feedstock production, biomass logistics of storage and transportation, biofuel production, and distribution to end consumers. Similar to most other supply chains, a biofuel supply chain involves various distinct stages with different ownership entities such as farmers, biorefineries, distributors, and oil companies, and its performance highly depends on the network design, planning, and operations. Figure 2 depicts a schematic overview of an advanced biofuel supply chain network.

Specifics of the intermediate processes and logistics steps (conversion, conditioning, storage, and transportation) may vary depending on the types of biomass feedstocks, conversion technology, and biofuel form. However, the fundamental mechanism and flow of the process are very similar. Therefore, in the remainder of this chapter, we will primarily focus on cellulosic bioethanol as the representative case and discuss further issues and challenges of biofuel supply chain design and operations. For more details on production process and technologies of various types of biofuel, we refer the readers to [3, 5]. In what follows, we discuss the core elements of the supply chain: production process, logistics, material supply, and consumption demand.

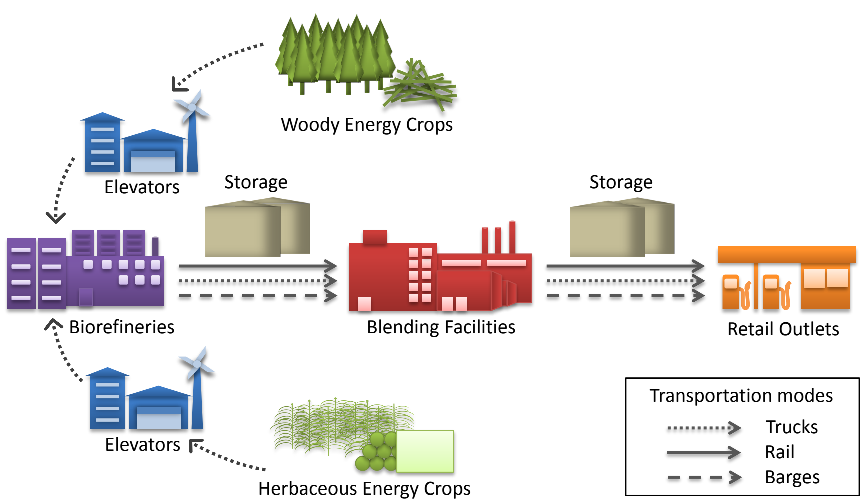

Fig. 2 Schematic description of advanced biofuel supply chain network

2.1 Stages of Biofuel Supply Chain

Feedstock Production. The fundamental source of biofuel is the biomass feedstock, which is made of renewable biological materials. Production of biomass feedstocks include all of the operations required for farmers to generate the feedstock including plant breeding, planting, managing, and harvesting the crops from farmland, field, or forest.

As of 2010, the primary biomass feedstock for biofuel production in the U.S. was corn grain, the majority of which is produced in the Midwest region. However, with the emergence of newer generation crops and the biomass mandate (per RFS2), the sources of feedstock supply are expected to be more diverse and their production regions are expected to expand, e.g., cellulosic feedstocks can be produced on relatively low-quality marginal lands. Feedstock growers are mostly individual farmers who often cooperate closely with local biorefineries through yearly contracts. Although not prevalent yet, long-term contracts are also expected to emerge as demand for cellulosic feedstock (i.e., perennial crops) is anticipated to increase rapidly.

Bioethanol Production. The harvested biomass from regional farms is first collected and staged at the nearby shipping terminal or elevators and then subsequently shipped to a nearby biorefinery. At the biorefineries, the biomass conversion occurs through bio-decomposition, fermentation, and distillation, yielding marketplace products such as ethanol and by-products. In essence, this process is analogous to the petroleum refining for the gasoline. The diversity of the biomass resource requires different conversion technologies including biochemical and thermochemical conversions. However, regardless of their sources, ethanol at this stage must satisfy all specific fuel criteria to offer the same performance as a regular fuel.

Constructing biorefineries is costly. In particular, integrated biorefineries that are capable of handling diverse sources of biomass feedstocks requires significant investment so as to achieve economies-of-scale. Currently, many first-generation bioethanol production systems are owned by regional companies or farm cooperatives in the U.S. As for the advanced-generation biorefineries, governmental aids and participation of large oil companies are expected given the high upfront capital investment.

Although not explicitly featured in the above supply chain, residues from the feedstock conversion process such as dried distillers grain with solubles (DDGS) are often marketed as livestock feed. Given the potential economic implications of by-products, the joint-consideration of biofuel and by-product distribution can potentially be another crucial element of a biofuel supply chain design.

Biofuel Production. The ethanol from the biorefinery is subsequently transported to blending facilities and blended with gasoline. After this stage, the biofuel is ready to be distributed as a commercial transportation fuel. Most existing vehicles today can run on biofuel blends and roughly half of the gasoline sold in the U.S. includes ethanol. A notable biofuel blend example is E10 which is a blend of 10% of ethanol and 90% gasoline. The use of bioethanol helps reduce toxic air pollutant emissions and increase octane components; for example, ethanol used in E10 contains 35% oxygen allowing a more complete burn in the engine leading to better combustion and fewer emissions [3]. Higher ethanol content blends such as E15, E20 have also been introduced in some states in the U.S. (e.g., E15 is available in many midwestern states) and other countries (e.g., E20 has been used in Brazil since 1970s). E85, a blend of 85% of ethanol and 15% gasoline, is another commonly used biofuel that can be used by flexible-fuel vehicles.

Retail Outlets. The final stage of a biofuel supply chain is the distribution and sales of fuels to end-consumers. Most of the biofuels in liquid form are shipped to retail outlets through existing fuel distribution systems to the transportation fuel market. These retail market outlets are typically gas stations owned by large oil corporates such as Exxon Mobil and BP, who also often own the biofuel blending facilities. Some biofuels are also used for residential/commercial heating and power generation, and these fuels are shipped directly to these end-user destinations.

2.2 Logistics

About 70% of petroleum products are transported via pipeline in the U.S. However, bioethanol is typically not compatible with existing petroleum pipelines because it is highly corrosive and more soluble in water than petroleum. For this reason, trucking is one of the most common transportation modes for ethanol shipment, especially for relatively short-distance shipment in the upstream supply chain. This includes shipping harvested biomass from the on-farm storage to local elevators and to the nearby biorefineries.

For the downstream side of the supply chain, the shipping between biorefineries and blending terminals (and the retail outlet) could be carried out through several competing modes. In the U.S., ethanol shipments are commonly made by one or more combinations of trains, trucks, and barges depending on the biofuel types and the region. The estimated transportation costs, adapted from [24], are summarized by mode of transportation in the table below. We note that these estimates are based on the optimized supply chain network, and their values may increase considerably otherwise.

Table 1 Estimated transportation cost and capacity

Transportation modes	Truck	Rail	Barge
Loading and unloading	$0.02/gal	$0.015/gal	$0.015/gal
Fixed or Variable cost	V: $32/hour/truckload	F: $8.80/100 gal	F: $1.40/100gal
Distance-dependent cost	$1.3/mile/truckload	$0.0075/mile/100gal	$0.015mile/100gal
Capacity	8,000gal	33,000gal	1,260,000gal

One of the key challenges in biomass transportation is the handling of its bulky volume. Unprocessed cellulosic biomass materials are typically low on energy-density and aerobically unstable, and hence require special pre-processing (e.g., conditioning and separating grain from the residue) involving significant manual labor. Also, the locations of various feedstock farms are geographically spread out due to land use policy, water availability, soil type, and climate. These characteristics collectively lead to high transportation costs. The transportation cost is estimated to be about 18-28% of the feedstock cost [5] depending on the type of biomass source.

Another key challenge in biomass feedstock logistics is maintaining a steady rate of supply to biorefineries. Many herbaceous feedstocks are only harvested during a short time window, typically 2-3 months or shorter. For example, corn stover is harvested within a few weeks. Since the biorefineries need to produce fuel all year round, biomass feedstock storage is needed at the refineries so as to ensure steady input. Due to low energy density and monetary value of material, storage infrastructure location and operations that minimize biomass quality losses (e.g., biological degradation during the storage leads to detrimental conversion yield) are actively being addressed in research and practice.

2.3 Supply and Demand

There are various sources of cellulosic biomass feedstocks, and their availabilities are location specific. In general, the main determinants of feedstock supply are the feedstock market price and the operating costs which include planting, growing, harvesting, and transporting biomass to elevators. Feedstock supply will also largely depend on the competing options such as the price of agricultural foods or other types of biocrops. Feedstock supply, as any other agricultural product, is subject to yield uncertainty due to weather and disease conditions. Thus, farmers exhibit risk-averse behavior in their land use and crop choice decisions, especially when long-term commitment is required for growing perennial energy crops [36]. A thorough overview of feedstock and its by-product supply in the U.S. is provided in [2].

Demand for biofuel and subsequently the demand for biomass feedstock is dependent on many factors, such as the price of other types of biomass feedstock, advancement of technology, and even the price of crude oil. In the long term, the demand is expected to increase as a result of increasing transportation fuel demand as well as limited availability of petroleum oil reserves.

Another critical factor in shaping the supply and demand of biofuel is government policy. To accelerate the development of the biofuel industry, the U.S. government is establishing various policies and imposing necessary instruments. The major legislation promoting biofuel demand is the RFS 1 and 2 that requires 36 billion gallons of biofuels by 2022 (at least about 45% of which be produced from cellulosic feedstocks). Although oil companies can import bioethanol (e.g., sugarcane ethanol from Brazil), the mandate certainly drives up the need for producing biofuels domestically. A complementary instrument to the mandate for promoting biofuel industry is subsidies provided in the form of direct payment, tax credits, and loans to the farmers and biorefineries. For example, the federal government established the Biomass Crop Assistance Program (BCAP) to incentivize farmers to grow biomass feedstocks [8]. Also, biorefineries are eligible for guaranteed low-interest loans from the USDA. These subsidies and assistance programs reduce the barriers for feedstock production and infrastructure investment.

3 Models of Biofuel Network Design and Operations

The biofuel industry is an emerging business in which the supply of reliable biomass feedstocks is a crucial part of its supply chain. As a result, a sound logistics network lies in the heart of its design.

In what follows, we introduce a generic biofuel supply chain network design problem, which focuses on optimizing its logistics network from farmers to the final retail outlets. Although the baseline model is simplified and stylized for illustrative purposes, it will serve as a baseline model to understand the core trade-offs and essential features of the problem. We will then discuss more advanced features and issues of the problem by reviewing the recent literature.

3.1 Logistics Network

One of the most fundamental trade-offs in a biofuel supply chain network is balancing the transportation costs and facility investments in the optimal distribution network. This includes determining the set of biorefinery locations, decisions of biomass transportation origins and destinations, and bioethanol import and distributions. To better understand the mathematical formulation of the distribution network and to quantitatively facilitate the discussion, we introduce the following simple model as an illustrative example.

Inputs:
$i \in I$ = set of all biomass farmland regions
$j \in J$ = set of all candidate biorefinery sites
$k \in K$ = set of all blending terminals
$\ell \in L$ = set of all retail outlets
$c \in C$ = set of biorefinery capacity levels
$h \in H$ = set of bioethanol import countries
$t \in [0, 1, \cdots, T]$ = planning horizon from time 0 to T
s_i^t = biomass crop yield at farmland i at t
d_ℓ^t = ethanol demand at outlet ℓ at t
$f_j^{c,t}$ = fixed cost of locating a biorefinery j with capacity c at t
a_j^c = capacity of c at biorefinery j
g_i^t = unit production cost of biomass feedstock at farmland i at t
p_j^t = unit processing cost of biorefinery j at t
b_k^t = unit blending cost of terminal k at t

u^t_{ij}, u^t_{jk}, $u^t_{k\ell}$ = unit transportation cost between two nodes at t
v^t_{hk} = unit import cost of bioethanol from country h to terminal k at t
α = conversion rate of biomass to ethanol

Decision Variables:
$X^{c,t}_j$ = 1 if a biorefinery of capacity c is located at site j at time t; 0 otherwise
Y^t_{ij}, Y^t_{jk}, $Y^t_{k\ell}$ = biomass (or bioethanol) amount shipped from site i to j (j to k, and k to ℓ, respectively) at t
Z^t_{hk} = bioethanol import amount from country h to terminal k at t

We can formulate the problem as the following mixed-integer linear program, where the biorefinery location (and capacity) decision **X** is defined as a binary variable while transportation/distribution decision **Y** and import amount decision **Z** are defined as non-negative variables:

$$\min \sum_{j,t,c} f^{c,t}_j X^{c,t}_j + \sum_{i,j,t} (g^t_i + u^t_{ij}) Y^t_{ij} + \sum_{j,k,t} (p^t_j + u^t_{jk}) Y^t_{jk} + \sum_{k,\ell,t} (b^t_k + u^t_{k\ell}) Y^t_{k\ell} + \sum_{h,k,t} v^t_{hk} Z^t_{hk}$$

$$\text{s.t.:} \tag{1}$$

$$\sum_j Y^t_{ij} \geq s^t_i, \quad \forall i,t \tag{2}$$

$$\sum_k Y^t_{k\ell} \leq d^t_\ell, \quad \forall \ell,t \tag{3}$$

$$\sum_j Y^t_{jk} \leq a^c_j X^{c,t}_j, \quad \forall i,t \tag{4}$$

$$\sum_i \alpha Y^t_{ij} \leq \sum_k Y^t_{jk} \quad \forall j,t \tag{5}$$

$$\sum_j Y^t_{jk} + \sum_h Z^t_{hk} \leq \sum_\ell Y^t_{k\ell} \quad \forall k,t \tag{6}$$

$$X^t_j \in \{0,1\} \ \forall j,t, \ \ Y^t_{ij}, Y^t_{jk}, Y^t_{k\ell}, Z^t_{hk} \geq 0, \ \forall i,j,k,\ell,h. \tag{7}$$

The objective function (1) consists of five terms. The first is the fixed cost associated with opening biorefineries. The next three are the relevant processing/operations and transportation costs for the farmers (planting, growing, harvesting biomass feedstocks and shipping them to biorefineries), biorefineries (converting biomass to bioethanol and shipping it to blending facilities), blenders (blending ethanol with gasoline and distributing it to retail outlets), respectively. The last term is the cost associated with bioethanol import from foreign/external sources. Additional considerations can be given to benefits from co-location of different types of facilities as in [22].

Constraints (2) and (3) ensure that biomass supply cannot be greater than the crop yield and the amount of bioethanol distributed to a retailer is not greater than its local demand, respectively. As we will discuss in §3.6, the demand constraint presented in this problem is a stylized one, and a set of more sophisticated market equilibrium constraints can be used to reflect the spatial supply-demand-price relationships (see [42]). Constraints (4) restrict the ethanol production level at each candidate site to the biorefinery capacity, if a facility is built. Additional constraints such as capacity or minimum/maximum facility utilization in each stage can be easily implemented. Constraints (5) and (6) are network balance constraints stipulating that the total inflow (biomass and/or biofuel) cannot be greater than the total outflow at each biorefinery and blending terminal. We note that the above problem assumes a centralized decision making setting covering all entities in the supply chain (farmers, biorefineries, blenders, and retail outlets), and the decision maker plans for the entire design and operations of the supply chain. The final constraints (7) stipulate binary condition for the location decision and non-negative constraints for the other decision variables. Whereas this problem can be used as a benchmark example, various levels of decentralized settings (e.g., monopolistic, oligopolistic, perfectly competitive) may need to be considered for studying conflicting objectives; this will be discussed further in §3.5.

Most network design models in the literature are formulated in mathematical programs such as the above, aiming to optimize the network design subject to varying objectives and constraints. Various additional features or specific application focus are also addressed in recent years (e.g., [23, 14, 10, 11]). For example, [11] propose a strategic modeling framework for designing the supply chain during the transitioning from first-generation biomass to the second generation. [15] incorporate the distribution of DDGS by-products to live stock farms in addition to the biofuel distribution in designing the distribution network. [13] present an extensive dynamic model to determine the biorefinery location along with the biomass supply planning to meet the required biofuel production mandate in the U.S. In general, due to large scale and high complexity, these models are usually challenging to solve within a reasonable time frame (most of which are NP-hard problems), and thus heuristic solution methods are often proposed.

A recent overview of biomass supply chain design models is given in [12], which also identifies remaining challenges and potential future work.

3.2 Transportation and Inventory Management

High transportation cost for bulky cellulosic biomass feedstocks and dispersed farmland sites pose some of the biggest challenges for commercializing the advanced generation biofuels. Since the choice of transportation mode and its travel distances have great impacts on the economic competitiveness of the biofuel industry [9], optimizing transportation mode choices and managing biomass inventory are critical to biofuel supply chain operations.

[20, 19, 18] proposed network design models that integrate the multi-modal transportation options into the design. They show that optimizing the choice of transportation mode results in significant cost differentials, compared to the case where truck is the sole transportation mode, due to geographical dispersion of demand and supply. The choice of transportation modes can be formulated by augmenting another dimension to the transportation decision variables, for example, in the illustrative example above, by changing Y^t_{ij} to $Y^{m,t}_{ij}$, where $m \in M$ represents the set of available transportation modes. The mode-specific transportation costs can then be defined accordingly.

On a related transportation issue, [17] study the impact on extra traffic congestion that is induced by the emerging biofuel industry, taking into account operational level decisions such as biomass shipment routing and impacts on public mobility. They demonstrate that the transportation cost along with the public congestion experience can be reduced considerably by integrating transportation congestion patterns into designing biofuel distribution networks.

Oftentimes, biomass feedstocks and ethanol fuels need to be staged for economies of scale, e.g., smaller in-bound shipments are held until there is sufficient out-bound shipment volume in order to take advantage of the larger vehicle capacity. In addition, biomass may need to be inventoried on storages near the refineries and blending facilities to ensure constant and timely supply to the station, hedging against time- and weather-sensitive crop yield. [23, 21, 25] explicitly consider such storage inventory decisions and jointly optimize the collection, storage, and transportation of biomass and bioethanol.

3.3 Uncertainties

Biofuel supply chains are subject to many uncertainties, which include, but are not limited to, seasonality and random yield of biomass, demand and price fluctuations, and production and logistical uncertainty. Other external factors such as unpredictable regulatory policy changes and technological breakthroughs also make biofuel supply chain management challenging. [35] discusses various sources of uncertainties in a biofuel supply chain along with possible choices of modeling methodologies. Further, they review the sustainability of the biofuel industry from the economic, social, and environmental perspectives.

Many biofuel supply chain network design models primarily focus on the supply side of uncertainties associated with crop yield and seasonality. [30, 33] establish models facing feedstock supply and fuel demand uncertainties in two-stage stochastic optimization models. The stochastic optimization approach allows them to evaluate supply chain performance based on different yield scenarios. For example, in a two-stage stochastic optimization formulation, uncertain yield scenarios $\omega \in \Omega$ can be incorporated into the definition of crop yield $s^{\omega,t}_i$. In the first stage, a set of planning decisions (such as location and size of refineries and storages) are made and, in the second stage, the subsequent operational decisions (such as storage and shipping decisions) are made after the realization of the actual yield. [25] extend the literature by incorporating the seasonality of feedstock supply in addition to yield variability. Whereas introducing seasonality to the model increases the dimension of the problem (i.e., static vs. dynamic) within each stage, an efficient solution method is also proposed to overcome the complexity of the problem. [18] also consider both the seasonality and variability of biomass supply, focusing particularly on the choice of cost-effective transportation modes for shipping bulky biomass feedstock and liquid biofuel.

One strategy for mitigating biomass feedstock supply uncertainty is crop mixing, which two or more types of crops are planted simultaneously in the same field in the same planting season. This is to hedge against uncertainties due to abnormal weather or pest conditions, which its impact may be type-specific. Crop mix and feedstock supply issues are carefully studied in [26, 27]. Also, a related issue regarding feedstock supply is a crop rotation, i.e., different crop types are rotationally planted in the same field over multiple years. [29] discusses the crop mix in relation to crop rotation.

Whereas above studies primarily focus on uncertainties from the supply side, [34] study the network design and capacity investment planning problem under uncertain price. They propose a stochastic optimization framework to show how the design and profitability of a supply chain are affected by the market condition (prices of ethanol and by-products). [28] investigate the production and storage capacity expansion decision under demand uncertainty. Another source of uncertainty may be from the reliability of the infrastructures themselves. [31, 32] incorporate the risk of biorefinery disruptions (e.g., due to flooding) in planning biofuel supply chain networks.

3.4 Land Use Change and Competition

One critical side effect that comes with the rapid development of biofuel industry is direct and indirect land use change. As farmers respond to high biomass prices due to government mandates and subsidies, which will be discussed in the next subsection, more farmland is diverted to biomass feedstock production. Such land use change represents a shift away from food production, and in turn, conversion of more pristine lands such as rainforests and grasslands into farmlands.

The series of direct and indirect land use changes have raised a global concern. First, farmland competition between the food and biomass has led to the so-called "food vs. energy" dilemma. Indeed, accompanying the rapid expansion of biofuel industry, the food price worldwide has increased significantly [43, 44]. For example, corn grain price in the U.S. increased from as low as \$1.5/bushel in 2000 to as high as \$7.1/bushel in 2013 [45], during the time period in which the corn was one of the main feedstocks to bioethanol production. In addition, land use change can potentially lead to negative environmental and ecological consequences such as increased GHG emissions, intensified soil erosion, and reduced wild animals' habitat. The potential negative impacts have been cautioned by many studies (e.g., [37, 39, 40, 41]), posing controversies over the biofuel industry; for example, [37] suggest that, in contrast to the commonly believed myth, bioethanol may nearly double the GHG emissions as compared to that of gasoline, since the increase in the farmland for biocrops production will accelerate the clearance of wilderness. [41]

also show that biofuel cultivation in the Amazonian forests can offset the carbon savings from biofuels, resulting in a net loss in the environmental welfare.

In the face of increased land use competition, studies have examined ways to sustainably nurture the biofuel industry while protecting food security and environmental sustainability. To understand the impact of biofuel production to land use, [49] propose a cause-and-effect framework based on the current state of research and arguments on land use competition. [50] review various modeling schemes to measure the impacts of land use changes and discuss the key factors that can influence the assessment. They further discuss the challenges in implementing policies to address the land use change. Focusing specifically on Brazil and the U.S., the two largest ethanol producing countries, [48] examine how land use changes affect the food and biofuel economy. Using an optimization model that endogenizes price, they analyze the impacts of government mandates and commodity trades on domestic and global markets as well as land use in various scenarios.

The farmland use competition in the context of biofuel supply chains is typically captured by formulation into a bi-level optimization problem, or one with equilibrium constraints (e.g., [42, 31]). That is, instead of the centralized decision making process in §3.1, the decisions are made by multiple decision makers (simultaneously or sequentially) from upstream to downstream of the supply chain. Hence, for example, farmers sometimes may need to make the land use decision in advance of the biorefineries making the production quantity decision. Using game theoretic models of Stackelberg and/or Nash equilibrium concepts to characterize farmers' land use choice (between growing food and biomass crops) and the resulting feedstock market equilibrium, [42, 55] formulate a biofuel manufacturer's supply chain design model to provide insights on optimal land use strategies and supply chain design. Extended view of farmland competition may also include an "environmental market" in addition to food and biofuel markets. For example, the U.S. Department of Agriculture recommends retiring farmlands from agricultural activities for an extended period of time for environmental preservation and preservation of land quality [46]. Such an environmental consideration aggravates the land use competition and leads to a farmland use trilemma among food, energy, and environment [38]. [47] consider this farmland allocation trilemma problem and study the role of governmental policies for stimulating the growth of the emerging biofuel industry and its supply chain in lieu of the incumbent food and environmental markets.

3.5 Environmental and Social Impacts

Closely related to the land use change issue are the environmental and social issues accompanied by the biofuel industry development. Such considerations have been integrated into the biofuel supply chain design with the objective of mitigating adverse environmental and social impacts while improving economic efficiency as well as social welfare. This comprehensive approach follows the triple-bottom-line perspective in the sustainable operations management.

One prevalent approach for assessing environmental and societal impacts is via life cycle assessment, which evaluates those impacts over each stage of the supply chain, from its production to distribution to consumption. Using this approach, [53] construct a multi-objective optimization model and analyze the trade-offs between three objectives throughout the lifetime of the supply chain: minimizing the sum of supply chain design and operations costs, minimizing GHG emissions, and maximizing accrued local jobs in a regional economy. Such a multi-objective problem can be transformed into one with a single objective by aggregating multiple objectives with proper weights based on the decision maker's utility.

In a similar vein, [52, 51] also consider the supply chain design problems with different model features, the former incorporating the carbon trading effect and the latter focusing on a specific feedstock from hybrid poplar (hence, considering some variations in its supply chain). [47] define the social welfare as the aggregate of consumer surpluses in food, energy, and environmental markets, and design a tax and subsidy mechanism for each land use purpose to induce the optimal spatial farmland use pattern that maximizes the social welfare.

3.6 Governmental Policies

Government plays a critical role in the biofuel industry, as it regulates and incentivizes the industry through various policy instruments. In the U.S., mandates (e.g., RFS) and subsidies (e.g., BCAP) are the two representative instruments in place. While the mandate and subsidies can be easily implemented in the supply chain model formulation (for example, mandate can be simply reflected with a constraint requiring the total influx to blender to exceed the mandate value; subsidy can be reflected by adjusting various costs for the corresponding entity), there are advanced models that incorporate these instruments to derive further implications to the biofuel supply chain. To carefully capture the impact of supply and demand subject to mandate and subsidies, instead of using a stylized demand constraint such as (7), the advanced models typically formulate the demand (and price) to be endogenously determined from market equilibrium (e.g., [55, 54, 47]). This, however, results in mathematical programs with equilibrium constraints (MPEC) which often require efficient solution methods.

A mechanism for enforcing the mandated biofuel production in the U.S. is the Renewable Identification Number (RIN), which requires the biofuel production companies to meet certain volumetric quotas each year. A company's RIN quota can be sold and traded to others, similar to the cap-and-trade mechanism in the emission permits. Incorporating the tradable RIN quotas, [55] investigates its impact on the biofuel supply chain design. One interesting finding is that a rigid mandate (i.e., flat rate penalty for defaulting the mandates) may lead to a reduction in the total biofuel production, and hence policy makers should be cautioned about the importance of mandate level choices. In [54], RIN is considered along with subsidies offered to different entities in the supply chain (farmer, producer, and blender). [47] address the coordination issues of mandate and subsidy in the biofuel industry.

Focusing specifically on the environmental policy side, [56] consider the carbon regulatory mechanisms for reducing GHG emissions. Considering regulatory policies such as carbon cap, tax, and cap-and-trade, they provide insights on the impacts of each potential policy on the biofuel supply chain. [50, 48] discuss implications for land use policy.

4 Conclusion

Biofuel is an alternative energy fuel that is converted from naturally grown renewable resources. With compelling benefits and potential over the economic, environmental, and social dimensions, it is deemed as one of the most promising and ideal alternatives for transportation fuel. To this end, governments around the world, including the U.S., are strongly supporting the development of biofuel production with various policies and regulations including mandate and subsidy programs. In the last decade, from 2003 to 2013, global biofuels production has increased from 14.7 billion tons per year in 2003 to 65.3 billion in 2013. The increase in the U.S. was even steeper as it grew from 5.2 billion to 28.4 billion during the same time period [57].

While technological and engineering advancements are key to the success of biofuel industry, providing an efficient and reliable supply chain network design and operations is another critical component to its success. This chapter provides an introduction to the nascent biofuel production industry and key features and issues of its biofuel supply chain. Starting from a basic supply chain design model, we review fundamental trade-offs and the main design and operational issues that rise in a biofuel supply chain and the related economic, social, and environmental contexts. In addition, we provide literature review of recent modeling studies related to the biofuel supply chain design. Finally, we discuss how various operational challenges and policy considerations related to agricultural production, industry manufacturing, market mechanisms, and government regulations are addressed in the recent modeling literature.

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