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Designing a Renewable Jet Fuel Supply Chain: Leveraging Incentive Policies to Drive Commercialization and Sustainability

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Abstract: Renewable jet fuel (RJF) production has been recognized as a promising approach for reducing the aviation sector's carbon footprint. Over the last decade, the commercial production of RJF has piqued the interest of airlines and governments around the world. However, RJF production can be challenging due to its dispersed supply resources. Furthermore, the production of RJF is more costly compared to producing conventional jet fuel. In this study, using a mixed integer linear programming (MILP), we design a corn-stover-based RJF supply chain network in which we obtain an optimized configuration of the supply chain and determine operational decisions required to meet RJF demand at airports. To accelerate the commercialization of RJF production, we examined four incentive programs designed to cover the supply chain's costs, with agricultural statistics districts serving as the designated supply regions. This study is validated by employing the model to design the supply chain in the Midwestern United States. The results from this study are promising as they show the supply chain can achieve commercialization with partial financial coverage from the incentive programs. Based on the findings of this study, policymakers can devise policies to commercialize RJF production and accelerate its adoption by the industry.

Keywords: renewable jet fuel; supply chain optimization; monetary incentives; incentive policy

MSC: 90B06

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1. Introduction and Literature Review

Finding cleaner sources of energy is critical to addressing concerns about energy security, food, and the environment. The aviation industry is responsible for 2% of the global carbon emissions [1]. However, the industry will continue to expand, and emissions will rise accordingly. Although electric and hydro-powered vehicles are replacing vehicles powered by fluid fuels such as fossil-based and biomass-based fluid fuels; there are no similar options for the aviation industry. In 2005, the aviation industry committed to cut its net carbon footprint to less than half of its volume by 2050 [2]. To achieve this goal, renewable jet fuel (RJF) has been proposed as a viable replacement that will effectively reduce the consumption rate of fossil-based jet fuels as well as the environmental effects of jet fuel consumption [3]. RJF production can provide economic benefits for farmers, reduced greenhouse gas (GHG) emissions, energy savings for future generations, improved diversity of energy resources, and improved resilience to oil price changes and supply risks [4–6].

Several types of feedstocks can be considered as biomass for producing RJF. However, feedstock derived from food crops is contentious because it can also be used as food [7]. Most of the expected sustainability impacts of RJF stem from feedstock choice and its associated characteristics [8]. To address these concerns and improve sustainability in producing RJF, the aviation industry has committed to using second-generation feedstock that does not compromise food security, requires low energy to produce, uses minimal land with high yield, and improves socio-economic values in local areas where biomass is planted. Second-generation biomass comprises crop residues (e.g., corn stover, wheat straw, rice straw, and rice hull), forestry residues (e.g., wood pulp, wood chips, and sawdust), waste products (e.g., used cooking oils), or crops cultivated in perennial fields as biomass that does not induce food conflicts (e.g., switchgrass, camelina, and carinata). As Perkis and Tyner [9] stated, after meeting the U.S. Renewable Fuel Standard (RFS) requirements for first-generation corn ethanol, many states are now looking for other generations of biomass feedstock such as cellulosic crops. According to the U.S. Billion-Ton Update, there are sufficient biomass resources to meet the advanced biofuel standards of the RFS [10]. The Midwestern US entails regions where corn is widely cultivated, and its residue, called corn stover, appears to be a reliable resource for RJF production.

Wang and Tao [11] provided a comprehensive review of the pathways (process technologies) applied to RJF production. Pathways such as alcohol-to-jet (ATJ) [11,12], Fischer Tropsch (FT) [13], hydrothermal liquefaction (HTL) [14], and hydroprocessed esters and fatty acids (HEFA) [5] can be used to convert biomass to RJF. The pathways are certified or under review by the American Society for Testing and Materials (ASTM) [15]. Many studies, known as techno-economic analysis (TEA), compared the feasibility of using conversion technologies [11,15–19]. In a study comparing the feasibility of technologies such as FT, ATJ, and HTL, de Jong et al. [16] discovered that RJF price ranges are higher than conventional jet fuel prices. Furthermore, several studies known as life-cycle analysis (LCA) have been conducted to estimate GHG emissions caused by the implementation of various pathway technologies [20].

Despite rigorous assessment of the application of TEA and LCA approaches in the literature, the related studies fail to consider the complexity of RJF supply chains. These studies do not take into consideration the optimized number and location of biorefineries that could potentially affect the supply chain costs [21]. Due to the dispersed nature of biomass supply sources and their low energy density, a biofuel supply chain requires a large sourcing area that can meet the biofuel production requirements to meet the demands and eventually result in a profitable supply chain [22]. To achieve this goal, it is critical to locate biorefineries optimally to reduce transportation costs and emissions while also ensuring feedstock availability [21].

To become commercially feasible, RJF production cost must become competitive with the production cost of fossil-based jet fuel [23]. The costs incurred by RJF production need to be covered by government assistance and subsidies [24]. Noh et al. [25] conducted a comprehensive study in which they discussed multiple existing incentive policies that were already in use in US agencies and could be considered for incentivizing RJF production. In another study, Ebrahimi et al. [21] investigated the application of three monetary incentives to cover the costs of an RJF supply chain. They considered three different incentive programs including the biomass crop assistance program (BCAP), the producer credit program (PCP), and the biorefinery assistance program (BAP). In BCAP, governments and agencies cover the costs related to supplying biomass feedstock for producing biofuel. This program has been provided by the US Department of Agriculture (USDA). BAP has provided financial support to cover capital and production costs at biorefineries. The Department of Energy (DOE) has already applied BAP incentives to incentivize biofuel production. PCP provides comprehensive support to cover all types of costs associated with RJF production in the supply chain, including costs associated with biomass supply, production, and transportation. PCP has already been employed by agencies such as the Internal Revenue Service (IRS), USDA, and DOE. Carbon trading has also been considered in several studies as a means to help renewable energy producers compete with the cost of conventional fossil fuel production [22,26]. Also, cap-and-trade (CT) is one of the carbon policies that restrict carbon emissions generated by industries. To implement this policy, the government sets a cap on allowed carbon emissions so that companies that surpass the cap are penalized, while those whose emissions are under the cap can sell unused carbon credits. As a result, the policy could potentially incentivize an industry by allowing producers to trade/sell their unused carbon credits [27]. The European Union, the state of California in the United States, Quebec in Canada, and seven regions in China have already adopted cap-and-trade policies to promote the development of renewable energy resources [28].

While many studies have examined the economic and environmental aspects of RJF production, few have investigated how various monetary incentives could be employed to cover costs related to RJF production [25,29,30]. In this study, after designing an optimized RJF supply chain network in the Midwest, we study the impact of four various monetary incentives to commercialize RJF production. The monetary incentives include programs such as PCP, BCAP, BAP, and CT.

The availability of biomass feedstock is one of the most significant barriers to achieving cost-effective biofuel supply chains [31]. Therefore, ensuring a reliable biomass feedstock resource substantially increases the likelihood of commercializing biofuel production. When designing a supply chain network in strategic-level decision making, many renewable fuel supply chain network design studies have assumed county seats as potential locations for supply regions and biorefinery locations, while agricultural aspects of the regions may not have been taken into account. Agricultural statistics districts (ASDs) are state-defined county groups with similar geography and climate, influencing crop choices and agricultural practices [32]. Only one previous study utilized ASDs in the development of a supply chain for RJF, specifically considering the collection of oilseed feedstock from the southwestern United States. Table 1 presents a summary of the literature pertaining to the development of RJF supply chains.

Table 1. Summary of related works on RJF supply chain network design.

Reference	Zoning	Region	Incentive Policies	Feedstocks	Method
[33]	County	California	BAP	Wheat straw, Corn stover, forest residues, and camelina	MILP
[34]	County	Midwest (7 states)	-	Corn stover	MILP
[35]	County	Illinois	BAP and PCP	crop residues, wood residues, and energy crops	MILFP
[36]	County	Georgia	-	Carinata	GIS + MILP
[37]	County	USA	-	Hardwood biomass	MILP
[38]	County	Alabama, Florida, and Georgia	-	Carinata	MILP
[21]	ASD	Alabama, Florida, and Georgia	BCAP, BAP, and PCP	Carinata	MILP
Current study	ASD	Midwest (12 states)	BCAP, BAP, PCP, and CT	Corn stover	MILP

The research questions this study aims to answer are as follows:

- What is the optimal corn-stover-based supply chain network design that can meet RJF demand in the Midwest?
  - Which regions are the optimal locations to supply biomass feedstock to biorefineries?
  - How many and where should biorefineries be established to meet the demand at airports?
  - How much are the costs and revenues generated by the supply chain?
- Can the four incentive programs cover the RJF supply chain costs?
- This study contributes to the literature by
- Determining prospective agricultural sites in the Midwest where corn stover can be collected from lands planted by corn. In this study, we utilize agricultural statistics districts (ASDs) as more robust strategic-level supply regions compared to a previous

study on RJF supply chain network design in the Midwest by Huang et al., which focused on counties as supply regions [34].

- Designing a three-echelon RJF supply chain network using corn stover in the Midwest. The region's lands are abundantly planted with corn. The production of RJF from corn stover promises to improve the farming economy of the region and the sustainability of jet fuel used by airports. This study is the first to examine the entire Midwest (12 states) as a supply region for RJF production. Similar research by Huang et al. [34] also studied RJF supply chain network design but only considered seven states as the supply region.
- Analyzing the impact of four distinct monetary incentives on the profitability of a corn-stover-based RJF supply chain. There have been few studies comparing the profitability of RJF supply chains based on potential direct monetary incentives. This study offers one more incentive policy (CT) compared to the study by Ebrahimi et al. [21] in which they only applied PCP, BCAP, and BAP in their carinata-based RJF supply chain network.

The body of this paper is structured in five Sections. In Section 2, the data used in the case study are presented and assumptions related to it are discussed. Also, the RJF supply chain network design model, inspired by a real case in the Midwestern US, is described. The suggested model is solved and the results are analyzed in Section 3. In Section 4, the managerial implications are discussed. Section 5 outlines various limitations in the research while also suggesting potential avenues for future research.

2. Materials and Methods

2.1. The RJF Supply Chain Configuration

Corn is widely planted in the Midwest and its residues are considered good for producing second-generation biofuels. In this study, we developed models that could be used to design an RJF supply chain using corn stover. The models determined the supply chain's profit by producing RJF. Due to its low capital and operational costs compared to other conversion pathways such as HTL and ATJ, we considered FT to produce RJF from corn stover [34]. The outputs from the production process include RJF, renewable diesel fuel (RDF), naphtha, and electricity [39].

We consider a supply chain with three tiers: supplier nodes, biorefineries, and demand nodes. The biomass feedstock flows from supplier nodes to biorefineries where, after being preprocessed and going through the conversion process, the RJF produced in biorefineries is disseminated to demand nodes (airports). Figure 1 illustrates the three echelons of the RJF supply chain and its components.

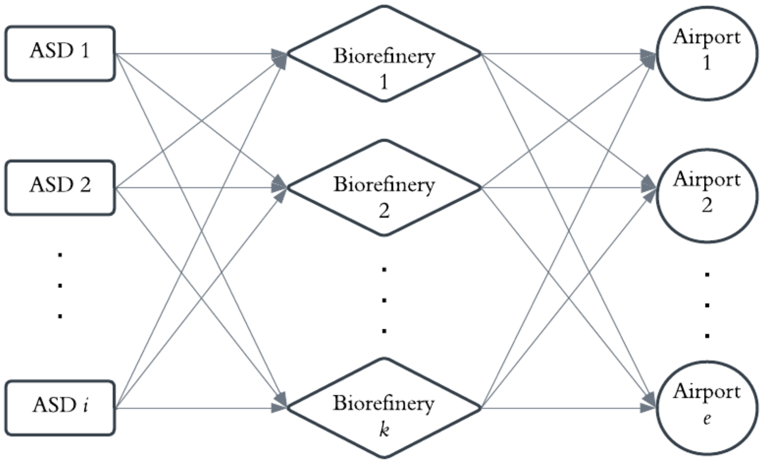

Figure 1. A three-stage supply chain network for RJF production (created by the authors).

For our study, we consider the Midwest in the United States. The Midwest comprises the states of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. For supplier nodes, we consider each agricultural statistics district (ASD) as a supply node [21,29]. Supply for each ASD includes supply from all farms planting corn in the corresponding ASDs. However, to determine the amount of corn stover that can be extracted from farms, we excluded 50% of the available corn stover and assumed that only 35% of farmers would be interested in selling their corn stover [40]. The quantity of biomass feedstock was calculated by multiplying the area planted with corn [41] by the yield rate of corn stover, which was 3.099 tonnes per acre [42]. The biorefineries can be supplied by 2000 million tonnes of corn stover annually [34].

Since we wanted to determine the annual profit of the supply chain, we needed to annualize the capital cost of biorefineries. Equation (1) is used to annualize the initial investment of a biorefinery with an expected life of n years and an interest rate of q%. The expected life of the biorefineries was set at 20 years, with an 11.5% interest rate [43,44]. The biorefinery's initial investment cost was USD 331.63 million [34], whereas its corresponding annual cost was estimated at USD 45.51 million.

$$Annualized\ cost = [q * (Initial\ investment)]/\left[1 - (1+q)^{-n}\right] \tag{1}$$

Figure 2 shows the spatial placement of the RJF supply chain, including the supply areas as well as potential biorefinery locations and airports.

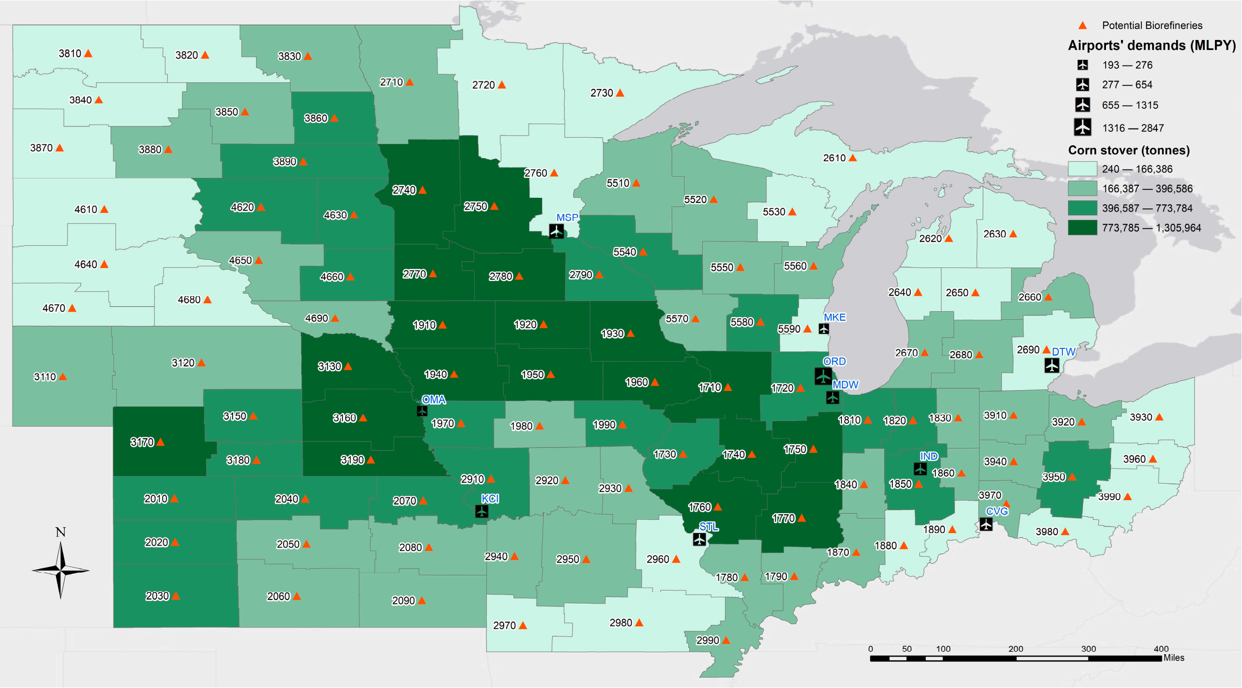

Figure 2. Spatial distribution of the RJF supply chain components in the Midwest (created by the authors).

Due to a 50% maximum blending limit of RJF produced through FT, only half of the required jet fuel demand was projected to be fulfilled by RJF. To consider a reliable RJF demand source, we only considered airports in the Midwest with annual domestic RJF demands greater than 100 million gallons [34]. The total demand in airports was determined by calculating the average jet fuel consumption per domestic flight in the United States using data from the Bureau of Transportation Statistics (BTS) website (2015-19) [45] and multiplying this average by the domestic flight departures for each airport, thereby obtaining the annual jet fuel consumption for each airport. The airports with their corresponding demands are depicted in Table 2.

Table 2. The estimated domestic RJF demand in the airports.

Airports	**Total Jet Fuel Demand (MLPY)**	**Estimated RJF Demand (MLPY)**
O'Hare International Airport (ORD)	2846.51	1423.25
Minneapolis-Saint Paul International Airport (MSP)	1301.50	650.75
Detroit Metropolitan Wayne County Airport (DTW)	1314.88	657.44
Chicago Midway International Airport (MDW)	653.79	326.90
St. Louis Lambert International Airport (STL)	618.58	309.29
Kansas City International Airport (KCI)	415.03	207.51
Indianapolis International Airport (IND)	375.96	187.98
Cincinnati/Northern Kentucky International Airport (CVG)	365.37	182.69
General Mitchell International Airport (MKE)	276.33	138.16
Eppley Airfield (OMA)	192.90	96.45
Total	8360.84	4180.42

Other data related to the parameters used in the RJF supply chain model is provided in Table A1 in Appendix A.

2.2. Model Formulation

We developed five MILPs: a base model with no monetary incentives and four models with incentive programs, including PCP, BCAP, BAP, and CT. The models were designed to maximize the total profit of the RJF supply chain. The supply chain's revenue included earnings from selling RJF, biofuel coproducts (RDF, naphtha), electricity, and unused carbon credits. On the other hand, the costs consisted of expenses associated with purchasing corn stover, transportation, establishing biorefineries, production, and purchasing extra carbon credits. Moreover, the models found the optimal number and location of biorefineries to be established, as well as their suppliers and the airports they supply to. In addition, the model determined the optimal flow of biomass to biorefineries from farmlands as well as the flow of RJF from biorefineries to airports. The optimization models are subject to several limitations that are outlined as constraints (3)–(11) and (16) within the five models. Table 3 shows the notation used in the models.

Table 3. Sets, decision variables, and parameters.

Indices	**Description**	**Indices**	**Description**
Sets		Parameters	
I	Set of suppliers, indexed by i	γ^b	Transportation fixed cost of corn stover via truck (USD/tonne)
K	Set of biorefineries, indexed by k	η^b	Transportation variable cost of corn stover via truck (USD/tonne km)
E	Set of demand zones, indexed by e	γ^m	Transportation fixed cost of RJF via truck (USD/L)
J	Set of byproducts, indexed by j; naphtha, RDF, and electricity	η^m	Transportation variable cost of RJF via truck (USD/L km)
Variables		ω_j	Selling price of byproduct j (USD/L)
Y^k	1 if a biorefinery is activated at location k; 0 otherwise	D_e	Annual RJF demand level at demand node e (L)
Q_{ik}	Quantity of biomass transported from supply area i to biorefinery k (tonnes)	ρ	Production cost of RJF at biorefinery (USD/L)
Q_{ke}	Quantity of RJF transported from biorefinery k to demand zone e (L)	p^+	Buying price of one kg of carbon (CO_2e) in the carbon market (USD)
Q_k^j	Quantity of byproduct j produced at biorefinery k (L)	p^-	Selling price of one kg of carbon (CO_2e) in the carbon market (USD)
e^+	Number of carbon credits purchased	e_b	Emission factor of transporting corn stover (kg CO_2e /tonne km)
e^-	Number of carbon credits sold	e_j	Emission factor of transporting RJF (kg CO_2e /L km)

Table 3. *Cont.*

Indices	Description	Indices	Description
π	RJF selling price (USD/L)	$e^{acquisition}$	Emission factor of corn stover acquisition (kg CO_2e /tonne)
φ	BAP discount rate	$e^{production}$	Emission factor of producing RJF from corn stover (kg CO_2e /L)
β	BCAP discount rate	d_{ik}	Distance from supplier *i* to biorefinery *k* (km)
λ	Monetary incentive for PCP program (USD/L)	d_{ke}	Distance from biorefinery *k* to demand zone *e* (km)
α	Selling price of corn stover (USD/tonne)	T	Capacity of a biorefinery (tonne)
a_i	Quantity of corn stover available at supply node *i*	f	Annualized fixed cost of biorefinery (USD)
θ	RJF conversion rate from corn stover (L/tonne)	V	Annualized variable cost of biorefinery (USD)
σ^j	Conversion rate of fuel byproduct *j* from corn stover (L/tonne)	C^{cap}	Carbon capacity allowed for the RJF supply chain (kg CO_2e)

2.2.1. RJF Supply Chain with no Monetary Incentives

In this section, no carbon policy is considered in the supply chain. Equation (2) presents the objective function used in this model to maximize profits. The first two components of the statement represent revenue from selling RJF to the airports and coproducts including RDF, naphtha, and electricity at biorefineries. The remainder of the statement represents costs incurred by purchasing biomass feedstock from suppliers, establishing biorefineries, RJF production, transportation of biomass feedstock from farms to biorefineries, and transportation of RJF from biorefineries to airports.

$$\begin{aligned}\text{Max } Z = \pi\sum_{k\in K}\sum_{e\in E} Q_{ke} + \sum_{j\in J}\sum_{k\in K}\omega_j Q_k^j - \alpha\sum_{i\in I}\sum_{k\in K} Q_{ik} - f\sum_{k\in K} Y^k - \rho\sum_{k\in K}\sum_{e\in E} Q_{ke} \\ -\sum_{i\in I}\sum_{k\in K}(\gamma^b + \eta^b d_{ik})Q_{ik} - \sum_{k\in K}\sum_{e\in E}(\gamma^m + \eta^m d_{ke})Q_{ke}\end{aligned} \tag{2}$$

Subject to:

$$\sum_{k\in K} Q_{ik} \le a^i \quad \forall i \in I \tag{3}$$

$$\theta\sum_{i\in I} Q_{ik} = Q_{ke} \quad \forall k \in K \tag{4}$$

$$\sigma^j\sum_{i\in I} Q_{ik} = Q_k^j \quad \forall k \in K,\ \forall j \in J \tag{5}$$

$$\sum_{k\in K} Q_{ke} \ge D_e \quad \forall e \in E \tag{6}$$

$$\sum_{i\in I} Q_{ik} \le TY^k \quad \forall k \in K \tag{7}$$

$$Y^k = \{0,1\} \quad \forall k \in K \tag{8}$$

$$Y^k \ge 0 \quad \forall k \in K \tag{9}$$

$$Q_{ik} \ge 0 \quad \forall i \in I,\ \forall k \in K \tag{10}$$

$$Q_{ke} \ge 0 \quad \forall k \in K,\ \forall e \in E \tag{11}$$

Equations (3) to (11) represent the constraints for the RJF supply chain. Constraint (3) is a supply constraint for feedstock availability and ensures that the amount of corn stover purchased does not exceed the maximum biomass feedstock available at supplier nodes. Constraint (4) presents material flow in the supply chain and ensures the quantity of RJF converted from corn stover in a biorefinery is equal to the quantity of RJF leaving the biorefinery to demand nodes. Equation (5) shows the quantity of coproducts generated at each established biorefinery. Constraint (6) guarantees the RJF transported from biorefineries to an airport will meet the RJF demand at the airport. Equation (7) ensures that a biorefinery at location k (if activated) cannot accept more corn stover to process than its designated capacity. Equations (8)–(11) express the nature and non-negativity of the variables.

2.2.2. RJF Supply Chain Incentivized with PCP

This part provides PCP incentives to the supply chain for each liter of RJF produced by biorefineries. To apply the PCP incentives in the model, we added parameter λ to the first component of the objective function in Equation (12). However, the rest of the equation is identical to Equation (2). For the given objective function in Equation (12), the same constraints apply as in Equation (2).

$$\begin{aligned}\text{Max } Z = (\pi+\lambda)\sum_{k\in K}\sum_{e\in E} Q_{ke} + \sum_{j\in J}\sum_{k\in K}\omega_j Q_k^j - \alpha\sum_{i\in I}\sum_{k\in K} Q_{ik} - f\sum_{k\in K} Y^k - \rho\sum_{k\in K}\sum_{e\in E} Q_{ke} \\ -\sum_{i\in I}\sum_{k\in K}(\gamma^b+\eta^b d_{ik})Q_{ik} - \sum_{k\in K}\sum_{e\in E}(\gamma^m+\eta^m d_{ke})Q_{ke}\end{aligned} \tag{12}$$

Subject to constraints (3) to (11).

2.2.3. RJF Supply Chain Incentivized with BCAP

This section employs BCAP to incentivize the supply chain, with all components in Equation (13) identical to those in Equation (2), except for the monetary incentives to purchase corn stover (discounts on corn stover's purchasing price) in the third component. For the objective function in Equation (13), the same constraints apply as in Equation (2).

$$\begin{aligned}\text{Max } Z = \pi\sum_{k\in K}\sum_{e\in E} Q_{ke} + \sum_{j\in J}\sum_{k\in K}\omega_j Q_k^j - (1-\beta)\alpha\sum_{i\in I}\sum_{k\in K} Q_{ik} - f\sum_{k\in K} Y^k - \rho\sum_{k\in K}\sum_{e\in E} Q_{ke} \\ -\sum_{i\in I}\sum_{k\in K}(\gamma^b+\eta^b d_{ik})Q_{ik} - \sum_{k\in K}\sum_{e\in E}(\gamma^m+\eta^m d_{ke})Q_{ke}\end{aligned} \tag{13}$$

Subject to constraints (3) to (11).

2.2.4. RJF Supply Chain Incentivized with BAP

In this section, the supply chain is incentivized using BAP, with each component in Equation (14) being identical to those in Equation (2), except for monetary incentives that are factored into the fourth composite component, including costs related to capital and operational costs at biorefineries. For the given objective function in Equation (14), the same constraints apply as in Equation (1).

$$\begin{aligned}\text{Max } Z = \pi\sum_{k\in K}\sum_{e\in E} Q_{ke} + \sum_{j\in J}\sum_{k\in K}\omega_j Q_k^j - \alpha\sum_{i\in I}\sum_{k\in K} Q_{ik} - (1-\varphi)\left(f\sum_{k\in K} Y^k + \rho\sum_{k\in K}\sum_{e\in E} Q_{ke}\right) \\ -\sum_{i\in I}\sum_{k\in K}(\gamma^b+\eta^b d_{ik})Q_{ik} - \sum_{k\in K}\sum_{e\in E}(\gamma^m+\eta^m d_{ke})Q_{ke}\end{aligned} \tag{14}$$

Subject to constraints (3) to (11).

2.2.5. RJF Supply Chain Incentivized with Cap-and-Trade Policy

This section considers CT for emissions created by the RJF supply chain. CT considers a carbon capacity for the supply chain, while it also allows trading unused carbon credits. In other words, to meet demand in a supply chain with capacitated emission levels, the network might either generate less carbon credits than the designated cap and sell unused carbon emissions or exceed the carbon emission cap and then purchase extra carbon credits. In the objective function presented in Equation (15), e^+ and e^- are defined as the quantity of carbon credits purchased and sold, respectively. However, if needed, the capacity could be increased by purchasing carbon credits. For the objective function in Equation (15), the same constraints apply as in Equation (2), plus constraint (16) which is related to the carbon cap. Equation (16) ensures the carbon generated throughout the supply chain does not exceed the carbon cap considered for the supply chain.

$$\begin{aligned} Max\ Z = \pi \sum_{k\in K}\sum_{e\in E} Q_{ke} + \sum_{j\in J}\sum_{k\in K} \omega_j Q_k^j - \alpha \sum_{i\in I}\sum_{k\in K} Q_{ik} - f\sum_{k\in K} Y^k - \rho \sum_{k\in K}\sum_{e\in E} Q_{ke} \\ - \sum_{i\in I}\sum_{k\in K} (\gamma^b + \eta^b d_{ik}) Q_{ik} - \sum_{k\in K}\sum_{e\in E} (\gamma^m + \eta^m d_{ke}) Q_{ke} - [p^+ e^+ - p^- e^-] \end{aligned} \tag{15}$$

Subject to constraints (3) to (11) and

$$\begin{aligned} e^{acquizition} \sum_{i\in I}\sum_{k\in K} Q_{ik} + e^{production} \sum_{k\in K}\sum_{e\in E} Q_{ke} + \sum_{i\in I}\sum_{k\in K} e_b d_{ik} Q_{ik} + \sum_{k\in K}\sum_{e\in E} e_j d_{ke} Q_{ke} + e^- \\ \leq\ C^{cap} + e^+ \end{aligned} \tag{16}$$

2.3. Assumptions

In formulating and modeling the problem, this research integrated the following assumptions:

- All the products, including RJF and coproducts, produced by the biorefineries will be sold.
- Transporting biomass feedstock from farms to biorefineries and transporting RJF from biorefineries to airports is carried out by trucks.
- RDF and naphtha are sold at biorefineries, with customers being responsible for transportation costs.
- For transportation purposes, each supply node at an ASD is considered to originate from the center of the ASD (centroid).
- For the case where the supply node and biorefinery are located in the same ASD, the transportation distance is assumed to be 2/3 of the radius of that ASD which is calculated using the area of each ASD [34].
- Preprocessing of corn stover is performed at biorefineries.
- The model utilizes the average demand for US domestic jet fuel spanning the years 2015 to 2019 for a robust and reliable estimate.

3. Results and Discussion

In this section, we first determined the optimal configuration of the RJF supply chain network, including the number and location of biorefineries (strategic decisions), as well as the material flow between the various supply chain components (tactical decisions). Afterwards, the application of the four incentive policies on the profitability of the supply chain is discussed. We assume that the minimal incentive to commercialize RJF production is the level that reduces profit loss to zero. Finally, the impacts of changes in various parameters of the supply chain on its profitability are analyzed. The optimization problems were developed in Python 3.7 and solved by the Gurobi 9.1.2 optimization solver in which the optimality gap was set at 1%. The solver used a linear-programming-based branch-and-bound algorithm to solve the MILPs. Interested readers are directed to peruse comprehensive guidelines elucidating the MILP-solving process with Gurobi, accessible through Gurobi's web portal [46].

3.1. Supply Chain Analysis with no Monetary Incentives

The results from the optimization model showed that 10 biorefineries in ASDs 1710, 1720, 1750, 1850, 2690, 2750, 2790, 2910, 2960, and 5590 were established to meet the demand at airports. In terms of the biomass feedstock necessary to supply the biorefineries, 28.96 million tonnes of corn stover were required to produce the desired RJF. The region had a potential availability of 44.44 million tonnes of corn stover (for conversion to RJF), which could provide 6417 million liters of RJF a year. Because of the blending limitations (50%), we assumed airports could only refill their airplanes with RJF by up to 50% of their capacity. As a result, only 4180.42 million liters of RJF were expected to be supplied to the selected airports. The optimal assignments of the supply and demand nodes to the activated biorefineries are shown in Table A2.

According to the findings, the supply chain resulted in a profit loss of USD 481.65 million, which equates to a profit loss of USD 0.12 per liter. As shown in Figure 3, the majority of supply chain revenue (46%) could be attributed to the revenue from selling RJF, while the lowest revenue share (15%) could be attributed to the sale of power generated during the manufacturing process.

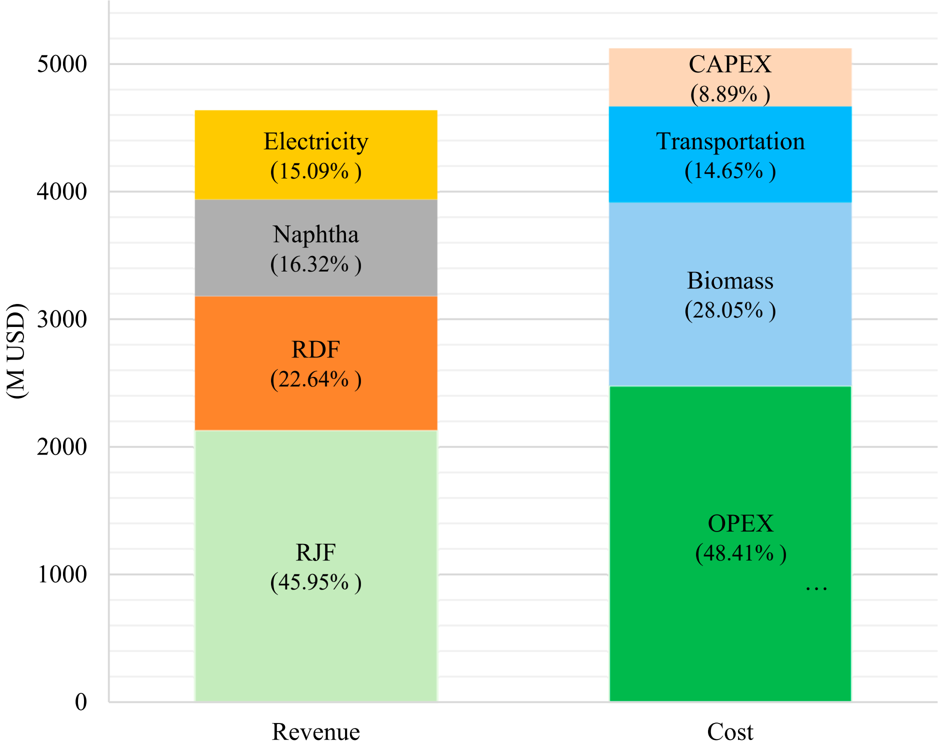

Figure 3. Total revenue and cost breakdowns for producing RJF.

Supply chain costs include operating costs (OPEX), capital costs (CAPEX), transportation costs, and purchasing costs of biomass feedstock, where operational costs constitute the largest portion of the costs. In terms of transportation costs, 25.53% and 41.48% of the total transportation costs were due to the fixed and variable transportation costs for transporting corn stover, while 0.22% and 32.78% of the total were allocated to the fixed and variable transportation costs for transporting RJF from biorefineries to airports. The results could be attributed to the higher transportation costs of biomass (fixed and variable transportation costs) as well as their lower density compared to RJF [21,34]. The contribution of each cost component to the total supply chain cost in the current study closely aligns with the findings of Huang et al. [34]. However, when comparing the share of transportation costs in the corn-stover-based RJF supply chain to that of an oil-seed-based RJF supply chain [21], it becomes evident that the current supply chain bears a doubled transportation cost share. This disparity is attributed to the lower density of corn stover compared to oilseeds (carinata) during the transportation of supplies to biorefineries in the upstream RJF supply chain.

Also, Figure 4 shows the spatial configuration of the optimized RJF supply chain network including the location of farms and their potential to supply the supply chain with available corn stover, the location of activated biorefineries, and the location of the airports. According to the results, the 10 activated biorefineries were located in ASDs where there was a balanced distance between biorefineries and airports, as well as between farms and refineries. Thus, the model located biorefineries at ASDs where biomass feedstock was abundantly available in their vicinity while also reducing transportation costs between the biorefineries and the airports. It should be noted that the model did not use the corn stover from ASDs located in the western Midwest to supply the activated biorefineries. This can be attributed to the fact that the majority of the airports were located in the central and eastern parts of the Midwest, where there was enough biomass feedstock to supply their supporting biorefineries. The ASDs that did not supply the biorefineries are differentiated from those that did with hatched lines. It should also be stated that only 18% of the available corn stover in ASD 4630 was utilized to supply the RJF production in the supply chain (illustrated with crosshatched lines in Figure 4).

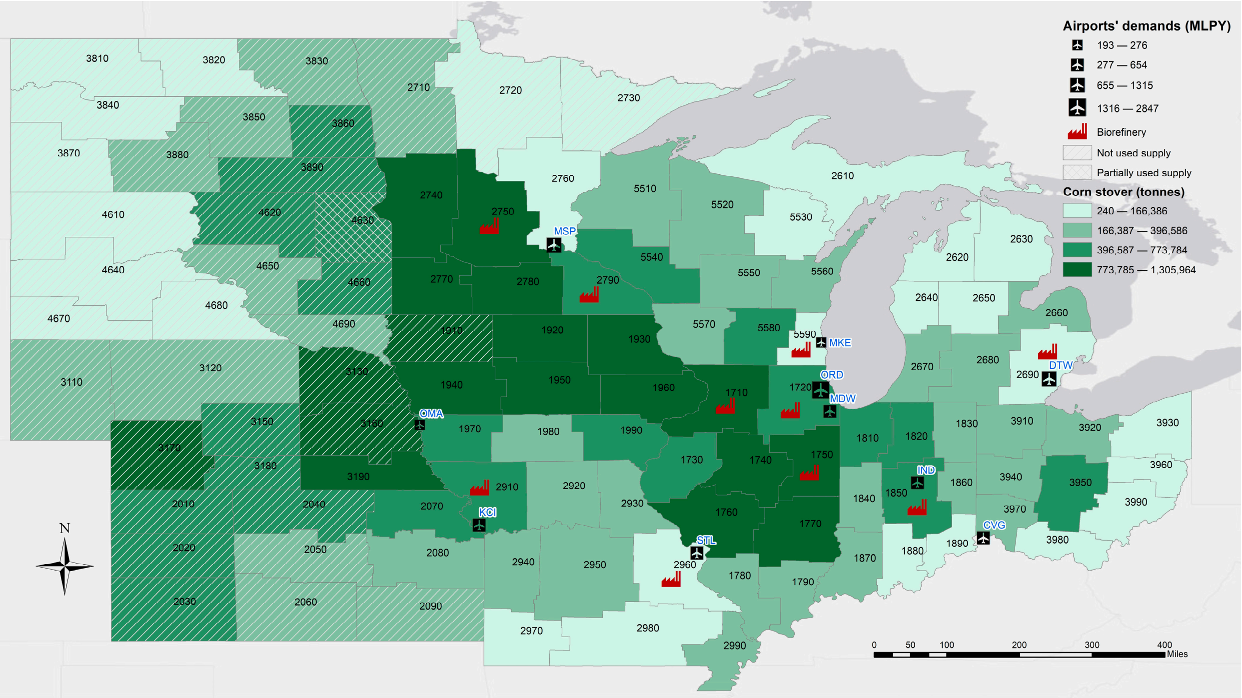

Figure 4. Configuration of the RJF supply chain for the base model (created by the authors).

3.2. Supply Chain Analysis with Application of Different Monetary Incentives and Their Corresponding Sensitivity Analyses

In this section, we provide the results regarding the application of the monetary incentives PCP, BCAP, BAP, and CT on the RJF supply chain profitability. Additionally, a sensitivity analysis of the incentive programs applied to the supply chain is conducted.

3.2.1. Supply Chain Incentivized with PCP and Its Sensitivity Analysis

PCP allocates direct monetary incentives to each liter of produced RJF. PCP incentives were considered to cover the total costs in the supply chain including purchasing costs of the biomass feedstock, transportation costs, and capital and operational costs. Figure 5 shows the impact of PCP incentive programs on reducing supply chain costs. The supply chain breaks even if the PCP incentive program covers 9.04% of its total costs.

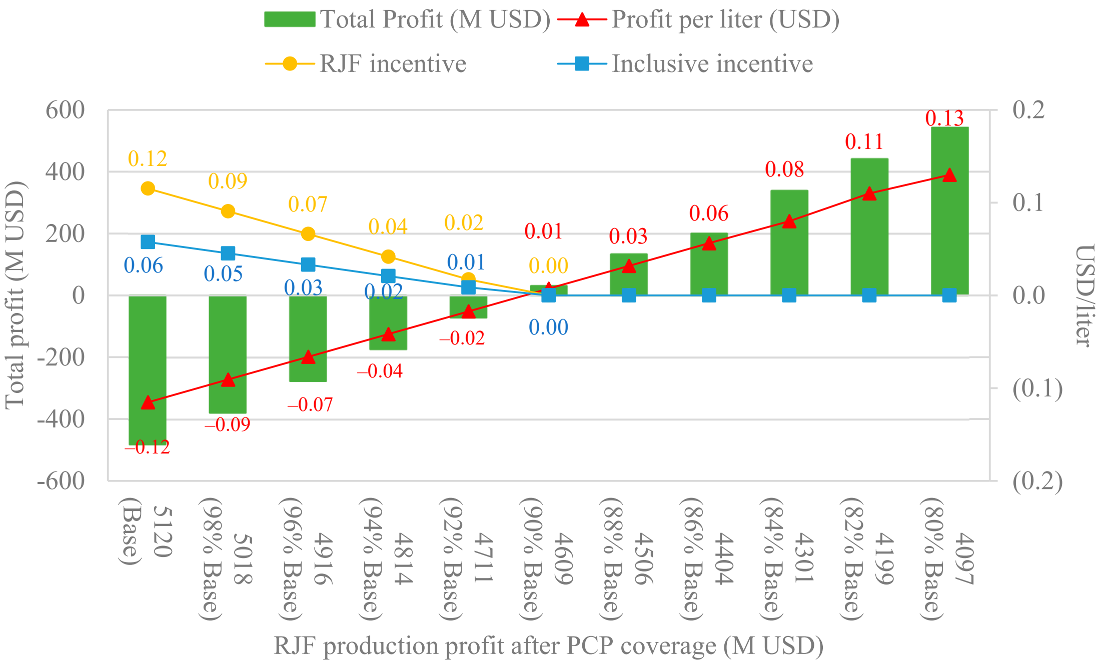

Figure 5. RJF supply chain profit, with regard to various PCP incentive scenarios.

Since monetary incentives could also be employed for other biofuels produced along RJF, including RDF and naphtha, we calculated the number of monetary incentives that could be applied to the total amount of biofuel produced. In this study, the corresponding incentives would be referred to as inclusive incentives [21]. According to the results illustrated in Figure 5, the supply chain needed an incentive of USD 0.12 per liter of RJF produced to obtain profitability, whereas it needed an inclusive monetary incentive of only USD 0.06 per liter.

3.2.2. Supply Chain Incentivized with BCAP and Its Sensitivity Analysis

In this section, we investigated the application of BCAP to cover costs associated with purchasing corn stover from farmers (Figure 6). The results showed that the RJF supply chain could achieve profitability if 33.53% of the costs related to purchasing corn stover were covered by the incentive program. The greater percentage of the biomass purchasing costs covered by the incentive program compared to the coverage rate by the PCP program is due to a lower share of the costs associated with the purchase of biomass feedstock compared to the total costs in the supply chain.

3.2.3. Supply Chain Incentivized with BAP and Its Sensitivity Analysis

The costs associated with the biorefineries, including CAPEX and OPEX, could be compensated by BAP as an incentive program. According to the results, presented in Figure 7, the BAP incentive program could potentially reduce the profit loss to the commercialization level by covering at least 16.64% of the CAPEX and OPEX in the supply chain. As a result of the high share of CAPEX and OPEX among the supply chain costs (57.3%), the BAP program provided a low coverage rate to reach the commercialization level. We also considered PCP incentives as a complementary incentive program to cover the remaining costs of the supply chain. Furthermore, how much of an inclusive incentive is needed to reach commercialization is also shown in Figure 7.

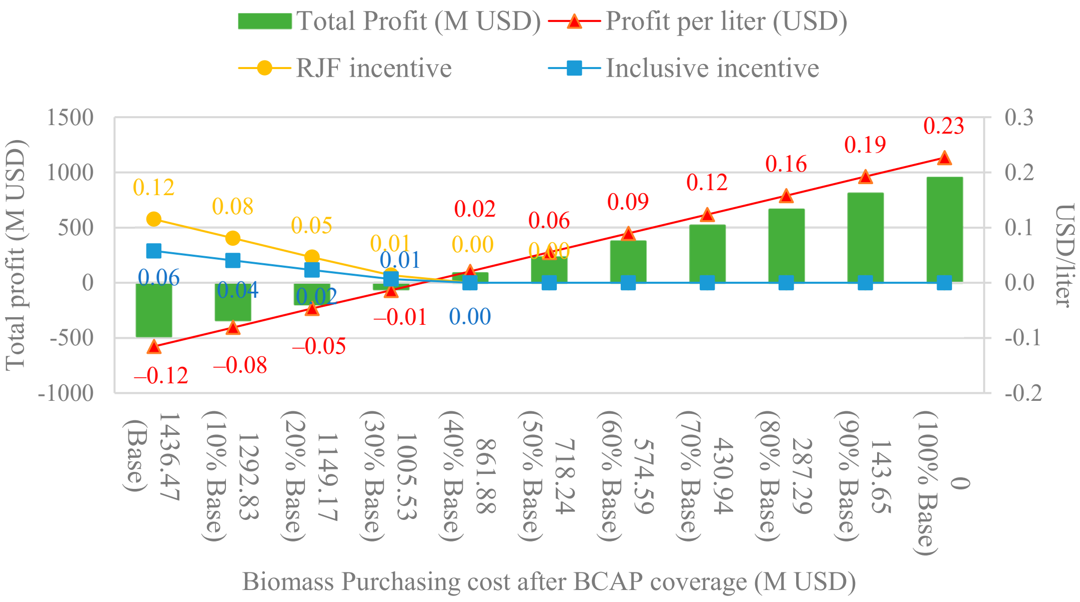

Figure 6. RJF production profit, with regard to various BCAP incentive scenarios.

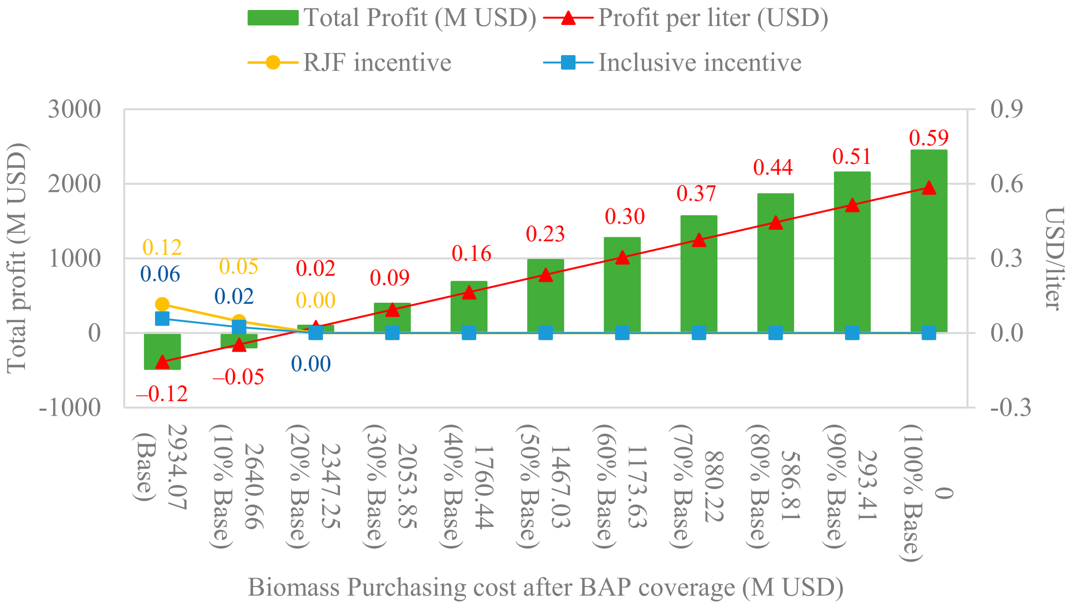

Figure 7. RJF supply chain profit, with regard to various BAP incentive scenarios.

3.2.4. Supply Chain Incentivized with the Carbon Cap-and-Trade Policy and Its Sensitivity Analysis

In implementing CT, we considered a cap for the carbon generated through the supply chain. To satisfy production and fulfill RJF demand, the supply chain members can sell or buy carbon. Due to RJF's lower carbon footprint compared to conventional jet fuel production, we expect the RJF supply chain to have unused carbon credits that can be sold. As such, carbon policies can serve as an efficient mechanism to incentivize and support RJF production and commercialization.

We assumed that an additional kilogram of carbon emissions incurs a social cost of USD 0.22 [20,34]. The same price was considered for selling unused carbon credits (the carbon units below a specified carbon cap). The carbon emissions generated by the supply chain were 0.46 million tonnes. However, we established the baseline carbon cap based on the quantity of carbon emissions that could be produced by producing the same amount of conventional jet fuel (12.89 million tonnes). An emission rate of 3.08 kg CO_2e per liter was used for producing conventional jet fuel [20].

We examined the policy under four different scenarios where the carbon generation via the supply chain was capacitated to various levels with regard to carbon generation for producing the same amount of conventional jet fuel. The carbon emission capacity was set to 100%, 75%, 50%, and 25% of the carbon generated through producing the same amount of conventional jet fuel. The corresponding results are illustrated in Table 4. Comparing the results related to the profit loss from the base model with cases having monetary incentives from CT demonstrates the significant impact of implementing CT on incentivizing RJF production. The policy had the potential to change the supply chain profit from a loss of USD 0.12 per liter to a gain of USD 0.53 per liter.

Table 4. Supply chain performance under carbon cap-and-trade policy.

	Carbon Cap with Regard to Emission Created by Fossil-Based Jet Fuel				
	Base	**25%**	**50%**	**75%**	**100%**
Total profit (USD M)	−481.65	126.59	826.27	1526.82	2210.26
Sold carbon credit (Mg)	0	2795	6013	9236	12,442
Profit per liter (USD)	−0.12	0.03	0.19	0.37	0.53

It was observed that when a 20% reduction in carbon emissions was desired (compared to the base emission level from conventional jet fuel), the RJF supply chain was profitable. The results also showed that if we capped the carbon emission in the supply chain to the total emissions made by conventional jet fuel, the supply chain profit was USD 0.5 per liter.

3.3. Sensitivity Analysis with Regard to Changes in Parameters

In this section, we evaluated the effect of changing various model parameters on supply chain profitability. Figure 8 indicates that lowering the demand fulfillment rate allows lower monetary incentives to commercialize RJF manufacturing. However, given the social costs of using conventional jet fuel, creating more RJF and its associated social and environmental advantages balances the impact of additional monetary incentives required for greater demand fulfillment rates.

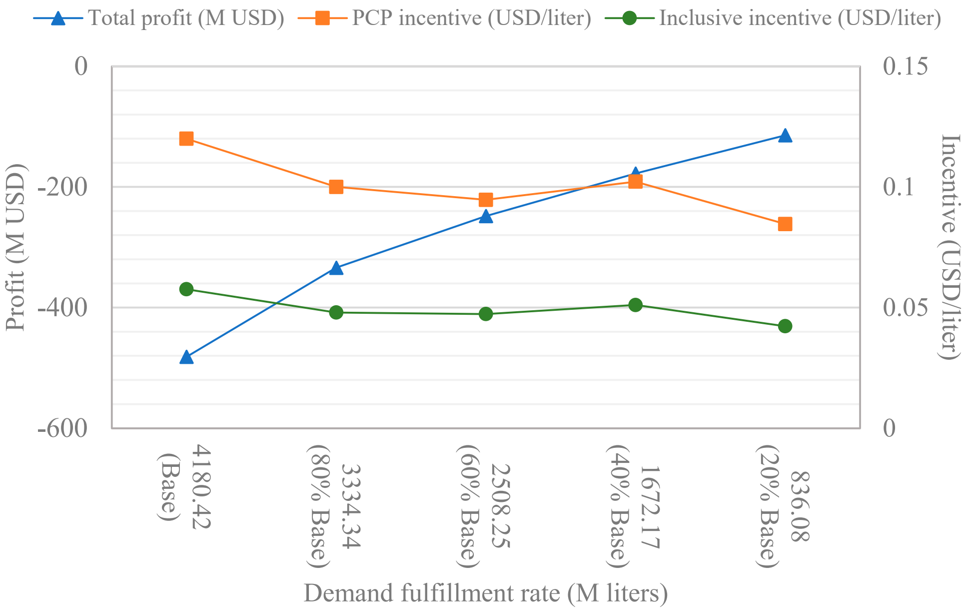

Figure 8. The effects of different demand fulfillment rates on RJF supply chain profitability.

We also investigated the impact of changing biofuel prices on the profitability of the RJF supply chain. Based on the data from [47], the lowest average price for conventional jet fuel was from 2020 at 1.293 USD/gallon, while the highest average price was from 2012 at 3.104 USD/gallon. Comparing the base price (USD 0.51 per liter) with the maximum and minimum prices experienced through recent years, it can be concluded that the jet fuel price fluctuated between 30% less and 60% higher than the base price. If biofuel prices rise by 60% above the basis price, the supply chain will become profitable, resulting in a profit of USD 0.45 per liter of RJF produced, whereas if biofuel prices fall 30% below the base price, there will be a profit loss of USD 0.40 per liter of RJF produced. It can also be concluded that if biofuel prices (RJF, RDF, and naphtha prices) increased by 12% over the base case, the supply chain could become profitable.

4. Managerial Implications

The commercialization of RJF can be highly dependent on the lower cost of RJF supply chains that can efficiently and effectively produce the required RJF to meet demand at airports. Using proper biomass that is abundantly available and does not pose a threat to food and feed production is essential. Furthermore, RJF production can cost more compared to the production of fossil-based jet fuel. Using MILPs, we developed a supply chain for corn stover that did not compete with any food resources and accessed a large supply of biomass feedstock. The current US administration's interest in accelerating RJF production as well as the lack of a comprehensive understanding of all aspects of producing RJF stimulate investigations to find ways to accelerate the commercialization of RJF.

In this study, we investigated the impacts on profitability of applying four different monetary incentives to RJF production. From the results, we concluded that all four incentive policies can make the RJF supply chain profitable. It is worth mentioning that while PCP, BCAP, and BAP were merely aimed at subsidizing the supply chain by covering its costs, CT offered monetary incentives that could be earned by selling unused carbon credits and encouraging reductions in carbon emissions. Furthermore, PCP required the lowest share of coverage (9.04% of the total costs as incentives) to achieve commercialization thresholds compared with other incentive policies. Other monetary incentives in terms of the minimum coverage required to make the supply chain profitable were BAP covering 16.64% of the production cost, CT capped at 20% of the carbon generated by producing conventional jet fuel, and BCAP with 33.53% of the costs related to purchasing corn stover. It should be noted that all the incentive programs were aimed at covering the same amount of the supply chain costs. However, they differed based on the types of costs they covered (total supply chain cost, biomass purchasing cost, or operational cost). Furthermore, due to the high sensitivity of the RJF supply chain's profitability to changes in the biofuel price and considering the increase in the oil price (which can affect biofuel price), it is expected that a price increase will result in a profitable RJF supply chain, even without application of monetary incentives.

These results shed light on the complexity of RJF supply chain networks and their corresponding costs. Considering the fact that the incentive policies have been inspired by several incentive policies already employed by agencies such as USDA, DOE, and IRS, the observation of applying the programs to incentivize RJF production may encourage them to devise such policies to promote the commercialization of RJF production. In addition, commercializing corn-stover-based RJF production will grow the interest of farmers in selling their crop residues, thus providing a greater supply to support RJF demand fulfillment. Furthermore, setting up infrastructure such as biorefineries is important as it can lead to new industries, job opportunities, and economic growth. While the case study in this paper has unique aspects regarding RJF production, the basic principles and conflicts between economic and environmental goals are highly applicable to other renewable fuel supply chains.

The findings of our study provide several management and policy implications, as follows:

- Diversifying incentive policies: Managers can explore and implement various monetary incentive policies, such as PCP, BCAP, BAP, and CT, to make the RJF supply chain profitable. This provides flexibility and allows for the selection of incentives that align with specific organizational goals.
- Strategic use of carbon trading (CT): Recognizing CT as a reward-based mechanism opens avenues for supply chains to strategically focus on reducing carbon emissions. CT not only ensures profitability but also creates an opportunity to earn additional revenue by selling unused carbon credits. This highlights the importance of adopting environmentally sustainable practices.
- Cost-efficiency considerations: Understanding that different incentive policies require varying levels of coverage to achieve profitability can guide managers in selecting the most cost-effective approach. For instance, PCP, with the lowest coverage requirement, might be an attractive option for achieving commercialization thresholds.
- Cost allocation strategy: Managers should carefully consider the types of costs covered by different incentive programs. Whether it is total supply chain costs, biomass purchasing costs, or operational costs, aligning the incentive program with the specific cost components can optimize the impact on profitability.
- Sensitivity to external factors: Given the high sensitivity of RJF supply chain profitability to changes in biofuel prices and oil prices, managers should stay vigilant about market dynamics. Anticipating potential price increases, particularly in biofuels, allows for strategic decision-making even without the application of monetary incentives.
- Utilizing ASDs: Managers may explore the integration of ASDs as designated supply regions in the Midwest. This zoning strategy can enhance the efficiency of biomass feedstock sourcing by identifying regions with consistent and suitable sources. This approach aligns with sustainable and strategic sourcing practices, contributing to the reliability and stability of the RJF supply chain.

5. Limitations and Future Scope of the Study

One constraint in this research lies in the dynamic nature of the parameters incorporated in the model. Those parameters such as demand, availability of biomass feedstock, availability of labor, land use, oil price, incentive policies, transportation cost, and operational and capital costs, may undergo changes over time, introducing new types of challenges not accounted for in our study. Another limitation of this research that we encountered was related to discrepancies in important parameter values related to production costs used across past RJF research. This matter caused an issue of inconsistency in the RJF production costs which made the comparison of results from different studies fairly challenging. Given the present enthusiasm for RJF production and the numerous ongoing pilot projects in this domain, it is anticipated that the parameters will achieve greater consistency. As more practical projects are undertaken and their outcomes are disseminated, a more standardized set of parameters can be expected to emerge. Future research focusing on expediting this process by analyzing the parameter values in detail holds particular promise.

In this research, we considered converting corn stover to RJF whereas crop residues, such as wheat straw, can also be used, either singly or in combination with other crop residues. Our work can also be extended to address more strategic and operational decisions such as intermodal transportation for logistics decisions and co-locating RJF biorefineries with existing facilities that produce other biofuels. Also, considering uncertainties in the supply chain model's parameters, using stochastic programming may be worthy of future exploration.

Author Contributions: S.E.: Conceptualization, Investigation, Data curation, Methodology, Formal analysis, Software, Visualization, and Writing—original draft. J.S.: Conceptualization, Investigation, Methodology, Validation, and Writing—review and editing. B.G.: Data curation, Visualization, and Writing—review and editing. S.A.H.E.: Validation and Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ASD	Agricultural statistics districts
ASTM	American Society for Testing and Materials
ATJ	alcohol-to-jet
BAP	Biorefinery assistance program
BCAP	Biomass crop assistance program
CO_2e	Carbon dioxide equivalent
CT	Cap-and-trade
CVG	Cincinnati/Northern Kentucky International Airport
DOE	Department of Energy
DTW	Detroit Metropolitan Wayne County Airport
FT	Fischer Tropsch
GHG	Greenhouse gas
GIS	Geographic Information Systems
HEFA	Hydroprocessed esters and fatty acids
HTL	Hydrothermal liquefaction
IND	Indianapolis International Airport
IRS	Internal Revenue Service
KCI	Kansas City International Airport
LCA	life-cycle analysis
MDW	Chicago Midway International Airport
MILFP	Mixed-integer linear fractional programming
MILP	Mixed-integer Linear Programming
MKE	General Mitchell International Airport
MSP	Minneapolis-Saint Paul International Airport
OMA	Eppley Airfield
ORD	O'Hare International Airport
PCP	Producer credit program
RDF	Renewable diesel fuel
RFS	Renewable Fuel Standard
RJF	Renewable jet fuel
STL	St. Louis Lambert International Airport
TEA	Techno-economic analysis
USDA	US Department of Agriculture

Appendix A

Table A1. Values of input parameters for RJF supply chain with corn stover feedstock.

Parameter and Value	Description	Reference
$\omega_{naphtha} = 0.36$	Selling price of naphtha (USD/L)	[21]
$\omega_{RDF} = 0.50$	Selling price of RDF (USD/L)	[21]
$\pi = 0.51$	Selling price of RJF (USD/L)	[34]
$\alpha_c = 49.61$	Selling price of corn stover (USD/tonne)	[29]
$\rho = 0.59$	Production cost of RJF at biorefinery (USD/L)	[39]
$\theta = 144.38$	RJF conversion rate from corn stover (L/tonne)	[39]
$\sigma^{naphtha} = 72.25$	Fuel coproduct j (naphtha) conversion rate from corn stover (L/tonne)	[39]
$\sigma^{RDF} = 72.25$	Fuel coproduct j (RDF) conversion rate from corn stover (L/tonne)	[39]
$\gamma^b = 6.615$	Transportation fixed cost of corn stover via truck (USD/tonne)	[48]
$\eta^b = 0.0548$	Transportation variable cost of corn stover via truck (USD/tonne-km)	[48]
$\gamma^m = 0.0031$	Transportation fixed cost of RJF via truck (USD/L)	[49]
$\eta^m = 0.000394$	Transportation variable cost of RJF via truck (USD/L-km)	[49]

Table A1. *Cont.*

Parameter and Value	Description	Reference
$e_c = 0.0756$	Emission factor of transporting corn stover (kg CO_2e/tonne-km)	[50]
$e_j^{truck} = 0.00009235$	Emission factor of transporting RJF (kg CO_2e/L-km)	[51]
$e_c^{acquisition} = 0.0001654$	Emission factor of corn stover acquisition (kg CO_2e/tonne)	[50]
$e_F^{production} = -0.344$ [a]	Emission factor of producing RJF through FT pathway from corn stover (kg CO_2e/L)	[34]
$f = 45.51$	Annual fixed cost of biorefinery (M USD)	[34]
$\rho = 0.59$	Production cost of RJF at biorefinery (USD/L)	[39]

[a] This emission factor is a result of emission generated by preprocessing corn stover and transforming it to RJF. The negative sign refers to the fact that the emission credits awarded by electricity generated by producing RJF outweigh the emissions generated by preprocessing corn stover and other operations to produce RJF at biorefineries [20].

Table A2. Optimal assignment of supply zones and demand nodes to activated biorefineries.

Supplier District (Share of Supply Assignment)	Activated Biorefinery and Its Capacity	Demand Node (Share of Demand Fulfillment)
S [b]1940 (34.82%), S1950 (38.53%), S1960 (26.65%).	B [c]1710	ORD (100%).
S1710 (34.07%), S1720 (16.16%), S1810 (17.09%), S1930 (5.30%), S1980 (10.40%), S1990 (16.98%).	B1720	MDW (1.11%), ORD (98.89).
S1730 (19.75%), S1740 (29.67%), S1750 (28.36%), S1760 (21.18%), S1810 (1.04%).	B1750	MDW (71.53%), DTW (28.47%).
S1770 (26.67%), S1820 (10.88%), S1840 (12.69%), S1850 (18.06%), S1860 (7.59%), S1870 (12.28%), S1880 (3.09%), S1890 (2.45%), S3790 (5.98%).	B1850	CVG (40.60%), DTW (17.63%), IND (41.77%).
S1820 (3.03%), S1830 (8.21%), S2610 (0.38%), S2620 (1.10%), S2630 (0.83%), S2640 (1.78%), S2650 (5.34%), S2660 (8.19%), S2670 (7.53%), S2680 (12.20%), S2690 (3.76%), S3910 (6.09%), S3920 (7.08%), S3930 (4.12%), S3940 (11.77%), S3950 (13.56%), S3960 (1.67%), S3980 (2.03%), S3990 (1.32%).	B2690	DTW (100%).
S2740 (31.79%), S2750 (29.97%), S2760 (3.18%), S2770 (25.42%), S4630 (3.06%), S5510 (6.58%).	B2750	MSP (100%).
S1920 (40.24%), S2780 (34.29%), S2790 (23.51%), S5540 (1.96%).	B2790	MSP (48.12%), ORD (51.88%).
S1970 (30.36%), S2070 (20.13%), S2080 (8.74%), S2910 (21.21%), S3190 (19.56%).	B2910	OMA (31.73), KCI (68.27%).
S1760 (10.14%), S1780 (12.06%), S1790 (12.14%), S2080 (0.92%), S2920 (9.76%), S2930 (15.18%), S2940 (10.23%), S2950 (11.37%), S2960 (4.62%), S2970 (3.82%), S2980 (0.56%), S2990 (9.21%).	B2960	STL (100%).
S1930 (27.65%), S5520 (6.59%), S5530 (3.97%), S5540 (11.67%), S5550 (8.04%), S5560 (10.36%), S5570 (11.36%), S5580 (16.32%), S5590 (4.06%).	B5590	MKE (30.70%), ORD (69.30%).

[b] The letter "S" in the beginning of the biorefinery node indicates that the supply node is located at ASD 1940.

[c] The letter "B" in the beginning of the biorefinery node indicates that the biorefinery node is located at ASD 1720.

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