# Life Cycle Optimization of Biomass-to-Liquids Supply Chains with Distributed-Centralized Processing Networks

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## Abstract

This paper addresses the optimal design and planning of biomass-to-liquids (BTL) supply chains under economic and environmental criteria. The supply chain consists of multisite distributed-centralized processing networks for biomass conversion and liquid transportation fuel production. The economic objective is measured by the total annualized cost, and the measure of environmental performance is the life cycle greenhouse gas emissions. A multi-objective, multi-period, mixed-integer linear programming model is proposed that takes into account diverse conversion pathways and technologies, feedstock seasonality, geographical diversity, biomass degradation, infrastructure compatibility, demand distribution, and government incentives. The model simultaneously predicts the optimal network design, facility location, technology selection, capital investment, production planning, inventory control, and logistics management decisions. The problem is formulated as a bicriterion optimization model and solved with the ε-constraint method. The resulting Pareto-optimal curve reveals how the optimal annualized cost and the BTL processing network structure change with different environmental performance of the supply chain. The proposed approach is illustrated through a county-level case study for the state of Iowa.

**Key words:** Design, planning, biofuels supply chains, multiobjective optimization, life cycle analysis

# 1. Introduction

Cellulosic biofuels have been proposed as part of the solution to climate change and the dependence on fossil fuels, not only because they can be produced domestically from a variety of renewable biomass feedstocks, but also because they can reduce the greenhouse gas emissions, since the carbon dioxide captured when the feedstock crops are grown and cultivated balances the carbon dioxide released when the fuels are burned.[1-4] According to the Energy Information Administration, biofuel consumption in primary markets is expected to reach 20% of renewable energy sources by 2030.[5] Although corn ethanol has led the adoption of renewable biofuels in the transportation industry, the Renewable Fuels Standard (RFS), part of the Energy Independence and Security Act of 2007,[6] establishes a target of 36 billion gallons of renewable fuels by 2022 with cellulosic biofuels contributing more (16 billion gallons) than corn ethanol (15 billion gallons).[6-8] Biomass-to-liquids (BTL) technology, which converts cellulosic biomass to liquid transportation fuels, has been considered a promising approach for overcoming the market barrier resulting from the current vehicle technology and fuel distribution infrastructure.[9-10] Compared with ethanol, biomass-derived liquid transportation fuels have the following advantages:[10]

- Biomass-derived gasoline and diesel fuels can be used directly in today's gasoline- and diesel-powered vehicles.
- Biomass-derived gasoline and diesel fuels are compatible with the current gasoline and diesel distribution infrastructure and could be transported directly through existing gasoline/diesel pipelines, dispensed at existing fueling stations, and sold at any existing retail station pumps.
- BTL fuels provide vehicle performance similar to or better than their conventional counterparts.
- BTL fuels have been shown to reduce regulated exhaust emissions from a variety of diesel engines and vehicles, and the near-zero sulfur content of these fuels can enable the use of advanced emission control devices.

Existing BTL technologies either are based on biomass gasification followed by Fischer-Tropsch (FT) conversion or are based on biomass fast pyrolysis followed by

hydroprocessing.[11-14] A number of pre-conversion technologies have also been developed that convert biomass into a denser energy carrier or intermediate products, such as bio-oil or bio-slurry, before upgrading to liquid transportation fuels.[15-16] This approach allows the biomass feedstocks to be converted into liquid fuels through distributed-centralized processing networks, in which a number of distributed pre-conversion processes are constructed to reduce the feedstock transportation costs and a centralized intermediate upgrading plant is built to take advantage of the economy of scale. However, the distributed-centralized processing network introduces more tradeoffs among capital, operating, transportation and storage costs, and it is a nontrivial task to determine the most economic design of the BTL processing network in order to overcome the commercialization barrier. Moreover, in observance of the RFS mandatory production target, the BTL supply chain must not only be economically viable but also be environmentally sustainable. Therefore, it is important to optimize the design and operations decision of BTL supply chain from both strategic and operational levels and to assess and improve the economic and environmental performance of biomass-derived liquid fuels from a life cycle perspective.

In this work, we address the optimal design and planning of BTL supply chains under economic and environmental criteria. The supply chain consists of multisite distributed-centralized processing networks for biomass conversion and liquid transportation fuel production. A multiperiod mixed-integer linear programming (MILP) model is proposed that takes into account the main characteristics of BTL supply chains, such as seasonality of feedstock supply, biomass deterioration with time, geographical diversity, availability of biomass resources, moisture content, diverse conversion pathways and technologies, infrastructure compatibility, demand distribution, and government subsidies. The MILP model integrates decision-making across multiple temporal and spatial scales and simultaneously predicts the optimal network design, facility location, technology selection, capital investment, production operations, inventory control, and logistics management decisions. In addition to the economic objective of minimizing the total annualized cost, the MILP model is integrated with life cycle analysis (LCA) through a multiobjective optimization scheme to include another objective of environmental performance measured by life-cycle greenhouse gas emissions. The multiobjective

optimization framework allows the model to establish tradeoffs between the economic and environmental performances of the BTL supply chains in a systematic way. The multiobjective optimization problem is solved with the ε-constraint method and produces Pareto-optimal curves that reveal how the optimal annualized cost, biomass processing, and fuel production network structures change with different environmental performance of the BTL supply chain. The proposed optimization approach is illustrated through a case study based on the BTL supply chain for the state of Iowa. County-level results are presented that provide regionally based insight into transition pathways and consequent economic and environmental impacts of distributed-centralized BTL processing networks.

The rest of the paper is organized as follows. We briefly review related literature and highlight the novelty of this work in the next section. That is followed by a discussion of major BTL conversion and preconversion technologies and an introduction to the life cycle optimization approach. The tradeoffs in the design of BTL supply chain networks are illustrated through a small example. We then present a formal problem statement along with the key assumptions and describe the proposed mixed-integer optimization model. Case studies for the county-level case studies and concluding remarks are given at the end of this paper.

## 2. Literature Review

A general review on the optimal design and operations of the process supply chain was presented by Shah[17] and Papageorgiou.[18] The papers most relevant to the problem addressed in this work are reviewed below.

Dunnett et al.[19] presented a spatially explicit MILP model to investigate cost-optimal system configurations for a number of technological, system scale, biomass supply, and ethanol demand distribution scenarios specific to European agricultural land and population densities. Zamboni et al.[20] presented a MILP model for the strategic design of biofuel supply networks. The model takes into account the issues affecting a general biofuel supply chain simultaneously, such as agricultural practice, biomass supplier allocation, production site locations, capacity assignment, logistics distribution, and transport system optimization. A spatially explicit approach is used to capture the strong geographical dependence of the biomass cultivation practice performance. Mansoornejad

et al.[21] presented a methodology in which product portfolio design and forest biorefinery supply chain design are linked in order to build an integrated design decision-making framework through a margins-based operating policy for the biorefinery supply chain. Following the work by Zamboni et al.,[20] Dal Mas et al.[22] developed a dynamic MILP model for the optimal design and planning of biomass-based fuel supply networks according to financial criteria, taking into account uncertainty in market conditions. Recently, Kim et al.[23] proposed a MILP model for the optimal design of biorefinery supply chains. The model aims to maximize the overall profit and takes into account different types of biomass, conversion technologies, and several feedstock and plant locations. Central and distributed systems are analyzed in their work. Aksoy et al.[24] investigated four biorefinery technologies for feedstock allocation, optimal facility location, economic feasibility, and their economic impacts in Alabama, through a MILP-based facility location model that minimizes the total transportation cost and takes into account county-level information. Another recent contribution in this area is the work by Corsano et al.[25] The authors proposed a mixed-integer nonlinear programming (MINLP) model for the design and behavior analysis of sugar/ethanol supply chain. In their work, a plant performance model is integrated with the supply chain design model for simultaneous optimization, which allows the evaluation of several compromises among design and process variables. Akgul et al.[26] recently presented a MILP model based on the one proposed by Zamboni et al.[20] for the optimal design of a bioethanol supply chain with the objective of minimizing the total supply chain cost. Their model aims to optimize the locations and scales of the bioethanol production plants, biomass and bioethanol flows between regions, and the number of transport units required for the transfer of these products between regions as well as for local delivery. The model also determines the optimal bioethanol production and biomass cultivation rates. A case study for northern Italy is presented to illustrate the applicability of the proposed model.

All these works focus on improving the economic performance of biofuel supply chains by either maximizing the profit or minimizing the cost. However, the design and operations of process supply chains may need to consider multiple performance measures and tradeoffs among conflicting goals, including environmental impacts,[27-28] responsiveness,[29-31] flexibility,[32] and risk management.[33-34] Very limited work has been

done using multiobjective optimization for the design and operation of biofuel supply chains. Zamboni et al.[35] presented a static MILP model with spatially explicit characteristics for the strategic design of a biofuel supply chain that accounts for the simultaneous minimization of the supply chain operating costs as well as the environmental impact in terms of greenhouse gas (GHG) emissions. Mele et al.[36] addressed the optimal planning of supply chains for bioethanol and sugar production with economic and environmental concerns. They proposed a bicriterion MILP model for the simultaneous minimization of the total cost of a sugar/ethanol production network and its environmental performance over the entire life cycle of the sugar and ethanol. You et al.[37] proposed a multiobjective MILP framework to optimize the economic, environmental, and social dimensions of sustainable cellulosic ethanol supply chains. Recently, Elia et al.[38] developed a MILP model for the optimal energy-supply network based on hybrid coal, biomass, and natural gas to liquid plants using carbon-based hydrogen production. Life cycle analysis (LCA) is performed as a postoptimization step to evaluate the environmental impacts.

To the best of our knowledge, this is the first work that addresses the optimization of BTL supply chains from a life cycle perspective under economic and environmental criteria. Moreover, preconversion technologies and distributed-centralized processing strategy, which have been shown to have great potential in large-scale utilization and transportation of biomass resources, have not been taken into account in the existing works on biofuels supply chains. An additional novelty of our work is that the proposed model takes into account most of the major characteristics of the BTL supply chains, such as biomass degradation, moisture content, supply seasonality, geographical availability, intermodal transportation of different types of biomass, diverse conversion pathways and technologies, byproduct credits, government incentives, and policy issues.


# 3. Technologies for the Conversion of Biomass to Liquid Transportation Fuels

Cellulosic biomass can be converted to liquid transportation fuels, such as gasoline and diesel, through a number of pathways.[9, 13-14] Typical conversion technologies include

gasification followed by FT synthesis[11, 14] and fast pyrolysis followed by hydroprocessing.[12-13] In addition, several preconversion technologies[15-16] can convert biomass into intermediates, which have higher transportation densities and can be upgraded to liquid fuels in BTL plants. In this section, we briefly review a few major BTL conversion technologies and pathways.

## 3.1 Integrated conversion technologies

The two major technologies reviewed here are gasification followed by Fischer-Tropsch synthesis and fast pyrolysis followed by hydroprocessing.
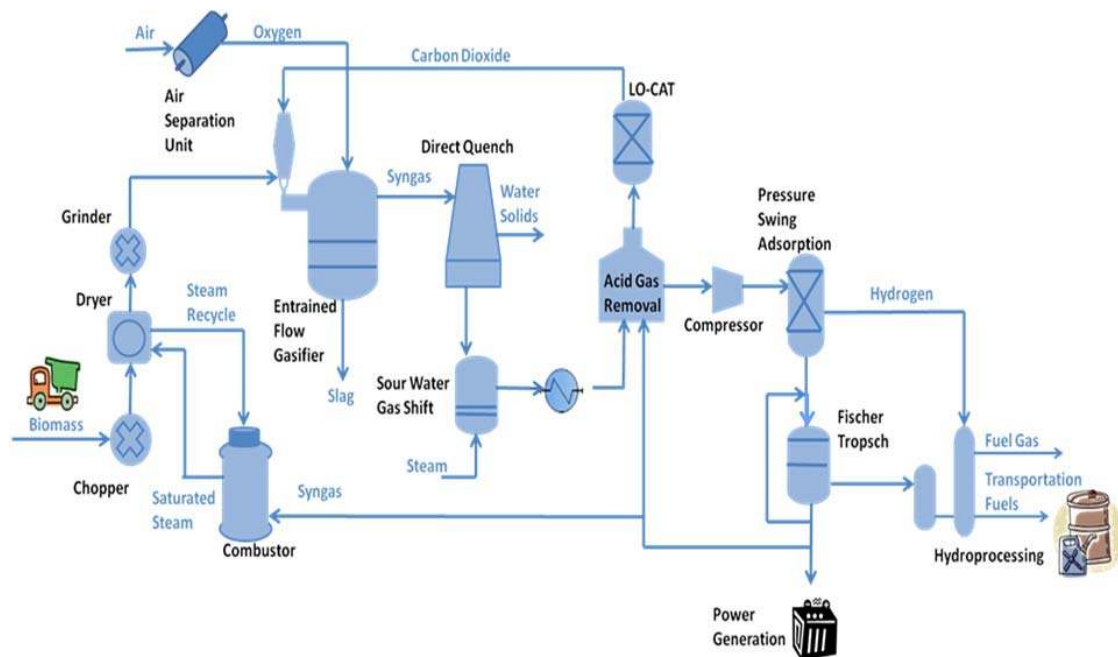
### *Gasification followed by FT synthesis*

The gasification technology produces transportation fuels through Fischer-Tropsch synthesis with electricity as byproduct.[11, 14] There exist two techniques of gasification: an oxygen-fed, low-temperature (870°C), nonslagging, fluidized bed gasifier and an oxygen-fed, high-temperature (1300°C), slagging, entrained flow gasifier. Both gasifiers are followed by Fischer-Tropsch synthesis, which involves converting carbon monoxide and hydrogen into liquid hydrocarbons. The major operational steps of this conversion technology are preprocessing, gasification, syngas cleaning, fuel synthesis, hydroprocessing, power generation, and air separation.

Biomass feedstocks are first dried to reduce the particle sizes during pretreatment. Each gasifier requires a specific particle size. The low-temperature (LT) option can handle larger feedstock size of 6 mm, whereas the high temperature (HT) option requires a smaller feedstock size of 1 mm. Low-temperature gasification also has the advantages of lower capital cost and high heat transfer rates within fluidized bed; but it has lower thermal and carbon efficiency. High-temperature gasification has advantages of higher carbon conversion, low tar, and methane content.

Dried biomass is pressurized during gasification and is converted into raw synthesis gas. The gasifier is operated with 95% pure oxygen and steam. This gasification step also includes a combustor, which provides heat for drying the biomass. In the next processing area, undesired compounds are removed in raw syngas by using a cold gas cleaning method. Direct quench syngas cooling removes ash and tars. Direct water

quench decreases the syngas temperature to approximately 40°C in the LT scenario and 300°C in the HT scenario. The LT scenario uses a water-gas shift reaction to adjust the hydrogen to carbon monoxide ratio to the optimal Fischer-Tropsch ratio of 2.1:1, whereas the HT scenario uses a sour water-gas shift. Then the processed syngas is processed by Fischer-Tropsch synthesis to produce liquid fuel. The main operations at this stage are zinc oxide/activated carbon gas polishing, syngas booster compression, hydrogen separation, Fischer-Tropsch synthesis, product separation, and unconverted syngas distribution. Steam methane reforming and water-gas shift are two additional processes that occur in this conversion pathway. The syngas is polished with a zinc oxide and activated carbon sorbent. Next, the syngas is compressed to the required FT operating pressure, 25 bar. A portion of the syngas, after the acid gas removal process, goes through a pressure swing adsorption process in order to provide a hydrogen source to the hydroprocessing stage. The syngas then reacts in FT synthesis. After FT synthesis, part of the unconverted syngas is recycled back to the FT reactor, and some is sent to the acid gas removal system. The remaining portion is sent to the power generation area, which provides power for the air separation unit. The air separation unit provides pure oxygen for gasification. Raw fuel is hydrocracked during hydroprocessing to produce transportation fuels.
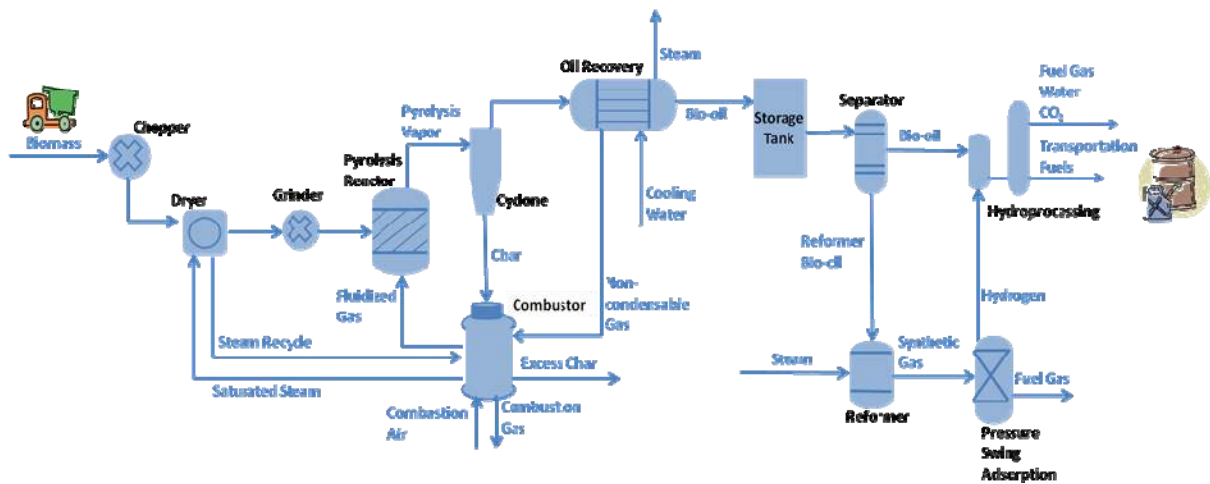


**Figure 1.   Process flow diagram of the gasification + FT synthesis technology.**

## Fast pyrolysis followed by hydroprocessing

Fast pyrolysis is a process of heating biomass without oxygen that converts feedstock into gaseous, liquid, and solid products.[12-13] Its processing steps include biomass pretreatment, fast pyrolysis, solids removal, oil recovery, char combustion, and hydroprocessing. Biomass feedstocks are dried to around 7% moisture content, and particle size is reduced to diameter of 3 mm during pretreatment. The dried biomass is then fed into a fluid bed pyrolyzer operating at 480°C and atmospheric pressure. Pyrolysis vapors enter a cyclone, which separates solids and vapors. The vapors are then condensed in an indirect heat exchanger that yields bio-oil. Noncondensable gases and solids from the pyrolysis reaction are sent to a combustor to produce the required heat for the drying and pyrolysis processes. Bio-oil is collected in a storage tank that acts as a buffer to the upgrading process.



**Figure 2.   Process flow diagram of the fast pyrolysis + hydroprocessing technology.**

The hydroprocessing step involves hydrotreating and hydrocracking. Hydrotreating is an exothermic process that removes undesired compounds such as oxygen in bio-oil. Hydrocracking is a process that breaks down larger molecules into naphtha and diesel. During hydrotreating, hydrogen can be provided from outside source or can be extracted from the bio-oil. Around one-third of the bio-oil is needed to produce the required amount of hydrogen in the hydrogen production scenario. Separator, reformer, and pressure swing adsorption are needed before hydroprocessing. A gravity separator

separates pyrolysis lignin from the water-soluble bio-oil. Aqueous bio-oil and steam are sent to a high-temperature reformer, which produces syngas. This syngas is fed with methane into a pressure swing adsorption reactor to produce hydrogen. In the end, bio-oil is converted into transportation fuels via hydroprocessing.

## 3.2 Preconversion technologies

A preconversion process converts the biomass into a denser energy carrier to reduce transportation costs.[15-16, 39] Different types of reactors, such as a rotating cone reactor or fluidized bed reactor, are used in the pyrolysis process.

### *Rotating cone reactor pyrolysis*

In the rotating cone reactor pyrolysis process, wet biomass and sand are sent into rotating cone pyrolysis reactor that produces pyrolysis vapors (see Figure 3). Then the vapors are condensed into liquid feedstock, bio-oil. Riser air and char from pyrolyzer are sent into a combustor to produce flue gas and the hot sand needed in pyrolysis.
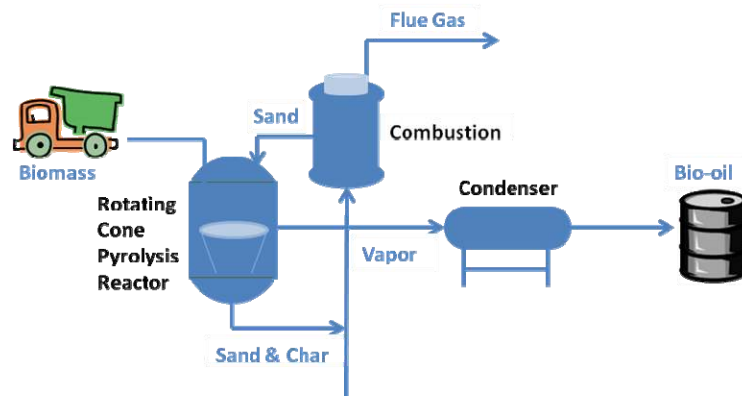


**Figure 3.   Process flow diagram of rotating cone reactor pyrolysis technology.**

### *Fluidized bed reactor pyrolysis*

In the fluidized bed reactor pyrolysis type of preconversion process, wet biomass and fluidizing air react in fluidized bed pyrolysis reactor (see Figure 4). Next, the products from the pyrolyzer are sent into cyclones to separate chars and vapors. After quenching, the final products of bio-slurry and flue gas are present.
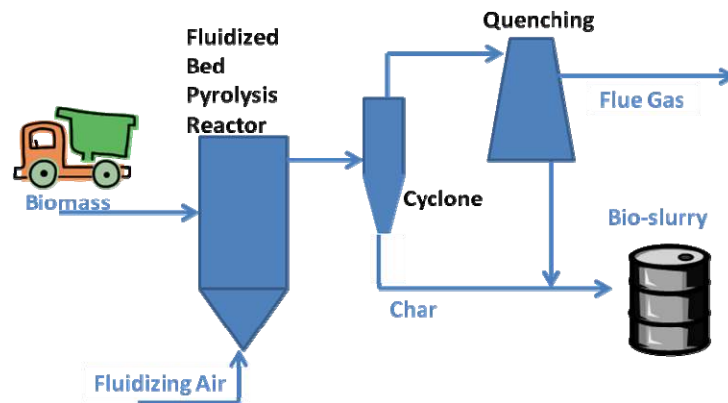
**Figure 4.  Process flow diagram of the fluidized bed reactor pyrolysis technology.**

## 3.3 Intermediate upgrading technologies

The so-called intermediate upgrading technology (involving gasification + FT synthesis from bio-oil/bio-slurry) produces transportation fuels from the products of preconversion processes.[15-16, 39] The major operational steps of this bio-oil/bio-slurry-to-liquids technology are gasification, syngas cleaning, fuel synthesis, hydroprocessing, power generation, and air separation unit (see Figure 5). Feedstock (bio-oil/bio-slurry) produced from preconversion process is pressurized during gasification and becomes raw syngas. In the next processing step, undesired compounds are removed in raw syngas and are cooled. Then the processed syngas is sent into Fischer-Tropsch synthesis to produce hydrocarbons raw fuel. After the synthesis process, the unconverted syngas is combusted to provide power for the air separation unit. This unit removes nitrogen from the air in order to provide pure oxygen for gasification. The raw fuel is refined during hydroprocessing to produce the desired transportation fuels.
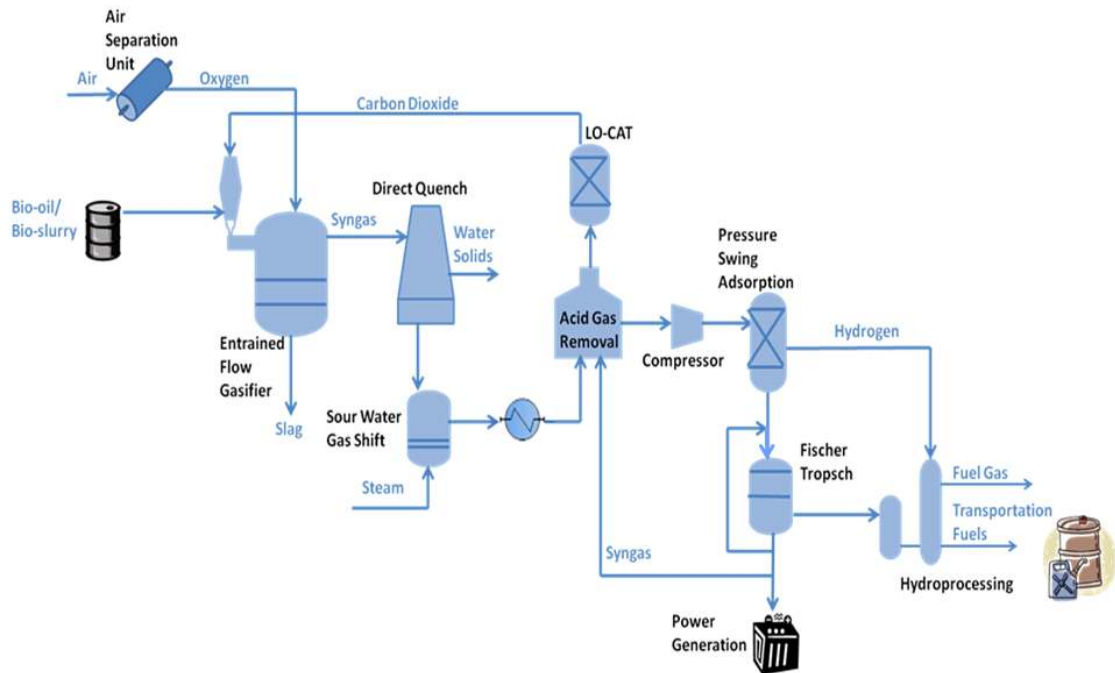
**Figure 5.   Process flow diagram of the intermediate upgrading technology.**

## 4. "Life Cycle Optimization" of BTL Supply Chains

The objective of this work is to optimize the design and operations of BTL supply chains under economic and environmental objectives. A life cycle optimization approach, which integrates a multiobjective optimization scheme and a field-to-wheel life cycle analysis method, is used to improve the economic and environmental performance of the entire BTL supply chain from biomass feedstock production to fuel production and to fuel end use (see Figure 6).

The annualized total cost is selected to be the quantitative measure of economic performance; it should be minimized in the life cycle optimization framework. The environmental objective is to minimize the total annual GHG emissions (converting to $CO_2$-equivalent per year); to this end, we adopt a "field-to-wheel" approach that accounts for the supply chain network operating impact on global warming over the life cycle of biomass-derived liquid transportation fuels. Specifically, a classical, process-based LCA technique, following the principles and standards laid out in ISO 14040/14044, is used. LCA is a systematic, cradle-to-grave process that evaluates the environmental impacts of a product, while considering all stages of its life cycle. In this work, we integrate LCA

techniques with the multiobjective optimization approach, creating a systematic method that enables the automatic generation and assessment of process and supply chain alternatives that may lead to significant environmental and economic benefits.[28] The application of this integrated approach involves four main phases of LCA, as shown in Figure 6.
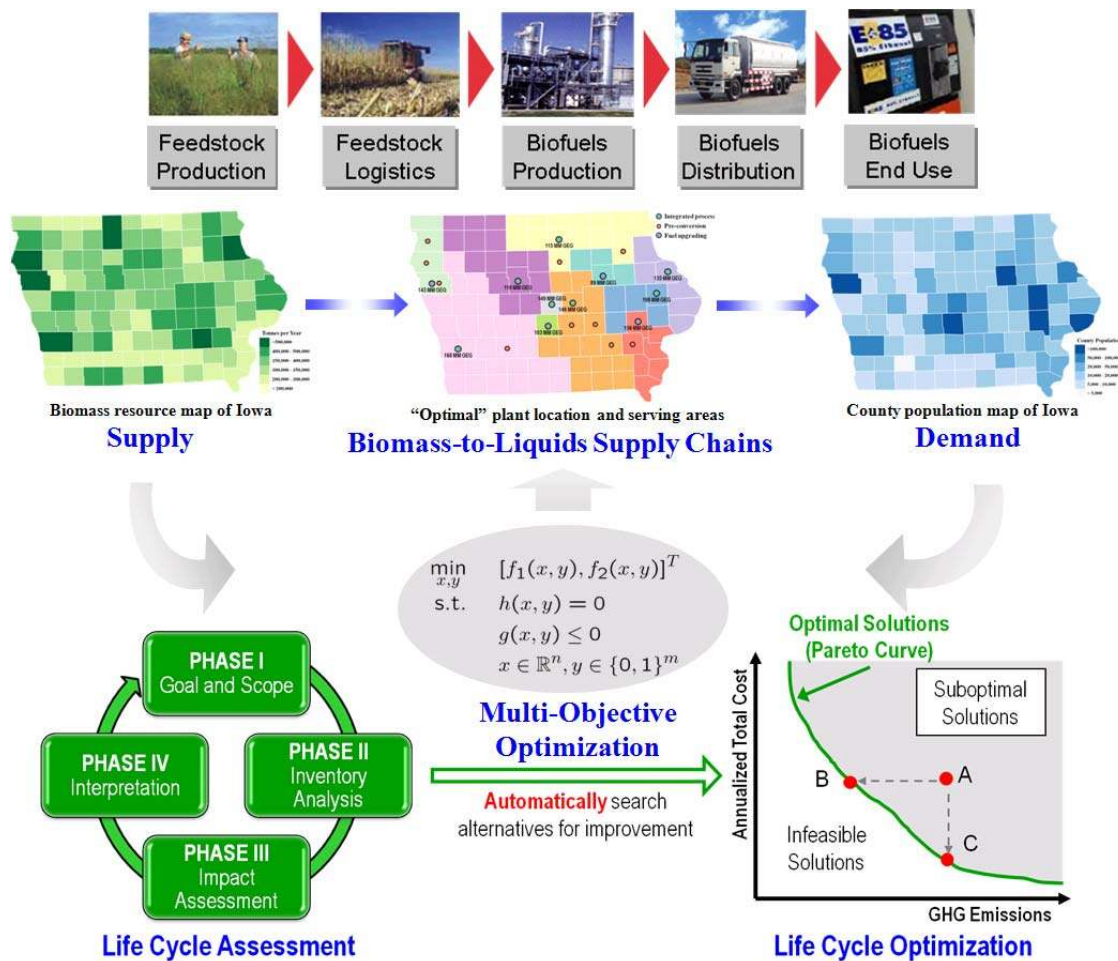


**Figure 6. Integration of life cycle assessment with multiobjective optimization.**

The first and most important phase of LCA is the goal and scope definition, in which systems boundary and the precision and the representative value of the assessment are defined. In order to obtain a satisfactory estimation of the emissions, special attention must be given to the choice of the life cycle stages to be included. For instance, the set of life cycle stages considered in evaluating "field-to-wheel" emissions of the BTL system

are feedstock production, growth, and acquisition, soil carbon sequestration of biomass feedstocks, biomass transportation, feedstock storage, intermediate and fuel production, intermediate transportation, intermediate storage, liquid fuel transportation and distribution, and fuel combustion in vehicle operations.

The second phase is to analyze the life cycle inventory associated with each process included in the life cycle stages. In order to identify and quantify the emissions released to the environment from each process, data from the Argonne GREET Model,[40] the U.S. Life Cycle Inventory Database,[41] and relevant literature on process design[11-16, 39] are used.

In the third phase, the information from the inventory analysis is further translated into a set of environmental impacts that can be aggregated into an environmental performance indicator. In this work, emissions of three GHG emissions—$CO_2$, $CH_4$, and $NO_x$—are grouped together into a single indicator in terms of carbon dioxide-equivalent emissions per year ($CO_2$-equiv/year), which is based on the concept of 100-year global warming potentials as specified by the International Panel on Climate Change, although other environmental impact indicators, such as eco-indicator 99,[42] can also be used in the proposed framework.

In the fourth phase, the LCA results are analyzed, and a set of conclusions or recommendations for the system is formulated. The goal of LCA is to provide criteria and quantitative measures for comparing different supply chain design and operation alternatives. However, the LCA framework does not include a systematic way of generating such alternatives and identifying the best ones in terms of environmental performance. To circumvent these limitations, we follow an integrated approach that incorporates the impact assessment results into a multiobjective optimization framework to assess diverse process alternatives that may be implemented to achieve improvement of environmental performance (e.g., GHG emissions). Thus, in our work the preferences are articulated in the postoptimal analysis of the Pareto-optimal solutions (see Figure 6). For instance, if the two objectives are to minimize the total annualized cost and to minimize the environmental GHG emissions, the optimal solutions will yield a Pareto-optimal curve. This curve represents the set of all the optimal solutions taking into account both economic and environmental objectives. All the solutions above this curve are suboptimal solutions that can be improved by using optimization methods (e.g., from

point A to point B and from point A to point C in Figure 6). Any solution below this curve is infeasible, and the associated process alternative is impossible to achieve. This life cycle optimization approach provides further insights into the design problem and allows for a better understanding of the inherent tradeoffs between the economic and environmental objectives in the context of sustainability.

# 5. Illustrative Example: Tradeoffs in Distributed-Centralized BTL Processing Networks

To illustrate the tradeoffs in the design and operations of BTL supply chains under economic and environmental concerns, we consider a superstructure of the BTL processing networks in a hypothetical square area as shown in Figure 7. The square area consists of 16 square farms in a 4x4 array. The side of each square farm is 10 kilometers long, so the entire square area is 40 km x 40 km. The yield of biomass crop in each farm is evenly distributed. Five potential facility locations are located in the center of the square area and in the centers of four adjacent farms in the upper right, upper left, lower right and lower left corners of the square area. For an example, we consider only two conversion pathways as depicted in Wright et al.[43]: (1) converting biomass to liquid fuels in an integrated biorefinery through gasification and FT synthesis and (2) preconverting biomass into bio-oil in some fast pyrolysis plant and then upgrading the bio-oil to liquid fuels in a gasification plant. The demand zone is at the center of the square area. In other words, all the biomass feedstocks in the square area should be converted to liquid transportation fuels, which will be consumed in the center of the square area.
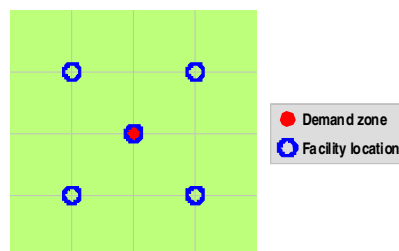


**Figure 7. Superstructure of the biomass-to-liquids processing networks of the illustrative example.**
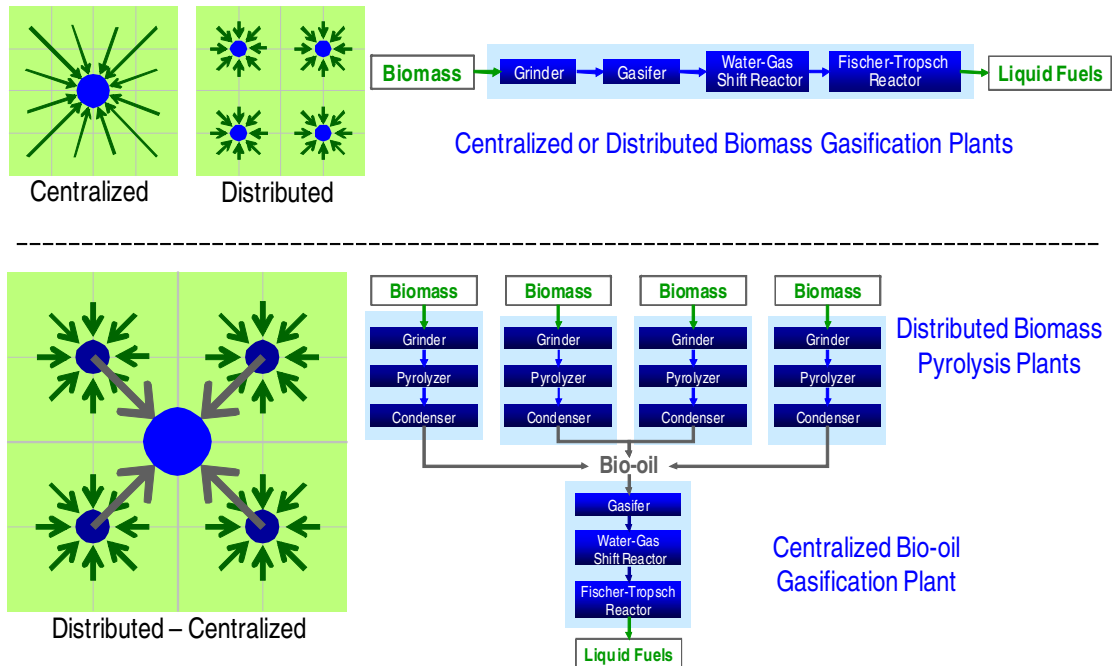
**Figure 8. Three biomass-to-liquids processing networks with different locations, capacities, conversion pathways for the illustrative example.**

Based on the superstructure, we consider three BTL processing networks with different conversion pathways, plant locations, and capacities, namely, "centralized," "distributed," and "distributed-centralized" designs (see Figure 8). In the centralized case, all the biomass feedstocks collected from the entire area are shipped to a large, centralized gasification plant, located in the center of the square area, for the conversion to liquid fuels. In the "distributed" design, four integrated gasification plants with smaller size for the conversion of biomass to liquid fuels are built in the center of four corners of the square area. The third design, which represents distributed-centralized processing network, includes four fast pyrolysis plants for the preconversion of biomass to bio-oil and a centralized gasification plant for the upgrading of bio-oil to liquid transportation fuels. The bio-oil gasification plant is located in the center of the square area, and the locations of the four pyrolysis plants are at the centers of four corners of the area.

In this example, we focus on the tradeoff between the costs from transportation and process construction/operations, because the major differences between the three designs are facility locations, production capacities, and technology selections. Economic and environmental performance of other activities, such as biomass cultivation and

acquisition, material storage, and fuel local distribution, are not considered in this example for simplicity, although they are taken into account in the bicriterion optimization model presented in the following sections.

Following the analysis by Wright et al.[43] and the data provided in Easterly,[44] we assume that the yield of biomass crop is 1,250 dry ton/km$^2$/year (i.e., 5 ton/acre/year), the biomass energy value is 19.5 MJ/kg, the bio-oil energy value is 19.7 MJ/liter, the liquid fuel energy value is 36 MJ/liter, and the energy value of one gasoline-equivalent gallon (GEG) is 120.3 MJ/GEG. Although the conversion efficiency might be dependent on the size of conversion facilities, for simplicity we assume they can be approximated to those values in Wright et al.[43]. Thus, we assume the efficiency of biomass to liquid fuel via gasification and FT synthesis to be 46% (MJ liquid fuel per MJ biomass), the efficiency of biomass to bio-oil via fast pyrolysis to be 69% (MJ bio-oil per MJ biomass), and the efficiency of bio-oil to liquid fuels via gasification and FT synthesis to be 58% (MJ liquid fuel per MJ bio-oil).

Based on energy balance and conversion efficiency data, we can determine the capacities of the conversion processes in the three designs, as well as the corresponding production and consumption amounts of feedstocks, intermediates, and final products. These results are summarized in Tables 1 and 2. We note that the capacities of gasification plants are measured by annual fuel output in terms of GEG, and the capacities of pyrolysis plants are measured by the amount of biomass converted annually. Since we assume the conversion efficiency of biomass gasification plants is not significantly affected by plant size, both the "centralized" and "distributed' designs convert the 2 million dry tons of biomass feedstocks into 498 million liters of FT liquid fuels. However, the "distributed-centralized" design yields only 434 million liters of FT liquid fuels because of the slightly lower conversion efficiency of the two-step processing strategy.

**Table 1   Total annual production/consumption/transportation quantity of biomass, bio-oil, and liquid fuels for the three network designs in the illustrative example**

|  | Biomass | Bio-Oil | Liquid Fuels |
|---|---|---|---|
| Centralized | 2 MM dry ton | 0 | 498 MM liters |
| Distributed | 2 MM dry ton | 0 | 498 MM liters |
| Distributed - | 2 MM dry ton | 1,365 MM liters | 434 MM liters |

Centralized

**Table 2 Capacities of the conversion processes for the three network designs in the example**

|  | Biomass Gasifier | Biomass Pyrolyzer | Bio-oil Gasifier |
|---|---|---|---|
| Centralized | 149 MM GEG/year | --- | --- |
| Distributed | 37 MM GEG/year $\times$ 4 | --- | --- |
| Distributed - Centralized | --- | 0.5 MM ton/year $\times$ 4 | 130 MM GEG/year |

We consider a scale factor of 0.6 (the six-tenth rule), as in Wright et al.,[43] to calculate the capital cost of the conversion processes in the three designs. The techno-economic analysis by Tijmensen et al.,[39] Ringer et al.,[45] and Wright et al.[43] provide data for three reference plants: biomass gasification and FT synthesis plant with a capacity of 35 million GEG per year involves a total capital cost of $341 million; fast pyrolysis plant converting biomass to bio-oil with capacity of 0.2 million dry ton of biomass per year costs $47.8 million; and bio-oil gasification and FT synthesis plant with a capacity of 35 million GEG per year has a total capital cost of $269.4 million. The scaling equation

$$Cost_{new}\Big/Cost_0 = \left(Size_{new}\Big/Size_0\right)^{0.6}$$ and the results of plant capacities listed in Table 1 are

used to determine the capital costs of the conversion processes. The annual operating cost includes a fixed capital charge and maintenance cost, which is proportional to the capital investment, and a variable production cost, which scales linearly with the production quantity. In this work, we use the same approach as Tijmensen et al.,[39] Ringer et al.,[45] and Wright et al.[43] to consider the annual operating cost: that of the gasification plant equals 17% of the capital investment plus $0.130857 per GEG produced, and that of the pyrolysis plant is 12.08% of the capital investment minus $1.485093 per dry ton of biomass processed. The negative variable production cost of the pyrolysis plant is due to the fact that charcoal, the major byproduct of the pyrolysis processes, not only has value as a carbon sequestration agent but also has potential as fertilizer and soil organic matter. Thus, we follow the analysis by Wright et al.[43] to assign a $50/ton credit to charcoal production. Based on this analysis, we calculate the capital investment costs and the annual operating costs of all the conversion processes in the three designs; these costs are listed in Tables 3 and 4, respectively.

**Table 3  Capital investments of the conversion processes for the three network designs in the illustrative example**

|  | Biomass Gasifier + FT | Biomass Pyrolyzer | Bio-Oil Gasifier + FT |
|---|---|---|---|
| Centralized | $814 MM | --- | --- |
| Distributed | $354 MM × 4 | --- | --- |
| Distributed - Centralized | --- | $83 MM × 4 | $591 MM |

**Table 4  Annual operating costs of the conversion processes for the three network designs in the illustrative example**

|  | Biomass Gasifier + FT | Biomass Pyrolyzer | Bio-Oil Gasifier + FT |
|---|---|---|---|
| Centralized | $158 MM/year | --- | --- |
| Distributed | $65 MM/year × 4 | --- | --- |
| Distributed - Centralized | --- | $9 MM/year × 4 | $117 MM/year |

Because of the locations of processing facilities and demand zone (in the center of the square area), there are different average transportation distances of biomass feedstocks, bio-oil (intermediate), and liquid fuels for the three designs. In the centralized processing network, only biomass feedstocks are shipped to the gasification plant, which is in the demand zone. Hence, the transportation activities of this design are only for shipments of biomass feedstocks from the entire square area to its center. The average distance from all the points inside a unit length square area to its center can be calculated through the integral $\int_{-\frac{1}{2}}^{\frac{1}{2}}\int_{-\frac{1}{2}}^{\frac{1}{2}}\sqrt{x^2+y^2}\,dxdy = \frac{1}{6}\left(\sqrt{2}+\sinh^{-1}(1)\right) \approx 0.382598$. Taking into account the side length of 40 kilometers of the entire square area, we calculate the average transportation distance of biomass for this design as 15.30 kilometers. Similarly, the average transportation distance of biomass feedstocks in the distributed design is 7.65 kilometers. The distances of shipping the final liquid fuels from the four distributed gasification plants to the demand zone, which is in the center of the square area, are the same and equal to the length of the diagonal of a 10 km x 10 km farm, that is, 14.14 kilometers. In the distributed-centralized processing network, bio-oil is produced in the four distributed pyrolyzers and then transported to the centralized gasification plant located in the demand zone. Thus, the average transportation distance of biomass feedstocks of this design is the same as the one for the distributed design, and the

distance of shipping bio-oil to the gasification plant equals 14.14 kilometers. The average transportation distances are summarized in Table 5.

**Table 5   Average transportation distances of biomass, bio-oil and liquid fuels for the three network designs in the illustrative example**

|  | Biomass | Bio-Oil | Liquid Fuels |
|---|---|---|---|
| Centralized | 15.30 kilometers | 0 | 0 |
| Distributed | 7.65 kilometers | 0 | 14.14 kilometers |
| Distributed - Centralized | 7.65 kilometers | 14.14 kilometers | 0 |

We assume trucks are the only transportation mode used in the three designs. The calculation of transportation cost, including distance fixed cost and distance variable cost, is based on data from Borjesson and Gustavsson,[46] Searchy et al.,[47] and Pootakhama and Kumar.[48] The distance variable transportation costs of biomass, bio-oil, and liquid fuels are \$0.456/ton/km, \$0.000119/liter/km, and \$0.000425/liter/km, respectively. The distance fixed costs of biomass feedstocks, bio-oil, and liquid fuels are \$4.839/ton, \$0.00567/liter and \$0.00328/liter, respectively. The moisture content of the biomass feedstock is assumed to be 35 wt%. Thus, we can determine the total transportation costs of the three materials in the three network designs. The results are listed in Table 6.

**Table 6   Total transportation costs of biomass, bio-oil, and liquid fuels for the three network designs in the illustrative example**

|  | Biomass | Bio-oil | Liquid fuels |
|---|---|---|---|
| Centralized | \$36.4 MM/year | 0 | 0 |
| Distributed | \$25.6 MM/year | 0 | \$4.63 MM/year |
| Distributed - Centralized | \$25.6 MM/year | \$10.0 MM/year | 0 |

We consider a 10% discount rate and a 20-year project lifetime. Thus, the annuity factor of the capital discount is given by $\left(10\% \times 1.1^{20}\right)\big/\left(1.1^{20}-1\right) = 0.11746$. Therefore, we have the annualized total discounted capital, production, and transportation costs of the centralized, distributed, and distributed-centralized network designs are \$290MM, \$457MM, and \$298MM, respectively. These results, coupled with those in Tables 1–6, show that the centralized design might be the best option for the 40 km x 40 km square area, because of the economy of scale and higher efficiency of integrated conversion

(gasification + FT synthesis in a single plant). Although the distributed-centralized design has the highest transportation cost and slightly higher capital cost than does the centralized design, it is still a viable approach because of its low operating cost resulting from the credit of charcoal, the major byproduct in the preconversion process. The distributed design, which has the minimum transportation cost, has higher capital and operating costs than do the other two designs.

**Table 7   Total discounted capital, production, and transportation costs of the three designs under different side lengths of the square area in the example**

|  | 40 kilometers | 60 kilometers | 135 kilometers | 200 kilometers |
|---|---|---|---|---|
| Centralized | $290 MM/year $1.94/GEG | $530 MM/year $1.58/GEG | $2,224 MM/year $1.31/GEG | $5,156 MM/year $1.38/GEG |
| Distributed | $457 MM/year $3.06/GEG | $786 MM/year $2.34/GEG | $2,610 MM/year $1.54/GEG | $5,126 MM/year $1.38/GEG |
| Distributed - Centralized | $298 MM/year $2.30/GEG | $528 MM/year $1.81/GEG | $1,927 MM/year $1.30/GEG | $4,031 MM/year $1.24/GEG |

We perform similar analysis by increasing the length of the side of the square area from 40 kilometers to 60 kilometers, 135 kilometers, and 200 kilometers. The results of the total discounted capital, production, and transportation costs and the unit costs per GEG are listed in Table 7. We can see that if the side length is 60 kilometers, the distributed-centralized design becomes the least cost option, because the larger area implies a higher growth rate of the transportation cost, which can be significantly reduced through distributed-centralized processing. We note that when the side length is 60 kilometers, the centralized design still yields the minimum unit cost of $1.58/GEG, because of the relatively low conversion efficiency of the two-step processing of the distributed-centralized design. When the side length increases to 135 kilometers and the size of the square area is close to that of Chicago, the distributed-centralized design has the minimum total cost and minimum unit cost. In this scenario, the difference between the costs of the centralized and distributed designs becomes smaller. When the side length increases to 200 kilometers, the distributed design becomes more cost-effective than the centralized design. The reason is that the higher transportation cost resulting from the larger area offsets the capital saving of the economy of scale in the "centralized design".

**Table 8   Total transportation emissions ($CO_2$-equiv) of the three designs under different side lengths of the square area in the illustrative example**

|  | Biomass | Bio-Oil | Liquid Fuels | Total Emissions |
|---|---|---|---|---|
| Centralized | 2,098 ton/year | 0 | 0 | 2,098 ton/year |
| Distributed | 1,049 ton/year | 0 | 348 ton/year | 1,367 ton/year |
| Distributed - Centralized | 1,049 ton/year | 1,615 ton/year | 0 | 2,664 ton/year |

In addition to the economic perspective, the tradeoffs in distributed-centralized BTL processing networks also reflect on the environmental impacts. Although the life cycle GHG emissions of the liquid fuels produced in the three designs should take into account all the life cycle stages as discussed in the previous section, we consider as a simplified example the total emissions resulting from the transportation activities of biomass, bio-oil, and liquid fuels. The results in terms of $CO_2$-equivalent/year for the original case of 40 km x 40 km square area are listed in Table 8. We note that the distributed design, which has the highest annualized cost, leads to minimum GHG emissions in transportation activities. Although the distributed-centralized design is a promising approach from the economic perspective, it leads to more environmental burdens than the other two designs because of the relatively heavy transportation activities for biomass feedstocks and intermediate products.


## 6. General Problem Statement

In this problem, we are given a set of biomass feedstocks, including crop residues (e.g., corn stover), energy crops (e.g., switchgrass and *miscanthus*), and wood residues (e.g., forest residues and primary mills, secondary mills, urban wood residues). Major properties of each type of feedstock (e.g., moisture content, degradation rate) are given.

The biomass feedstocks that can be converted to a set of liquid transportation fuels (e.g., gasoline and diesel) through a number of conversion technologies. These technologies include, but are not limited to, gasification followed by Fischer–Tropsch synthesis and fast pyrolysis followed by hydroprocessing.[9, 11-14] Biomass feedstocks can also be first converted into intermediate products (e.g. bio-oil and bio-slurry) through rotating cone reactor pyrolysis and fluidized bed reactor pyrolysis, before upgrading the intermediates to liquid fuel with corresponding technologies.

A planning horizon of one year is divided into several time periods. The duration of each time period is known, and the project lifetime in terms of years is given. We assume a constant discounted rate throughout the project lifetime. The government incentives, including production and construction incentives, are given.

We are also given a BTL supply chain network superstructure (see Figure 9), including a set of harvesting sites and a set of demand zones, as well as the potential locations of integrated biorefineries, preconversion facilities, and intermediate upgrading facilities. We are given the availability of each type of biomass feedstock in each harvesting site and the upper and lower bounds of the demands of liquid fuels in each demand zone at each time period. A set of capacity levels is given for all the production facilities and the costs of different technologies at different capacity levels are known. Intermediate and fuel yields and operating costs are also given. The unit cost and environmental burden associated with feedstock acquisition, liquid fuel distribution in local regions, biomass processing, and fuel production are known.

The network also includes different types of transportation links. Biomass feedstocks are shipped from harvesting sites to integrated biorefineries or preconversion facilities, liquid fuels are transported to demand zones from integrated biorefineries or intermediate upgrading facilities, and intermediate products are sent from preconversion facilities to fuel upgrading facilities. For each transportation link, the transportation capacity, available transportation modes, unit transportation cost of each mode, transportation distance, and emissions of each transportation type are known.

The objectives are simultaneous minimizing the annualized total cost (which is the measure of the economic performance) and the life cycle field-to-wheel GHG emissions (which measures the environmental performance) of the entire BTL supply chain through optimizing the following decision variables:

- Number, sizes, locations, and technology selections of each processing facilities
- Feedstock harvesting schedule at each harvesting site
- Inventory levels of feedstocks, intermediates, and liquid fuels at each facility in each time period
- Fuel yield and feedstock consumption rates at each facility in each time period
- Transportation profiles of each transportation link and transportation mode
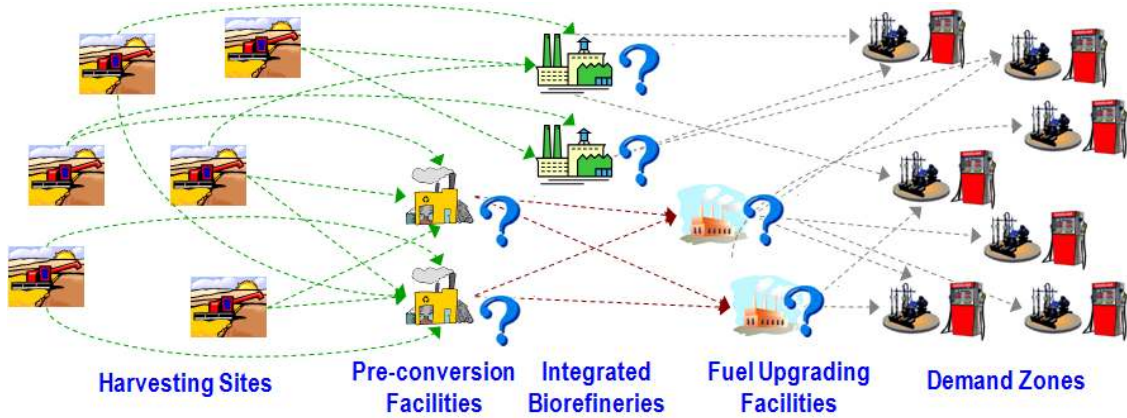
**Figure 9.  Cellulosic biofuel supply chain superstructure.**

# 7. Mathematical Model Formulation

We develop a bicriterion, multiperiod MILP model for the problem addressed in this work. Constraints (1)–(49) model the BTL supply chains and take into account their major characteristics (Section 7.1). Constraints (50)–(56) are for the capital and operational costs of the cellulosic biofuel supply chains; the economic objective is defined in (57) (Section 7.2). The environmental objective, which is modeled based on the principles of life cycle field-to-wheel analysis, is defined in (58)–(64) (Section 7.3). A list of indices, sets, parameters, and variables is given in the Nomenclature section at the end of this paper.

## 7.1 Constraints

### Biomass feedstock supply system

The total amount of biomass type $b$ acquired from harvesting location $i$ at time period $t$ ($bmp_{b,i,t}$) should not exceed its available amount ($BA_{b,i,t}$) in terms of dry weight:

$$bmp_{b,i,t} \le BA_{b,i,t}, \qquad\qquad\qquad \forall b \in B, i \in I, t \in T. \qquad (1)$$

where $BA_{b,i,t}$ is the available amount of biomass type $b$ in harvesting site $i$ at time period $t$. We note that seasonality, harvesting windows, and geographical availability of different biomass feedstocks can be taken into account through different values of the parameter $BA_{b,i,t}$ at different harvesting sites and time periods for different biomass types.[37]

The mass balance of harvesting site $i$ at time period $t$ for biomass type $b$ is given by the following equation:

$$bmp_{b,i,t} = \sum_j \sum_m fij_{b,i,j,m,t} + \sum_k \sum_m fik_{b,i,k,m,t}, \qquad \forall b \in B, i \in I, t \in T, \qquad (2)$$

where $fij_{b,i,j,m,t}$ is the amount (dry weight) of feedstock type $b$ shipped from harvesting site $i$ to integrated conversion facility $j$ with transportation mode $m$ in time period $t$, and $fik_{b,i,k,m,t}$ is the amount (dry weight) of feedstock type $b$ shipped from harvesting site $i$ to preconversion facility $k$ with transportation mode $m$ in time $t$. Since the harvesting sites do not store feedstocks, the total acquisition amount of feedstock should be equal to the total amount shipped to all the processing facilities.

The total transportation amount of biomass feedstock from harvesting site $i$ to integrated conversion facility $j$ with transportation mode $m$ at time period $t$ ($fij_{b,i,j,m,t}$) is constrained by the corresponding transportation capacity in weight. Since the feedstocks have not been dried during the transportation from the harvesting sites to the collection facilities, we need to consider their moisture content ($MC_b$) during the transportation. The intermodal transportation of multiple feedstocks with the same transportation link is taken into account through the factor $\rho_b$, which is the mass quantity of standard dry biomass for one dry ton of biomass type $b$. Thus, the transportation capacity constraint is given by

$$\sum_b \frac{\rho_b \cdot fij_{b,i,j,m,t}}{1 - MC_b} \le WCIJ_{i,j,m,t}, \qquad \forall i \in I, j \in J, m \in M, t \in T, \qquad (3)$$

where $WCIJ_{i,j,m,t}$ is the weight capacity the transportation of feedstock from harvesting site $i$ to integrated conversion facility $j$ with transportation mode $m$ at time period $t$.

Similarly, the total transportation amount of biomass feedstock from harvesting site $i$ to preconversion facility $k$ with transportation mode $m$ at time period $t$ ($fik_{b,i,k,m,t}$) is constrained by the corresponding weight capacity, after considering moisture content and adjusting the standardized biomass weight:

$$\sum_b \frac{\rho_b \cdot fik_{b,i,k,m,t}}{1 - MC_b} \le WCIK_{i,k,m,t}, \qquad \forall i \in I, k \in K, m \in M, t \in T, \qquad (4)$$

where $WCIK_{i,k,m,t}$ is the weight capacity the transportation of feedstock from harvesting site $i$ to preconversion facility $k$ with transportation mode $m$ at time period $t$.

*Integrated biomass-to-liquid conversion facilities*

The mass balance of feedstock $b$ in integrated biorefinery $k$ at time period $t$ requires that the total quantity of feedstock type $b$ transported from all the harvesting sites to integrated biorefinery $j$ with all the possible transportation modes at time period $t$ plus the inventory level of integrated biorefinery $j$ at the end of the previous time period after considering biomass deterioration be equal to the total quantity of this type of feedstock used for liquid transportation fuel production plus its inventory at the end of current period. This relationship is modeled through the following equations:

$$\sum_i \sum_m fij_{b,i,j,m,t} + \left(1 - \varepsilon_{b,t}\right) \cdot sbj_{b,j,t-1} = \sum_q wbj_{b,j,q,t} + sbj_{b,j,t}, \quad \forall b \in B, j \in J, t \geq 2, \tag{5}$$

$$\sum_i \sum_m fij_{b,i,j,m,t=1} + \left(1 - \varepsilon_{b,t=1}\right) \cdot sbj_{b,j,t=|T|} = \sum_q wbj_{b,j,q,t=1} + sbj_{b,j,t=1}, \quad \forall b \in B, j \in J, \tag{6}$$

where $fij_{b,i,j,m,t}$ is the amount of biomass type $b$ shipped from harvesting site $i$ to biorefinery $j$ with transportation mode $m$ in time $t$, $wbj_{b,j,q,t}$ is the amount of feedstock type $b$ used for the production of liquid transportation fuels through technology $q$ in integrated biorefinery $j$ at time $t$, $sbj_{b,j,t}$ is the inventory level of biomass type $b$ in integrated biorefinery $j$ at time period $t$, and $\varepsilon_{b,t}$ is the percentage of biomass type $b$ deteriorated in storage facility at time $t$. We note that the introduction of the deteriorated factor $\varepsilon_{b,t}$ captures the degradation characteristic of biomass feedstock.[37] To look into the annualized cost of biofuel, we consider a "cyclic" way for the inventory balance; that is, the inventory level at the beginning of the year is the same as the inventory level at the end of the year after considering biomass degradation. This "cyclic" inventory balance is given in (6).

Similarly, the mass balance relationship of liquid transportation fuel $p$ produced at integrated biorefinery $j$ at time period $t$ is given by the following equations:

$$\sum_q wpj_{j,p,q,t} + spj_{j,p,t-1} = \sum_d \sum_m fjd_{d,j,p,m,t} + spj_{j,p,t}, \quad \forall j \in J, p \in P, t \geq 2, \tag{7}$$

$$\sum_q wpj_{j,p,q,t=1} + spj_{j,p,t=|T|} = \sum_d \sum_m fjd_{d,j,p,m,t=1} + spj_{j,p,t=1}, \quad \forall j \in J, p \in P, \tag{8}$$

where $wpj_{j,p,q,t}$ is the amount of liquid fuel $p$ produced through technology $q$ in integrated biorefinery $j$ at time $t$, $spj_{j,p,t}$ is the inventory level of liquid fuel $p$ in integrated

biorefinery $j$ at time $t$, and $ffd_{d,j,p,m,t}$ is the amount of liquid fuel $p$ shipped from integrated biorefinery $j$ to demand zones $d$ with transportation mode $m$ at time period $t$.

A binary variable, $x_{j,q,r}$, is introduced to model the selection of conversion technology and capacity level of integrated biorefineries through the following constraints:

$$\sum_q \sum_r x_{j,q,r} \leq 1, \qquad\qquad\qquad \forall j \in J \tag{9}$$

$$\sum_j \sum_r x_{j,q,r} \leq NJ_q, \qquad\qquad\qquad \forall q \in Q \tag{10}$$

where $x_{j,q,r}$ equals 1 if the integrated biorefinery $j$ with technology $q$ and capacity level $r$ is constructed and $NJ_q$ is the maximum allowable number of integrated biorefineries with technology $q$. Constraint (9) shows that at most one type of conversion technology and capacity level can be chosen in an integrated biorefinery, and constraint (10) enforces an upper bound on the total number of integrated conversion facility with technology $q$.

From the definition of capacity level, the annual production capacity (in terms of gallons of gasoline equivalent) of the integrated biorefinery $j$ ($capj_{j,q,r}$) is given by the following constraints:

$$PRJ_{j,q,r-1} \cdot x_{j,q,r} \leq capj_{j,q,r} \leq PRJ_{j,q,r} \cdot x_{j,q,r}, \qquad \forall j \in J, q \in Q, r \in R, \tag{11}$$

where $PRJ_{j,q,r}$ is the upper bound of the capacity of integrated biorefinery $j$ with capacity level $r$ and technology $q$.

To account for economy of scale, we model the total capital investment of integrated biorefinery $j$ ($tcapj_j$) with an interpolated piece-wise linear curve[19, 37] for each capacity level:

$$tcapj_j = \sum_q \sum_r \left[ CRJ_{j,q,r-1} \cdot x_{j,q,r} + \left( capj_{j,q,r} - PRJ_{j,q,r-1} \cdot x_{j,q,r} \right) \cdot \left( \frac{CRJ_{j,q,r} - CRJ_{j,q,r-1}}{PRJ_{j,q,r} - PRJ_{j,q,r-1}} \right) \right]$$
$$, \qquad\qquad\qquad\qquad\qquad \forall j \in J \tag{12}$$

where $CRJ_{j,q,r}$ is the investment cost of installing integrated biorefinery $j$ with technology $q$ and capacity level $r$. Because of constraints (11) and (12), the total capital investment cost ($tcapj_j$) equals zero if $x_{j,q,r}$ is zero. Similarly, the fixed annual operations and maintenance (O&M) cost of integrated biorefinery $j$ ($tcfpj_j$) can be modeled through the following equation:

$$tcfpj_j = \sum_q \left\{ CFJ_{j,q} \cdot \sum_r \left[ CRJ_{j,q,r-1} \cdot x_{j,q,r} + \left( capj_{j,q,r} - PRJ_{j,q,r-1} \cdot x_{j,q,r} \right) \cdot \left( \frac{CRJ_{j,q,r} - CRJ_{j,q,r-1}}{PRJ_{j,q,r} - PRJ_{j,q,r-1}} \right) \right] \right\}$$

$$, \qquad\qquad\qquad\qquad\qquad\qquad \forall j \in J \qquad\qquad\qquad (13)$$

where $CFJ_{j,q}$ is the fixed annual O&M cost as a percentage of the total investment cost of integrated biorefinery $j$ with technology $q$. We note that the value of this parameter depends on the specific conversion technology used in the integrated biorefinery.

In most U.S. states, government incentives are provided for the construction of integrated biorefineries, with a minimum being a certain percentage of the total capital investment and a maximum allowable amount.[49] Thus, the total government incentive received for the construction of biorefinery $j$ ($incj_j$) is defined by the following two constraints:

$$incj_j \leq INCM \cdot \sum_q \sum_r x_{j,q,r} , \qquad\qquad\qquad \forall j \in J \qquad\qquad (14)$$

$$incj_j \leq INCP \cdot tcapj_j , \qquad\qquad\qquad\qquad \forall j \in J \qquad\qquad (15)$$

where $INCM$ is the maximum incentive that can be provided for the construction of biomass conversion facilities and $INCP$ is the maximum percentage of the total investment cost of biorefinery construction that can be supported by government incentive. Constraint (14) enforces that no incentive can be received if no biorefinery is selected to be constructed in location $j$.

The total production quantity of all the liquid transportation fuels (after converting to gallons of gasoline equivalent) in integrated biorefinery $j$ with conversion technology $q$ at time period $t$ ($wpj_{j,p,q,t}$) should not exceed the annual production capacity ($capj_{j,q,r}$) times the duration of the time period ($H_t$) divided by the effective production time of a year ($HY$). The lower bound of the total production quantity is placed through the introduction of a minimum capacity utilization percentage ($\theta_{j,q}$). Thus, the production capacity constraints are

$$\theta_{j,q} \cdot \frac{H_t}{HY} \cdot \sum_r capj_{j,q,r} \leq \sum_p \varphi_p \cdot wpj_{j,p,q,t} \leq \frac{H_t}{HY} \cdot \sum_r capj_{j,q,r} , \quad \forall j \in J, q \in Q, t \in T , \qquad (16)$$

where $\varphi_p$ is the gasoline-equivalent gallons of one gallon of fuel product $p$

The production amount of liquid fuel $p$ in integrated biorefinery $j$ at time period $t$ ($wpj_{j,p,q,t}$) relates to the biomass feedstock consumption amount ($wbj_{b,j,q,t}$) through the following mass balance equation:

$$wpj_{j,p,q,t} = \sum_b \alpha_{b,p,q} \cdot wbj_{b,j,q,t}, \qquad\qquad \forall j \in J, p \in P, q \in Q, t \in T, \qquad (17)$$

where $\alpha_{b,p,q}$ is the yield of liquid fuel product $p$ converted from unit quantity of biomass feedstock type $b$ at integrated biorefineries with conversion technology $q$. We note that this equation takes into account all the biomass feedstocks that can be converted to liquid fuel $p$ through technology $q$.

The inventory level of biomass feedstock ($sbj_{b,j,t}$) should not be lower than the safety stock level, in order to avoid potential supply disruption. Strictly speaking, the optimal safety stock level should be determined by using a stochastic inventory model[50-53] that integrates demand and supply uncertainty with supply chain design and operations. Because of the complexity of stochastic inventory approach, however, we use an empirical approach that relates the safety stock level to the feedstock consumption amount over a safety period ($SJ_{j,t}$). Thus, the minimum inventory level constraint is given by

$$sbj_{b,j,t} \geq \frac{SJ_{j,t}}{H_t} \cdot \sum_q wbj_{b,j,q,t}, \qquad\qquad \forall b \in B, j \in J, t \in T, \qquad (18)$$

where $H_t$ is the duration of time period $t$. The right-hand side of constraint (18) shows that the safety stock level of biomass type $b$ in integrated biorefinery $j$ at time $t$ is proportional to the corresponding consumption rate. We note that this constraint also implies that the minimum inventory level will be zero if the integrated biorefinery $j$ is not selected to be constructed.

### *Biomass preconversion facilities*

The mass balance of biomass feedstock $b$ in a preconversion facility $k$ at time period $t$ is similar to that of an integrated biorefinery and is given by the following equations:

$$\sum_i \sum_m fik_{b,i,k,m,t} + (1 - \varepsilon_{b,t}) \cdot sbk_{b,k,t-1} = \sum_{q'} wbk_{b,k,q',t} + sbk_{b,k,t}, \quad \forall b \in B, k \in K, t \geq 2, \qquad (19)$$

$$\sum_i \sum_m fik_{b,i,k,m,t=1} + (1 - \varepsilon_{b,t}) \cdot sbk_{b,k,t=|T|} = \sum_{q'} wbk_{b,k,q',t=1} + sbk_{b,k,t=1}, \quad \forall b \in B, k \in K, \qquad (20)$$

where $fik_{b,i,k,m,t}$ is the amount of biomass type $b$ shipped from harvesting site $i$ to preconversion facility $k$ with transportation mode $m$ in time $t$, $wbk_{b,k,q,t}$ is the amount of feedstock type $b$ used for the production of intermediate products through technology $q'$ in integrated biorefinery $j$ at time $t$, $sbk_{b,k,t}$ is the inventory level of biomass type $b$ in preconversion facility $k$ at time period $t$, and $\epsilon_{b,t}$ is the percentage of biomass type $b$ deteriorated in storage facility at time $t$. We similarly take into account the degradation characteristic of biomass feedstock and the "cyclic" inventory balance in the above constraints.

The outputs of preconversion facilities are intermediate products (e.g., bio-oil and bio-slurry), which are indexed by $g$. The corresponding mass balance at each time period is given by the following equations:

$$\sum_{q'} wgk_{g,k,q',t} + sgk_{g,k,t-1} = \sum_{l}\sum_{m} fkl_{g,k,l,m,t} + sgk_{g,k,t}, \quad \forall g \in G, k \in K, t \geq 2, \tag{21}$$

$$\sum_{q'} wgk_{g,k,q',t=1} + sgk_{g,k,t=|T|} = \sum_{l}\sum_{m} fkl_{g,k,l,m,t=1} + sgk_{g,k,t=1}, \quad \forall g \in G, k \in K, \tag{22}$$

where $wgk_{g,k,q',t}$ is the amount of intermediate $g$ produced through technology $q'$ in preconversion facility $k$ at time $t$, $sgk_{g,k,t}$ is the inventory level of intermediate products, and $fkl_{g,k,l,m,t}$ is the amount of intermediate $g$ shipped from preconversion facility $k$ to intermediate upgrading facility $l$ with transportation mode $m$ at time period $t$.

The technology and capacity level selection and the maximum number of preconversion facilities with the same technology are modeled through the following constraints:

$$\sum_{q'}\sum_{r} y_{k,q',r} \leq 1, \qquad\qquad\qquad \forall k \in K, \tag{23}$$

$$\sum_{k}\sum_{r} y_{k,q',r} \leq NK_{q'}, \qquad\qquad\qquad \forall q' \in Q \tag{24}$$

where $y_{k,q',r}$ is a binary variable that equals 1 if the preconversion facility $k$ with technology $q'$ and capacity level $r$ is constructed and $NK_{q'}$ is the maximum allowable number of this type.

The annual production capacity (in terms of dry tons of standard biomass processing) of preconversion facility $k$ ($capj_{j,q,r}$) is given by the following constraints:

$$PRK_{k,q',r-1} \cdot y_{k,q',r} \leq capk_{k,q',r} \leq PRK_{k,q',r} \cdot y_{k,q',r}, \quad \forall k \in K, q \in Q, r \in R, \tag{25}$$

where $PRK_{k,q',r}$ is the upper bound of the capacity of preconversion facility $k$ with capacity level $r$ and technology $q'$ and $capk_{k,q',r}$ is the capacity of facility $k$.

The total capital investment of preconversion facility $k$ ($tcapk_k$), the corresponding government incentives for construction ($inck_k$), and the corresponding fixed annual O&M cost of ($tcfpk_k$) are defined by the following constraints:

$$tcapk_k = \sum_{q'} \sum_{r} \left[ CRK_{k,q',r-1} \cdot y_{k,q',r} + \left( capk_{k,q',r} - PRK_{k,q',r-1} \cdot y_{k,q',r} \right) \cdot \left( \frac{CRK_{k,q',r} - CRK_{k,q',r-1}}{PRK_{k,q',r} - PRK_{k,q',r-1}} \right) \right]$$
$$, \qquad\qquad\qquad\qquad \forall k \in K \qquad\qquad (26)$$

$$inck_k \leq INCM \cdot \sum_{q'} \sum_{r} y_{k,q',r} , \qquad\qquad \forall k \in K \qquad\qquad (27)$$

$$inck_k \leq INCP \cdot tcapk_k , \qquad\qquad \forall k \in K \qquad\qquad (28)$$

$$tcfpk_k = \sum_{q'} \left\{ CFK_{k,q'} \cdot \sum_{r} \left[ CRK_{k,q',r-1} \cdot y_{k,q',r} + \left( capk_{k,q',r} - PRK_{k,q',r-1} \cdot y_{k,q',r} \right) \cdot \left( \frac{CRK_{k,q',r} - CRK_{k,q',r-1}}{PRK_{k,q',r} - PRK_{k,q',r-1}} \right) \right] \right\}$$
$$, \qquad\qquad\qquad\qquad \forall k \in K \qquad\qquad (29)$$

where $CRK_{k,q',r}$ is the investment cost of installing preconversion facility $k$ with technology $q'$ and capacity level $r$ and $CFK_{k,q'}$ is the fixed annual O&M cost as the percentage of the total investment cost of preconversion facility $k$ with technology $q'$.

The total amount of biomass feedstock (after converting to standard dry tons of biomass) processed in preconversion facility $k$ with conversion technology $q'$ at time period $t$ ($wbk_{b,k,q',t}$) should not exceed the production upper bound defined by the production capacity, the duration of the time period, and the effective production time of a year,

$$\sum_{b} \rho_b \cdot wbk_{b,k,q',t} \leq \frac{H_t}{HY} \cdot \sum_{r} capk_{k,q',r} , \qquad\qquad \forall k \in K, q' \in Q, t \in T , \qquad (30)$$

where $\rho_b$ is the mass quantity of standard dry biomass of one dry ton of biomass type $b$.

The consumption amount of biomass feedstock and the production amount of intermediate product $g$ in preconversion facility $k$ at time period $t$ is given by the following mass balance equation:

$$wgk_{g,k,q',t} = \sum_{b} \beta_{b,g,q'} \cdot wbk_{b,k,q',t} , \qquad\qquad \forall g \in G, k \in K, q' \in Q, t \in T , \qquad (31)$$

where $\beta_{b,g,q'}$ is the yield of intermediate product $g$ converted from unit quantity of biomass feedstock type $b$ at preconversion facilities with technology $q'$. This equation

also takes into account all the biomass feedstocks that can be converted to intermediate $g$ through technology $q'$.

The inventory level of biomass feedstock type $b$ ($sbk_{b,k,t}$) should not be lower than the safety stock level, which is defined by the feedstock consumption amount and the safety period ($SK_{k,t}$):

$$sbk_{b,k,t} \geq \frac{SK_{k,t}}{H_t} \cdot \sum_{q'} wbk_{b,k,q',t} , \qquad \forall b \in B, k \in K, t \in T . \qquad (32)$$

### *Intermediate upgrading facilities*

For intermediate $g$ in upgrading facility $l$ at each time period, the mass balance is given by the following equations:

$$\sum_{k} \sum_{m} fkl_{g,k,l,m,t} + sgl_{g,l,t-1} = \sum_{q''} wgl_{g,l,q'',t} + sgl_{g,l,t} , \quad \forall g \in G, l \in L, t \geq 2 , \qquad (33)$$

$$\sum_{k} \sum_{m} fkl_{g,k,l,m,t=1} + sgl_{g,l,t=|T|} = \sum_{q''} wgl_{g,l,q'',t=1} + sgl_{g,l,t=1} , \quad \forall g \in G, l \in L , \qquad (34)$$

where $wgl_{g,l,q'',t}$ is the amount of intermediate type $g$ used for the production of liquid transportation fuels through technology $q''$ in upgrading facility $l$ at time $t$, and $sgl_{g,l,t}$ is the corresponding inventory level.

Because intermediate products, such as bio-oil and bio-slurry, might be unstable for long-distance transportation, a maximum transportation distance ($MDS_{g,m,t}$) requirement can be considered in the logistics planning.

$$fkl_{g,k,l,m,t} = 0 , \quad \forall (g,k,l,m,t) \,|\, \left( MDS_{g,m,t} \leq DSKL_{k,l,m} \right) \qquad (35)$$

We should note that bio-oil has been found to be stable for international transportation over periods of several months,[54] so its maximum transportation distance might be too long enough to no impact on the solution results.

Similarly, the mass balance relationship of liquid transportation fuel $p$ produced at upgrading facility $l$ at time period $t$ is given by the following equations:

$$\sum_{q''} wpl_{l,p,q'',t} + spl_{l,p,t-1} = \sum_{d} \sum_{m} fld_{d,l,p,m,t} + spl_{l,p,t} , \quad \forall l \in L, p \in P, t \geq 2 , \qquad (36)$$

$$\sum_{q''} wpl_{l,p,q'',t=1} + spl_{l,p,t=|T|} = \sum_{d} \sum_{m} fld_{d,l,p,m,t=1} + spl_{l,p,t=1} , \quad \forall l \in L, p \in P , \qquad (37)$$

where $wpl_{l,p,q'',t}$ is the amount of liquid fuel $p$ produced through technology $q''$ in upgrading facility $l$ at time $t$, $spl_{l,p,t}$ is the corresponding inventory level of liquid fuel $p$, and $fjd_{d,j,p,m,t}$ is the amount of liquid fuel $p$ shipped from upgrading facility $l$ to demand zones $d$ with transportation mode $m$ at time period $t$.

The technology and capacity level selection constraint is given by

$$\sum_{q''}\sum_{r} z_{l,q'',r} \leq 1, \qquad\qquad \forall l \in L, \tag{38}$$

where $z_{l,q'',r}$ is a binary variable that equals 1 if the upgrading facility $l$ with technology $q''$ and capacity level $r$ is constructed.

The upper bound of intermediate upgrading facilities are given by

$$\sum_{l}\sum_{r} z_{l,q'',r} \leq NL_{q''}, \qquad\qquad \forall q'' \in Q \tag{39}$$

where $NL_{q''}$ is the corresponding upper bound.

The annual production capacity (in terms of gallons of gasoline equivalent) of the upgrading facility $l$ ($capl_{l,q'',r}$) is defined through the following constraints:

$$PRL_{l,q'',r-1} \cdot z_{l,q'',r} \leq capl_{l,q'',r} \leq PRL_{l,q'',r} \cdot z_{l,q'',r}, \qquad \forall l \in L, q \in Q, r \in R, \tag{40}$$

where $PRL_{l,q'',r}$ is the upper bound of the capacity of intermediate upgrading facility $l$ with capacity level $r$ and technology $q''$

The total capital investment of intermediate upgrading facility $l$ ($tcapl_l$), the corresponding government incentives for construction ($incl_l$), and the corresponding fixed annual O&M cost ($tcfpl_l$) are defined by the following constraints:

$$tcapl_l = \sum_{q''}\sum_{r}\left[ CRL_{l,q'',r-1} \cdot z_{l,q'',r} + \left(capl_{l,q'',r} - PRL_{l,q'',r-1} \cdot z_{l,q'',r}\right) \cdot \left(\frac{CRL_{l,q'',r} - CRL_{l,q'',r-1}}{PRL_{l,q'',r} - PRL_{l,q'',r-1}}\right)\right], \forall l \in L \tag{41}$$

$$incl_l \leq INCM \cdot \sum_{q''}\sum_{r} z_{l,q'',r}, \qquad\qquad \forall l \in L \tag{42}$$

$$incl_l \leq INCP \cdot tcapl_l, \qquad\qquad \forall l \in L \tag{43}$$

$$tcfpl_l = \sum_{q''}\left\{ CFL_{l,q''} \cdot \sum_{r}\left[ CRL_{l,q'',r-1} \cdot z_{l,q'',r} + \left(capl_{l,q'',r} - PRL_{l,q'',r-1} \cdot z_{l,q'',r}\right) \cdot \left(\frac{CRL_{l,q'',r} - CRL_{l,q'',r-1}}{PRL_{l,q'',r} - PRL_{l,q'',r-1}}\right)\right]\right\}$$
$$\forall l \in L \tag{44}$$

where $CRL_{l,q'',r}$ is the investment cost of installing upgrading facility $l$ with technology $q''$ and capacity level $r$ and $CFL_{l,q''}$ is the fixed annual O&M cost as the percentage of the

total investment cost of upgrading facility with technology $q''$.

The total production quantity of all the liquid transportation fuels (after converting to gallons of gasoline equivalent) in upgrading facility $l$ with conversion technology $q''$ at time period $t$ ($wpj_{j,p,q'',t}$) is bounded by the minimum production level and production capacity through the following constraints:

$$\eta_{l,q''} \cdot \frac{H_t}{HY} \cdot \sum_r capl_{l,q'',r} \leq \sum_p \varphi_p \cdot wpl_{l,p,q'',t} \leq \frac{H_t}{HY} \cdot \sum_r capl_{l,q'',r}, \quad \forall l \in L, q'' \in Q, t \in T, \quad (45)$$

where $\eta_{l,q''}$ is the minimum capacity utilization rate.

The mass balance relationship between the production amount of liquid fuel $p$ and to the intermediate consumption amount ($wgl_{g,l,q'',t}$) in upgrading facility $l$ with conversion technology $q''$ at time period $t$ is

$$wpl_{l,p,q'',t} = \sum_g \gamma_{g,p,q''} \cdot wgl_{g,l,q'',t}, \qquad \forall l \in L, p \in P, q'' \in Q, t \in T, \qquad (46)$$

where $\gamma_{g,p,q''}$ is the yield of liquid fuel product $p$ converted from unit quantity of intermediate type $g$ at upgrading facility $l$ with conversion technology $q''$.

The minimum inventory level of intermediate products ($sgl_{g,l,t}$) in upgrading facility $l$ at time period $t$ is given by the following constraint:

$$sgl_{g,l,t} \geq \frac{SL_{l,t}}{H_t} \cdot \sum_{q''} wgl_{g,l,q'',t}, \qquad \forall g \in G, l \in L, t \in T, \qquad (47)$$

where $SL_{l,t}$ is the duration of safety storage period.


### Liquid transportation fuel distribution system

The total amount of the liquid transportation fuel type $p$ sold to demand zones $d$ at time period $t$ ($sold_{d,p,t}$) equals the corresponding amount shipped from all the integrated biorefineries $j \in J$ and intermediate upgrading facilities $l \in L$ with all the possible transportation modes $m \in M$.

$$\sum_j \sum_m fjd_{d,j,p,m,t} + \sum_l \sum_m fld_{d,l,p,m,t} = sold_{d,p,t} \qquad \forall d \in D, p \in P, t \in T. \qquad (48)$$

Demand lower and upper bounds are placed for the fuel type $p$ sold to demand zones $d$ at time period $t$:

$$DEM_{d,p,t}^L \leq sold_{d,p,t} \leq DEM_{d,p,t}^U, \qquad \forall d \in D, p \in P, t \in T, \qquad (49)$$

where $DEM_{d,p,t}^{L}$ and $DEM_{d,p,t}^{U}$ are the lower and upper bounds of demand of liquid transportation fuel type $p$ in demand zones $d$ at time period $t$.

## 7.2 Economic objective – minimizing annualized total cost

The economic objective is to minimize the annualized total cost, including the total annualized capital cost, the annual operation cost, and the annual governmental incentive.

The total capital cost includes the total investment costs of integrated biorefineries, preconversion facilities, and intermediate upgrading facilities. The annualized total capital cost, after taking into account the investment discount, is given as follows:

$$C_{\text{capital}} = \frac{IR \cdot (1+IR)^{NY}}{(1+IR)^{NY} - 1} \cdot \left( \sum_{j} tcapj_{j} + \sum_{k} tcapk_{k} + \sum_{l} tcapl_{l} \right) \tag{50}$$

where $IR$ is the annual discount rate, $NY$ is the project lifetime in terms of years.

The annual operational cost includes biomass feedstock acquisition cost, the local distribution cost of final fuel product, the production costs of intermediate and final products, and the transportation and storage costs of biomass feedstocks, intermediates, and final products. In the production cost, we consider both the fixed annual operating cost, which is given as a percentage of the corresponding total capital investment, and the net variable cost, which is proportional to the processing amount. We note the credit from byproduct (e.g., charcoal) is taken into account in the "net" variable production cost. In the transportation cost, both distance-fixed cost and distance-variable cost are considered. The detailed formulation of these operational cost items is given in (51)–(55).

$$C_{\text{acquisition}} = \sum_{b} \sum_{i} \sum_{t} CBM_{b,i,t} \cdot bmp_{b,i,t} \tag{51}$$

$$C_{\text{distribution}} = \sum_{d} \sum_{p} \sum_{t} CLD_{d,p} \cdot sold_{d,p,t} \tag{52}$$

$$\begin{aligned}
C_{\text{production}} = & \sum_{j} tcfpj_{j} + \sum_{k} tcfpk_{k} + \sum_{l} tcfpl_{l} \\
& + \sum_{j} \sum_{p} \sum_{q} \sum_{t} CPJ_{j,q} \cdot \varphi_{p} \cdot wpj_{j,p,q,t} \\
& + \sum_{b} \sum_{k} \sum_{q'} \sum_{t} CPK_{k,q'} \cdot \rho_{b} \cdot wbk_{b,k,q',t} \\
& + \sum_{l} \sum_{p} \sum_{q''} \sum_{t} CPL_{l,q''} \cdot \varphi_{p} \cdot wpl_{l,p,q'',t}
\end{aligned} \tag{53}$$

$$C_{\text{transportation}} = \sum_b \sum_i \sum_j \sum_m \sum_t \left( DFCB_{b,m} + DVCB_{b,m} \cdot DSIJ_{i,j,m} \right) \cdot fij_{b,i,j,m,t}$$

$$+ \sum_b \sum_i \sum_k \sum_m \sum_t \left( DFCB_{b,m} + DVCB_{b,m} \cdot DSIK_{i,k,m} \right) \cdot fik_{b,i,k,m,t}$$

$$+ \sum_g \sum_k \sum_l \sum_m \sum_t \left( DFCG_{g,m} + DVCG_{g,m} \cdot DSKL_{k,l,m} \right) \cdot fkl_{g,k,l,m,t} \,, \qquad (54)$$

$$+ \sum_d \sum_j \sum_p \sum_m \sum_t \left( DFCP_{m,p} + DVCP_{m,p} \cdot DSJD_{d,j,m} \right) \cdot fjd_{d,j,p,m,t}$$

$$+ \sum_d \sum_l \sum_p \sum_m \sum_t \left( DFCP_{m,p} + DVCP_{m,p} \cdot DSLD_{d,l,m} \right) \cdot fld_{d,l,p,m,t}$$

$$C_{\text{storage}} = \sum_b \sum_j \sum_t H_t \cdot HBJ_{b,j,t} \cdot sbj_{b,j,t} + \sum_j \sum_p \sum_t H_t \cdot HPJ_{j,p,t} \cdot spj_{j,p,t}$$

$$+ \sum_b \sum_k \sum_t H_t \cdot HBK_{b,k,t} \cdot sbk_{b,k,t} + \sum_g \sum_k \sum_t H_t \cdot HGK_{g,k,t} \cdot sgk_{g,k,t} \,, \qquad (55)$$

$$+ \sum_g \sum_l \sum_t H_t \cdot HGL_{g,l,t} \cdot sgl_{g,l,t} + \sum_l \sum_p \sum_t H_t \cdot HPL_{l,p,t} \cdot spl_{l,p,t}$$

The government incentive includes construction incentive and volumetric incentive for biofuel production and usage. The construction incentive should be converted into annualized incentive after considering discount rate and project lifetime. The volumetric incentive for biofuel production and usage is proportional to the quantity of biomass-derived liquid transportation fuel sold to the demand zones. Thus, the annual government incentive is

$$C_{\text{Incentive}} = \frac{IR \cdot \left(1+IR\right)^{NY}}{\left(1+IR\right)^{NY} - 1} \cdot \left( \sum_j incj_j + \sum_k inck_k + \sum_l incl_l \right) + \sum_d \sum_p \sum_t INCV_{d,p} \cdot sold_{d,p,t} \,, \quad (56)$$

where $INCV_{d,p}$ is the volumetric incentive for biomass-derived liquid transportation fuel $p$ sold at demand zone $d$.

The total annual cost ($tc$) is expressed with the following equation.

$$\min \ tc = C_{\text{capital}} + C_{\text{acquisition}} + C_{\text{distribution}} + C_{\text{production}} + C_{\text{transportation}} + C_{\text{storage}} - C_{\text{Incentive}} \qquad (57)$$

We note that government incentive is considered as a credit of the annualized cost.


## 7.3 Environmental objective – minimizing GHG emissions (CO$_2$-equiv/year)

As discussed in Section 4, the environmental objective is to minimize the total annual CO$_2$-equivalent GHG emission (*te*) resulting from the operations of the BTL supply

chains. The formulation of this objective is based on the field-to-wheel life cycle analysis, which takes into account the following life cycle stages of biomass-based liquid transportation fuels:

- Biomass cultivation, growth, and acquisition
- Soil carbon sequestration of biomass feedstocks (emission credit)
- Biomass transportation of from source locations to processing facilities
- Biomass storage at integrated biorefineries and preconversion processes
- Emissions from integrated biorefineries and preconversion facilities
- Transportation of intermediate products from preconversion facilities to intermediate upgrading facilities
- Storage of intermediate products in intermediate upgrading facilities
- Emissions from intermediate upgrading facilities
- Transportation of liquid transportation fuels from integrated biorefineries and intermediate upgrading facilities to the demand zones
- Local distribution of liquid transportation fuels in demand zones
- Emissions from biofuels usage in vehicle operations

We note that carbon uptake resulting from biomass growth offsets the emissions from vehicle operation using biofuels and the emissions from biomass processing.[55] However, the emissions from production processes should include those from utility generation and byproduct (e.g., char) utilization. In addition, carbon sinks (such as soil carbon sequestration) should be taken into account as part of the emission credit in the life cycle analysis.[56] Therefore, the environmental objective accounts for the emissions from biomass acquisition, liquid transportation fuel distribution, biomass conversion and liquid fuel production, feedstock, intermediate and fuel product transportation, and biomass and intermediate storage, as well as emission credits from soil carbon sequestration.[55] This objective is defined in equations (58)–(64):

$$E_{\text{acquisition}} = \sum_b \sum_i \sum_t EBM_{b,i,t} \cdot bmp_{b,i,t} \tag{58}$$

$$E_{\text{distribution}} = \sum_d \sum_p \sum_t ELD_{d,p} \cdot sold_{d,p,t} \tag{59}$$

$$E_{\text{production}} = \sum_j \sum_p \sum_q \sum_t EPJ_{j,q} \cdot \varphi_p \cdot wpj_{j,p,q,t}$$

$$+ \sum_b \sum_k \sum_{q'} \sum_t EPK_{k,q'} \cdot \rho_b \cdot wbk_{b,k,q',t} \, , \tag{60}$$

$$+ \sum_l \sum_p \sum_{q''} \sum_t EPL_{l,q''} \cdot \varphi_p \cdot wpl_{l,p,q'',t}$$

$$E_{\text{transportation}} = \sum_b \sum_i \sum_j \sum_m \sum_t \left( ETRB_{b,m} \cdot DSIJ_{i,j,m} \right) \cdot fij_{b,i,j,m,t}$$

$$+ \sum_b \sum_i \sum_k \sum_m \sum_t \left( ETRB_{b,m} \cdot DSIK_{i,k,m} \right) \cdot fik_{b,i,k,m,t}$$

$$+ \sum_g \sum_k \sum_l \sum_m \sum_t \left( ETRG_{g,m} \cdot DSKL_{k,l,m} \right) \cdot fkl_{g,k,l,m,t} \, , \tag{61}$$

$$+ \sum_d \sum_j \sum_p \sum_m \sum_t \left( ETRP_{m,p} \cdot DSJD_{d,j,m} \right) \cdot fjd_{d,j,p,m,t}$$

$$+ \sum_d \sum_l \sum_p \sum_m \sum_t \left( ETRP_{m,p} \cdot DSLD_{d,l,m} \right) \cdot fld_{d,l,p,m,t}$$

$$E_{\text{storage}} = \sum_b \sum_j \sum_t H_t \cdot EHB_{b,t} \cdot sbj_{b,j,t} + \sum_j \sum_p \sum_t H_t \cdot EHP_{p,t} \cdot spj_{j,p,t}$$

$$+ \sum_b \sum_k \sum_t H_t \cdot EHB_{b,t} \cdot sbk_{b,k,t} + \sum_g \sum_k \sum_t H_t \cdot EHG_{g,t} \cdot sgk_{g,k,t} \, , \tag{62}$$

$$+ \sum_g \sum_l \sum_t H_t \cdot EHG_{g,t} \cdot sgl_{g,l,t} + \sum_l \sum_p \sum_t H_t \cdot EHP_{p,t} \cdot spl_{l,p,t}$$

$$E_{\text{sequestration}} = \sum_b \sum_i \sum_t ESCS_b \cdot bmp_{b,i,t} \, , \tag{63}$$

$$\min \ te = E_{\text{acquisition}} + E_{\text{distribution}} + E_{\text{production}} + E_{\text{transportation}} + E_{\text{storage}} - E_{\text{sequestration}} \tag{64}$$

where $EBM_{b,i,t}$ is the emission of cultivation and acquisition of unit quantity of biomass type $b$ from harvesting site $i$ at time $t$, $ELD_{d,p}$ is the emission due to local distribution of fuel product type $p$ at demand zone $d$, $EPJ_{j,p,q}$ is the emission of producing unit quantity of liquid transportation fuel product type $p$ in integrated biorefinery $j$ with technology $q$, $EPK_{b,k,q'}$ is the emission of processing unit quantity of biomass type $b$ in preconversion facility $k$ with technology $q'$, $EPL_{l,p,q''}$ is the emission of producing unit quantity of liquid transportation fuel product type $p$ in intermediate upgrading facility $l$ with technology $q''$, $ETRB_{b,m}$ is the emission of transporting unit amount of biomass type $b$ for unit distance with transportation mode $m$, $ETRG_{g,m}$ is the emission of transporting unit quantity of intermediate type $g$ for unit distance with transportation mode $m$, $ETRP_{m,p}$ is the emission of transporting unit quantity of fuel product type $p$ for unit distance with transportation mode $m$, $EHB_{b,t}$ is the emission of storing unit quantity of biomass type $b$ at time period $t$,

$EHG_{g,t}$ is the emission of storing unit quantity of intermediate type $g$ at time period $t$, $EHP_{p,t}$ is the emission of storing unit quantity of fuel product type $p$ at time period $t$, and $EECS_b$ is the emission credit of soil carbon sequestration due to biomass type $b$.

The values of these parameters for life cycle inventory are obtained from the Argonne GREET Model,[40] the U.S. Life Cycle Inventory Database,[41] and relevant literature,[11-16, 39] after grouping the GHGs (i.e., $CO_2$, $CH_4$, and $N_2O$) into a single indicator in terms of carbon dioxide equivalent emissions ($CO_2$-equiv/year) by using their respective global warming potentials (GWPs) based on the recommendation of Intergovernmental Panel on Climate Change Fourth Assessment Report for the one-hundred year time horizon as follows: 1 for $CO_2$, 25 for $CH_4$, and 298 for $N_2O$. In other words, one unit of $CH_4$ emission is equivalent to 25 units of $CO_2$ emissions.

# 8. County-Level Case Study for the State of Iowa

To illustrate the application of the proposed framework, we solved a county-level case study for the state of Iowa. All the computational studies were performed on a workstation with Intel Core2 Quad 2.40 GHz CPU and 3.24 GB RAM. The MILP model was coded in GAMS 23.6.3[57] and solved with the solver CPLEX 12 with four processing cores under parallel mode. The optimality tolerances were all set to 0.01%.

## 8.1 Input data

The state of Iowa comprises 99 counties (see Figure 10a). In this case study, each county in Iowa is considered as a harvesting site, a potential location of an integrated biorefinery facility, a possible preconversion facility location, a possible site of intermediate upgrading facility, and a demand zone. In other words, the BTL supply chain network consists of 99 harvesting sites, 99 potential integrated biorefinery site locations facilities, 99 possible locations of preconversion facilities, 99 candidate upgrading facilities, and 99 demand zones.

Three major types of biomass resources are considered in this case study: crop residues (e.g., corn stover), energy crops (e.g., switchgrass and *miscanthus*), and wood residues (e.g., forest residues and primary mills, secondary mills, urban wood residues).

The annual yield of these three types of biomass feedstocks in the 99 counties of Iowa are listed in Table 9 based on the data obtained from the U.S. Department of Agriculture statistical data,[58] and the corresponding spatial distribution in Iowa are shown in Figures 10b–10d. Feedstock deterioration rate is estimated to be 0.5% per month for on-site storage.[37] Some agricultural residues have specific harvesting window per year. For instance, corn stovers are harvested only from early October to the end of November.[59] To investigate the impacts of feedstock supply seasonality, twelve time periods are consider for each year (i.e., one month as a time period). We note that energy crops and wood residues do not have as strong a seasonality as do corn stovers. The farm-to-gate costs of three types of biomass feedstocks are obtained by subtracting the cost of transportation and storage from the 2008 baseline price provided in the study by America's Energy Future Panel on Alternative Liquid Transportation Fuels.[9] Specifically, the farm-to-gate costs for crop residues, energy crops, and wood residues are set to $84.5/tonne, $97.5/tonne, and $50/tonne, respectively.

Two types of liquid fuels products, gasoline and diesel, are produced through the BTL processing network and sold to the demand zones. Their demands in the state of Iowa in each month are obtained from U.S. Energy Information Administration forecasts[5] based on the year 2010 data and are listed in Table 10. We assume that the specific demand in each county (i.e., demand zone) is proportional to the county's population, which is listed in Table 9 based on the Census 2000 data.[60] The map of population density for Iowa is given in Figure 10d. Thus, the upper bound of the demand of each liquid fuel at each county in each month is set to the corresponding consumption amount based on the year 2010 data, and the demand lower bound is assumed to be 50% of the 2010 value.

**Table 9. Population and biomass resources of each county in Iowa**

| FIPS | County | Crop Residues (tonne/year) | Energy Crops (tonne/year) | Wood Residues (tonne/year) | Population |
|------|--------|---------------------------|--------------------------|---------------------------|------------|
| 19001 | Adair | 207544 | 158468 | 37834 | 8243 |
| 19003 | Adams | 120564 | 166910 | 1091 | 4482 |
| 19005 | Allamakee | 104096 | 226698 | 49560 | 14675 |
| 19007 | Appanoose | 62597 | 158696 | 4871 | 13721 |
| 19009 | Audubon | 216326 | 108766 | 795 | 6830 |
| 19011 | Benton | 368006 | 90809 | 36999 | 25308 |
| 19013 | Black Hawk | 275549 | 34417 | 15008 | 128012 |

| 19015 | Boone | 304428 | 36176 | 5669 | 26224 |
|---|---|---|---|---|---|
| 19017 | Bremer | 226666 | 33340 | 3025 | 23325 |
| 19019 | Buchanan | 300105 | 30417 | 2303 | 21093 |
| 19021 | Buena Vista | 329917 | 25583 | 7056 | 20411 |
| 19023 | Butler | 305132 | 77511 | 2363 | 15305 |
| 19025 | Calhoun | 336290 | 52717 | 1332 | 11115 |
| 19027 | Carroll | 321469 | 47399 | 2506 | 21421 |
| 19029 | Cass | 245404 | 117878 | 1850 | 14684 |
| 19031 | Cedar | 292242 | 73358 | 15486 | 18187 |
| 19033 | Cerro Gordo | 312822 | 44694 | 9659 | 46447 |
| 19035 | Cherokee | 300773 | 13891 | 1617 | 13035 |
| 19037 | Chickasaw | 243377 | 65542 | 15343 | 13095 |
| 19039 | Clarke | 59526 | 206227 | 3195 | 9133 |
| 19041 | Clay | 301505 | 33492 | 1977 | 17372 |
| 19043 | Clayton | 213017 | 295081 | 21053 | 18678 |
| 19045 | Clinton | 320323 | 98898 | 7774 | 50149 |
| 19047 | Crawford | 354043 | 66353 | 2174 | 16942 |
| 19049 | Dallas | 263520 | 49043 | 4888 | 40750 |
| 19051 | Davis | 72186 | 241596 | 11716 | 8541 |
| 19053 | Decatur | 63121 | 241743 | 2134 | 8689 |
| 19055 | Delaware | 283351 | 87880 | 8402 | 18404 |
| 19057 | Des Moines | 150372 | 43404 | 8713 | 42351 |
| 19059 | Dickinson | 179179 | 35027 | 1789 | 16424 |
| 19061 | Dubuque | 191066 | 145573 | 18525 | 89143 |
| 19063 | Emmet | 235187 | 37319 | 1809 | 11027 |
| 19065 | Fayette | 327972 | 132667 | 3976 | 22008 |
| 19067 | Floyd | 260402 | 86563 | 2091 | 16900 |
| 19069 | Franklin | 351814 | 49234 | 1290 | 10704 |
| 19071 | Fremont | 224907 | 50682 | 1991 | 8010 |
| 19073 | Greene | 335526 | 34695 | 1251 | 10366 |
| 19075 | Grundy | 335213 | 20635 | 1371 | 12369 |
| 19077 | Guthrie | 201383 | 156035 | 1354 | 11353 |
| 19079 | Hamilton | 347879 | 47378 | 2185 | 16438 |
| 19081 | Hancock | 333900 | 36497 | 1430 | 12100 |
| 19083 | Hardin | 345214 | 42566 | 2616 | 18812 |
| 19085 | Harrison | 296970 | 74289 | 3495 | 15666 |
| 19087 | Henry | 167174 | 148866 | 32984 | 20336 |
| 19089 | Howard | 215784 | 117012 | 2538 | 9932 |
| 19091 | Humboldt | 270367 | 30161 | 2081 | 10381 |
| 19093 | Ida | 226467 | 51874 | 1247 | 7837 |
| 19095 | Iowa | 220610 | 216351 | 7073 | 15671 |
| 19097 | Jackson | 145787 | 236480 | 19636 | 20296 |
| 19099 | Jasper | 343856 | 94227 | 4195 | 37213 |
| 19101 | Jefferson | 130550 | 198519 | 11242 | 16181 |

| 19103 | Johnson | 195808 | 120224 | 12200 | 111006 |
|---|---|---|---|---|---|
| 19105 | Jones | 239388 | 94586 | 4741 | 20221 |
| 19107 | Keokuk | 203545 | 304993 | 8945 | 11400 |
| 19109 | Kossuth | 604964 | 61584 | 1960 | 17163 |
| 19111 | Lee | 144404 | 92621 | 18088 | 38052 |
| 19113 | Linn | 269096 | 70168 | 23226 | 191701 |
| 19115 | Louisa | 148437 | 96454 | 2609 | 12183 |
| 19117 | Lucas | 45888 | 208072 | 1063 | 9422 |
| 19119 | Lyon | 312108 | 21784 | 1992 | 11763 |
| 19121 | Madison | 127743 | 114356 | 1463 | 14019 |
| 19123 | Mahaska | 246873 | 171254 | 3750 | 22335 |
| 19125 | Marion | 150946 | 160286 | 4084 | 32052 |
| 19127 | Marshall | 309358 | 55923 | 4352 | 39311 |
| 19129 | Mills | 193583 | 26035 | 1591 | 14547 |
| 19131 | Mitchell | 254929 | 41826 | 1691 | 10874 |
| 19133 | Monona | 284157 | 53768 | 1543 | 10020 |
| 19135 | Monroe | 51293 | 150847 | 3419 | 8016 |
| 19137 | Montgomery | 179984 | 89557 | 1396 | 11771 |
| 19139 | Muscatine | 169154 | 81653 | 6157 | 41722 |
| 19141 | O'Brien | 341767 | 21218 | 2237 | 15102 |
| 19143 | Osceola | 241731 | 38522 | 1153 | 7003 |
| 19145 | Page | 201928 | 134512 | 2039 | 16976 |
| 19147 | Palo Alto | 314439 | 54312 | 1319 | 10147 |
| 19149 | Plymouth | 422151 | 75312 | 2835 | 24849 |
| 19151 | Pocahontas | 354739 | 27673 | 1079 | 8662 |
| 19153 | Polk | 179825 | 24249 | 43392 | 374601 |
| 19155 | Pottawattamie | 445937 | 54002 | 13259 | 87704 |
| 19157 | Poweshiek | 271145 | 146602 | 3598 | 18815 |
| 19159 | Ringgold | 83221 | 337081 | 1632 | 5469 |
| 19161 | Sac | 308539 | 24837 | 1465 | 11529 |
| 19163 | Scott | 206671 | 23041 | 66769 | 158668 |
| 19165 | Shelby | 311662 | 47291 | 1454 | 13173 |
| 19167 | Sioux | 453357 | 29905 | 3729 | 31589 |
| 19169 | Story | 328499 | 31293 | 8626 | 79981 |
| 19171 | Tama | 334399 | 157129 | 4192 | 18103 |
| 19173 | Taylor | 128359 | 319619 | 1374 | 6958 |
| 19175 | Union | 98472 | 155964 | 1363 | 12309 |
| 19177 | Van Buren | 87570 | 162833 | 20381 | 7809 |
| 19179 | Wapello | 109296 | 111722 | 6753 | 36051 |
| 19181 | Warren | 131862 | 165332 | 4389 | 40671 |
| 19183 | Washington | 224597 | 226802 | 7827 | 20670 |
| 19185 | Wayne | 91601 | 328388 | 1209 | 6730 |
| 19187 | Webster | 403869 | 42473 | 4827 | 40235 |
| 19189 | Winnebago | 249421 | 65144 | 1304 | 11723 |

| 19191 | Winneshiek | 222642 | 195607 | 5915 | 21310 |
|---|---|---|---|---|---|
| 19193 | Woodbury | 356178 | 158457 | 11796 | 103877 |
| 19195 | Worth | 218520 | 39349 | 824 | 7909 |
| 19197 | Wright | 361208 | 64682 | 1940 | 14334 |

**Table 10. Monthly demands of gasoline and diesel in Iowa (year 2010 data)**

|  | **Gasoline** (MM gallons) | **Diesel** (MM gallons) |
|---|---|---|
| **January** | 94.2028 | 48.33153 |
| **February** | 101.9844 | 50.53522 |
| **March** | 114.1637 | 75.1936 |
| **April** | 115.686 | 79.42119 |
| **May** | 121.5851 | 74.61183 |
| **June** | 122.706 | 75.32403 |
| **July** | 124.5177 | 71.67408 |
| **August** | 124.2139 | 77.12414 |
| **September** | 118.818 | 82.19698 |
| **October** | 118.048 | 87.94998 |
| **November** | 109.665 | 71.34221 |
| **December** | 120.9496 | 61.76514 |

**Table 11  Capacities, total capital investments and yields of the six reference plants**

|  | Technology | Capacity | Capital Investment | Yields |
|---|---|---|---|---|
| Integrated conversion | Biomass gasification + FT synthesis | 35.0 MM GEG/year | $341.00 MM | 21.64 gallons of gasoline/ton of biomass<br>44.18 gallons of diesel/ton of biomass |
|  | Biomass pyrolysis + hydroprocessing | 35.4 MM GEG/year | $287.40 MM | 41.01 gallons of gasoline/ton of biomass<br>9.48 gallons of diesel/ton of biomass |
| Biomass pre-conversion | Rotating cone reactor pyrolysis | 200,750 ton/year | $31.67 MM | 143.60 gallons of bio-oil/ton of biomass |
|  | Fluidized bed reactor pyrolysis | 200,750 ton/year | $47.80 MM | 0.8318 tons of bio-slurry/ton of biomass |
| Intermediate upgrading | Bio-oil to FT liquids | 35 MM GEG/year | $185.62 MM | 0.0831 gallons of gasoline/gallon of bio-oil<br>0.1696 gallons of diesel/gallon of bio-oil |
|  | Bio-slurry to FT liquids | 35 MM GEG/year | $269.40 MM | 0.4810 gallons of gasoline/ton of bio-slurry<br>0.9822 gallons of diesel/ton of bio-slurry |

**Table 12  Emission data taken from the GREET model  on feedstock acquisition and transportation**

|  | Species | $CO_2$-equivalent emission |
|---|---|---|
| Feedstock acquisition | Crop residues | 0.139220 kg/dry kg biomass |
|  | Energy crops | 0.137800 kg/dry kg biomass |
|  | Wood residues | 0.069218 kg/dry kg biomass |
| Transportation | Truck | 0.068546 kg/ (ton·km) |

| | |
|---|---|
| Rail | 0.023048 kg/ (ton·km) |
| Pipeline | 0.016315 kg/ (ton·km) |

In this case study, we consider two integrated conversion method (gasification + FT synthesis and pyrolysis + hydroprocessing), two preconversion technologies (rotating cone reactor pyrolysis and fluidized bed reactor pyrolysis), and two types of intermediate upgrading facilities (bio-oil to FT liquids and bio-slurry to FT liquids). Three capacity levels are considered for each of the two integrated conversion facilities, with capacities ranges of 0–50 MM GEG/year, 50–100 MM GEG/year, and 100–200 MM GEG/year, respectively. The two types of preconversion facilities also have three capacity levels each, with capacities ranges of 0–0.5 MM dry ton/year, 0.5–1 MM dry ton/year, and 1–2 MM dry ton/year. We also consider three capacity levels, which have ranges of 0–50 MM GEG/year, 50–100 MM GEG/year, and 100–200 MM GEG/year, for the intermediate upgrading facilities. As in the illustrative example, reference plants based on literature data[11-14, 16, 39, 43] and a scale factor of 0.6 are used to calculate the capital cost of conversion facilities with the maximum and minimum capacities of each capacity level. The capacities, total capital investments, and yields of the six reference plants are listed in Table 11. The total capital investment costs of the six types of conversion facilities in each capacity level are then modeled through Equations (12), (13), (26), (29), (41), and (44) based on piecewise linear cost curve, so that economy of scale can be taken into account.

The distance between each pair of counties is obtained from Google Maps[61] by using the center points of the counties. Three major transportation modes (rail, trucks, and pipelines) are considered. Cost data related to transportation are obtained from Searcy et al.[47] and Mahmud and Flynn.[62] The safety storage periods for all the conversion facilities were set to 7 days for all concepts. The unit inventory cost for crop residues and energy crops is $2.07/(dry ton·day), and the unit storage cost of wood residues is set to $1.53/(dry ton·day).[63] Emission data related to transportation, storage, distribution, and biomass production is taken from the GREET model[40] developed at Argonne National Laboratory; some of the data are listed in Table 12. Emission data related to biofuel production are obtained from the design reports by Swanson et al.[11, 14] and by Wright et al.[12, 45] Other unlisted input data are available upon request.
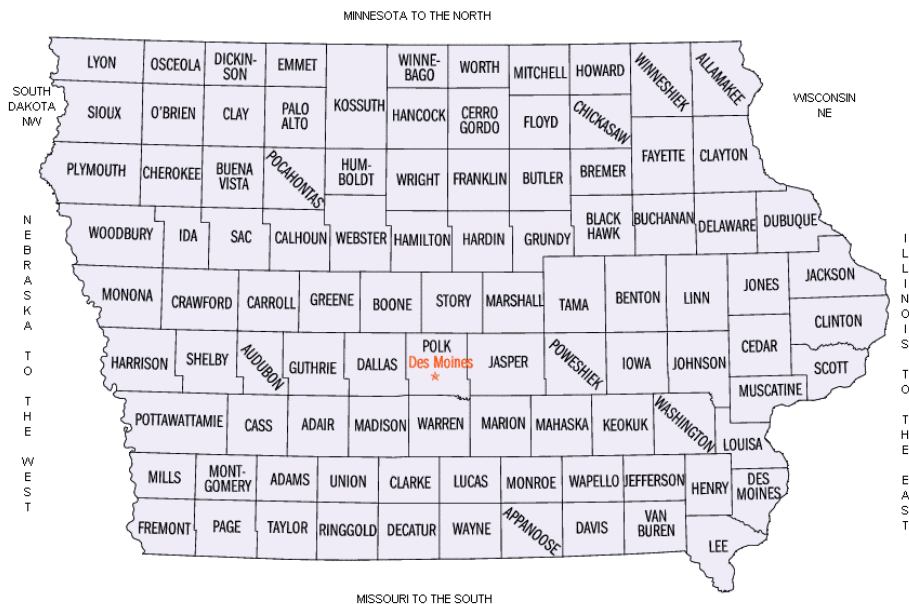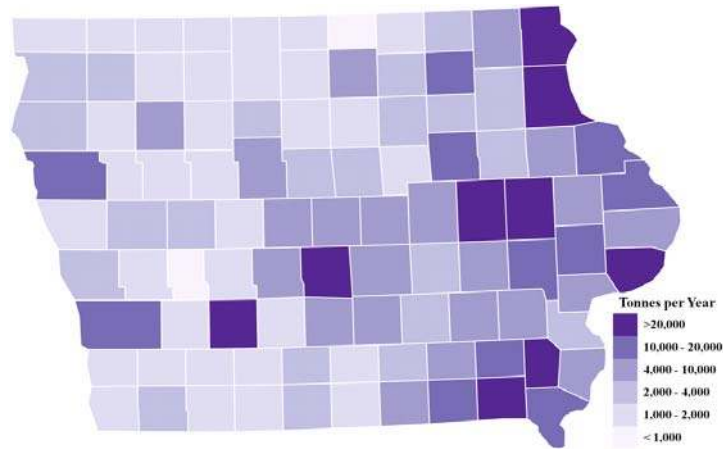
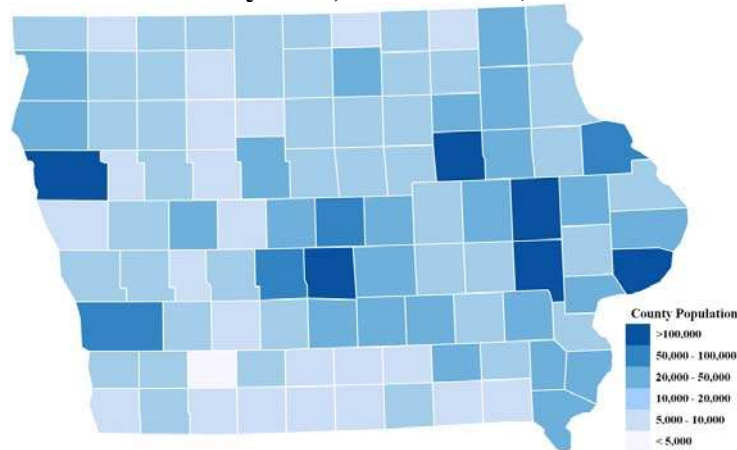**(a) The 99 counties in the state of Iowa**
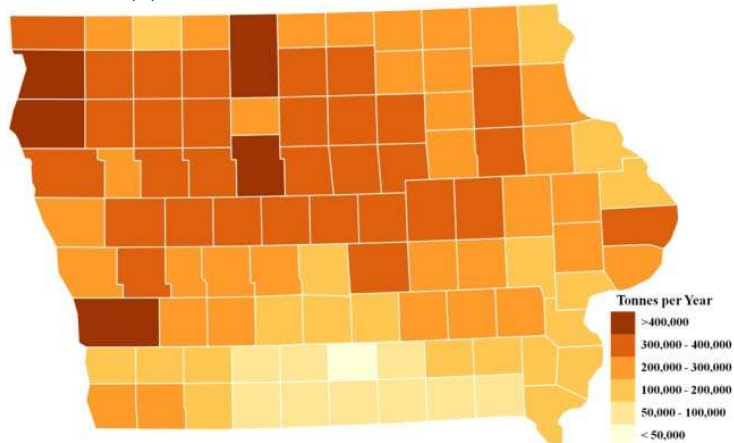


**(b) Spatial distribution of crop residues (e.g., corn stovers) in Iowa**
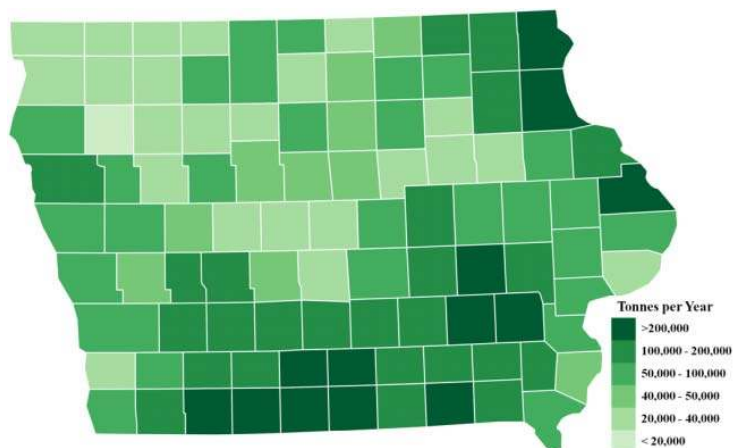


**(c) Spatial distribution of energy crops (e.g., switchgrass and miscanthus) in Iowa**

**(d) Spatial distribution of wood residues (e.g., forest and primary mill residues, secondary mills, urban woods) in Iowa**



**(e) Population distribution of Iowa**

**Figure 10. County-level distribution of biomass resources and the population density in Iowa.**

## 8.2 Results and Discussions

To simultaneously optimize the economic and environmental performances of the BTL supply chains, we solve the multiobjective optimization problem with the $\varepsilon$–constraint method. The resulting bicriterion MILP problem includes 1,782 binary variables, 4,294,326 continuous variables, and 772,506 constraints. The first step of the $\varepsilon$–constraint method is to determine the optimal lower and upper bounds of the annual $CO_2$-equivalent GHG emission. The lower bound is obtained by minimizing (64) subject to constraints (1)–(63). To obtain the Pareto-optimal upper bound, we solve an optimization problem with constraints (1)–(64) and the following objective function:

$$\min : tc + \chi \cdot te \ , \tag{65}$$

where $\chi$ is a very small value (on the order of $10^{-6}$). In the last step, we fix $\varepsilon$ to 20 values with identical intervals between the upper and lower bounds of the annual GHG emission and add the following constraint to the model, with the objective of minimizing (57).

$$te \leq \varepsilon \tag{66}$$

In this way we obtain an approximation of the Pareto-optimal curve for the proposed model, together with the optimal solutions for different values of GHG emissions. The entire solution process takes a total of 3,815,104 CPU-seconds (around 1,060 CPU-hours) for all 22 instances. The resulting Pareto curve is given in Figure 11.
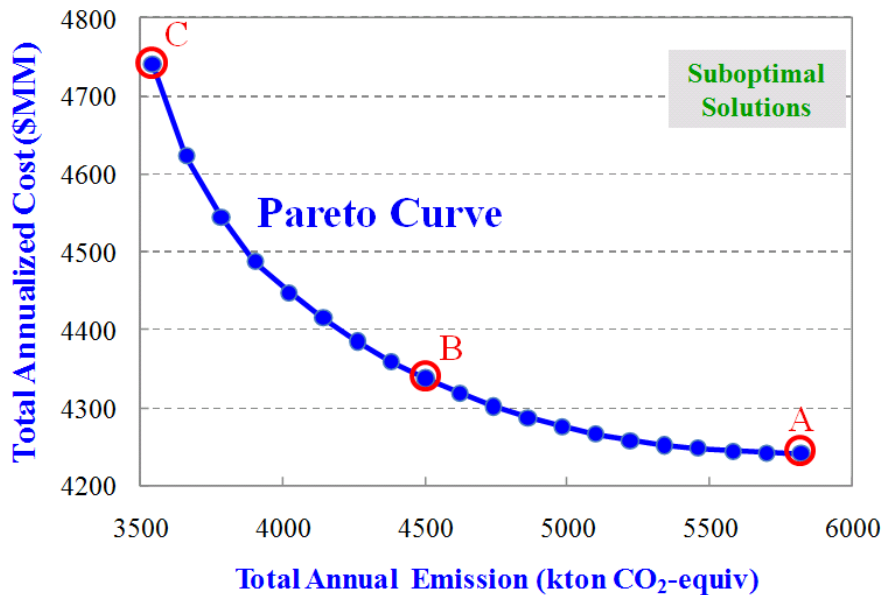


**Figure 11. Pareto curve showing tradeoff between economic and environmental performances of the BTL supply chain**

For this bi-criterion optimization problem, all the optimal solutions that take into account the economic and environmental objectives lie on the Pareto curve. Thus, the solutions above the curve in Figure 11 are suboptimal solutions, and any solution below this curve is infeasible. We can see from Figure 11 that as the optimal total annualized cost reduces from around $4,732 MM to around $4,233MM, the annual GHG emissions resulting from the operation of the BTL supply chain increases from around 3,543 Kton

CO$_2$-equiv to around 5,821 Kton CO$_2$-equiv. The trend of this Pareto curve reveals the tradeoff between economics and environmental performances, and shows that the lower the total annualized cost is, the more GHG emissions are resulted from the operation of the BTL supply chain. In particular, the unit supply chain costs of biomass-derived liquid fuels in points A, B and C are \$3.60/GEG, \$3.68/GEG and \$4.02/GEG, respectively, while their corresponding total annual GHG emissions are 5,821 Kton/CO$_2$-eq, 4,502 Kton/CO$_2$-eq, and 3,543 Kton/CO$_2$-eq, respectively. We can see that from point A to point B, the annual GHG emissions have been significantly reduced, while there is only small increase of the total unit fuel cost. It implies that the design of point B might be a "good choice" solution. We note that the annualized cost has taken into account government incentives, which include biorefinery construction incentives and volumetric incentives for fuel production (e.g. \$1.01/gallon for cellulosic biofuels and \$1.00/gallon for biodiesel).[64] The optimal number, size, location and technology selection of the all conversion processes for these three solutions are given in Figures 12-14.
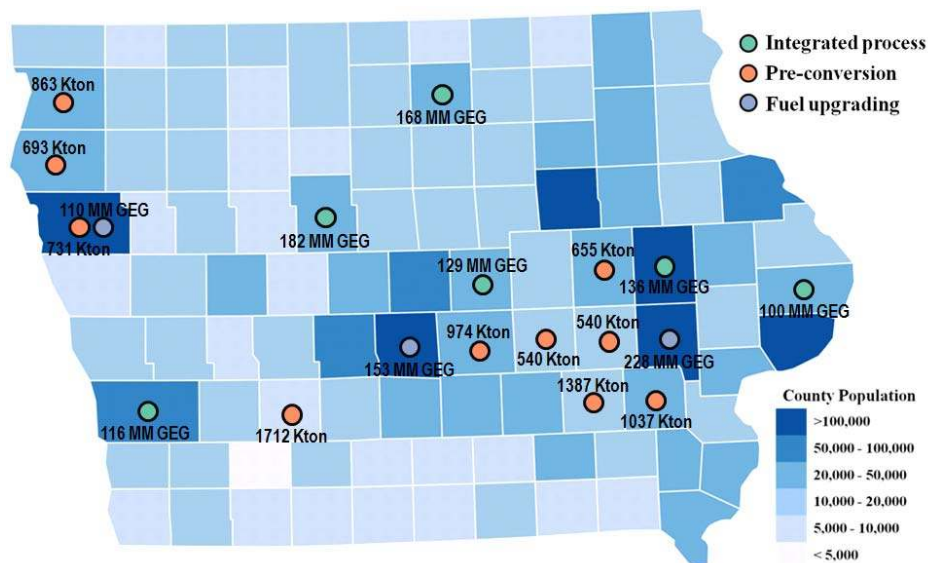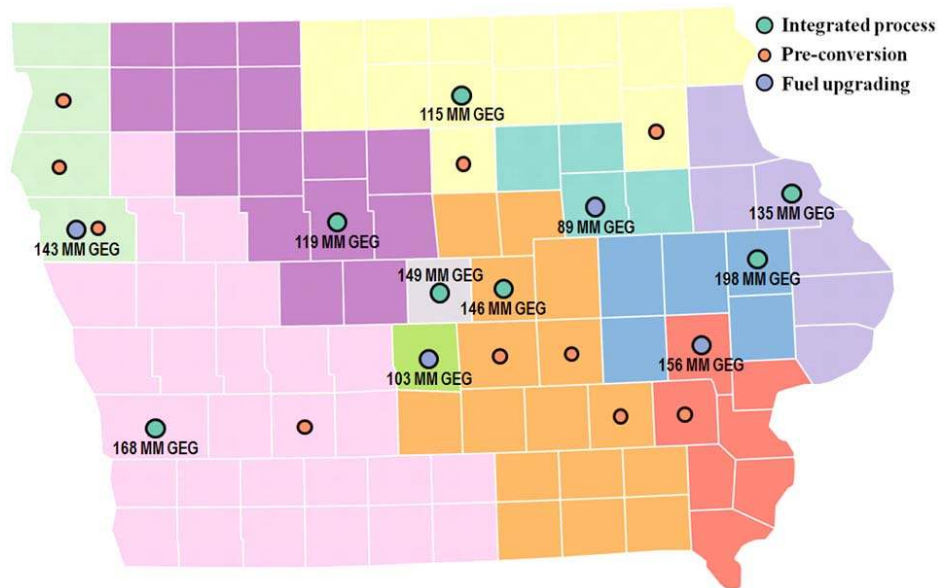


**Figure 12. Optimal plant types, locations, and capacities of the BTL supply chain for the minimum cost solution (point A of Figure 11). Background is the population distribution in Iowa.**
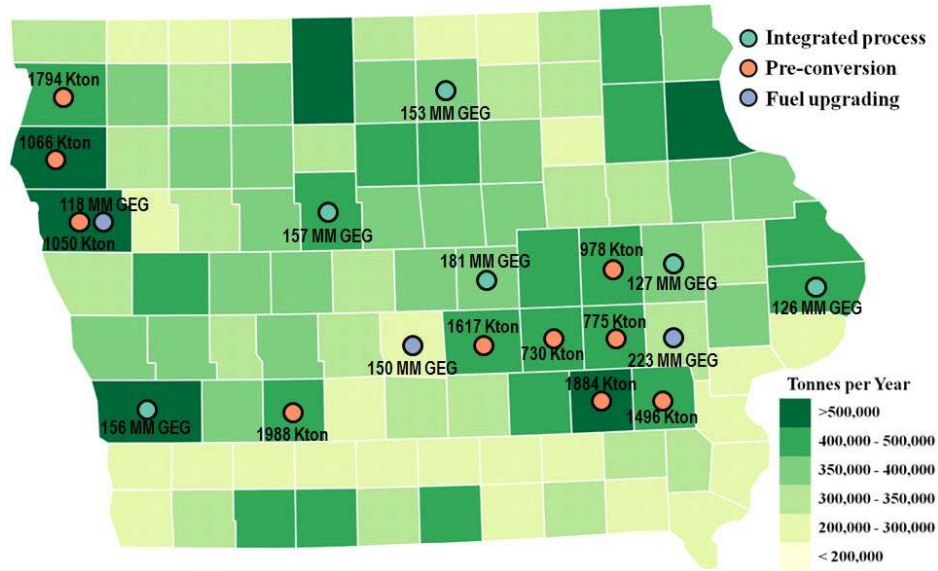
**Figure 13. Optimal plant types, locations, and capacities of the BTL supply chain for the "best choice" solution (point B of Figure 11). Background is the map for total biomass resources distribution in Iowa.**



**Figure 14. Optimal plant types, locations and capacities of the BTL supply chain for the minimum emission solution (point C of Figure 11). Background is a map for the serving areas of integrated conversion facilities and fuel upgrading facilities.**

Figure 12, which has the population density map as the background, is for the optimal BTL supply chain design for the minimum cost solution, corresponding to point A in Figure 11. We can see that in this case six integrated conversion facilities are built, with

capacities ranges from 100 MM GEG/year to 182 MM GEG/year. All the integrated conversion facilities in this case select the conversion technology of fast pyrolysis followed by hydroprocessing, because this technology has a relatively higher yield of gasoline, the demand for which is larger than for diesel in Iowa (see Tables 10 and 11). We can also see from this figure that 12 preconversion facilities and 3 fuel upgrading facilities are selected to be built. All the preconversion facilities utilize fluidized bed reactor pyrolysis, with capacities ranges from 540 Kton/year to 1712 Kton/year. Consequently, all the fuel upgrading facilities convert bio-slurry into FT liquids, with capacities rangeing from 110 MM GEG/year to 228 MM GEG/year. We note that all the integrated conversion facilities and fuel upgrading facilities are located in counties with relatively large population and that the preconversion facilities are usually in counties near the ones for fuel upgrading facilities. Such location decisions certainly lead to lower average transportation distance of intermediates and liquid transportation fuels.

In Figure 13, we show the optimal BTL supply chain design of the "good choice" solution (as point B in Figure 11) with a map of total biomass resources distribution in Iowa as the background. We observe that all the plant location and technology selection decisions are the same as the minimum cost solution, although the optimal sizes of the plant change. We can also see that preconversion facilities and integrated conversion facilities are located in counties with abundant biomass resources. As a result, both emission of biomass resources (which has relatively low density) and transportation cost can be reduced.

Figure 14 shows the optimal locations of the conversion processes, each plant's capacity and conversion technology, and the counties primarily supplied by the integrated conversion facilities or fuel upgrading facilities for the minimum emission solution (point C of Figure 11). We can see that there are 7 integrated conversion facilities, all using the technology of fast pyrolysis followed by hydroprocessing, with capacities ranging from 115 MM GEG to 198 MM GEG. In addition, 10 preconversion processes are built to produce bio-slurry, which are shipped to 4 fuel upgrading facilities with capacities ranging from 89 MM GEG to 156 MM GEG for the production of liquid fuels. More conversion facilities are selected to install in this case than in the previous two cases. Although the capital cost increases as the number of plants increases, because of

economy of scale, the average transportation distance for feedstock and fuel products is significantly reduced. Moreover, the shorter average transportation distance also leads to a reduction of total GHG emissions, since road transportation is the major mode for shipping feedstocks and intermediates. Figure 14 also shows the service area of each fuel production facility (integrated conversion facilities or fuel upgrading facilities). We note that if a county is supplied by more than one fuel production facilities, we consider this county to be served by its major supplier in terms of GEG. Similarly, the service areas of fuel production processes reveal the tradeoffs among capital, production, storage, and transportation cost.

The optimal designs of the three solutions have similarities. For instance, biomass conversion plants are usually located in the counties with abundant cellulosic biomass resources, whereas fuel production processes are usually closer to the counties with large population. Such facility location decisions are mainly due to the lower transportation density of cellulosic biomass resources and their high unit transportation costs and emissions.
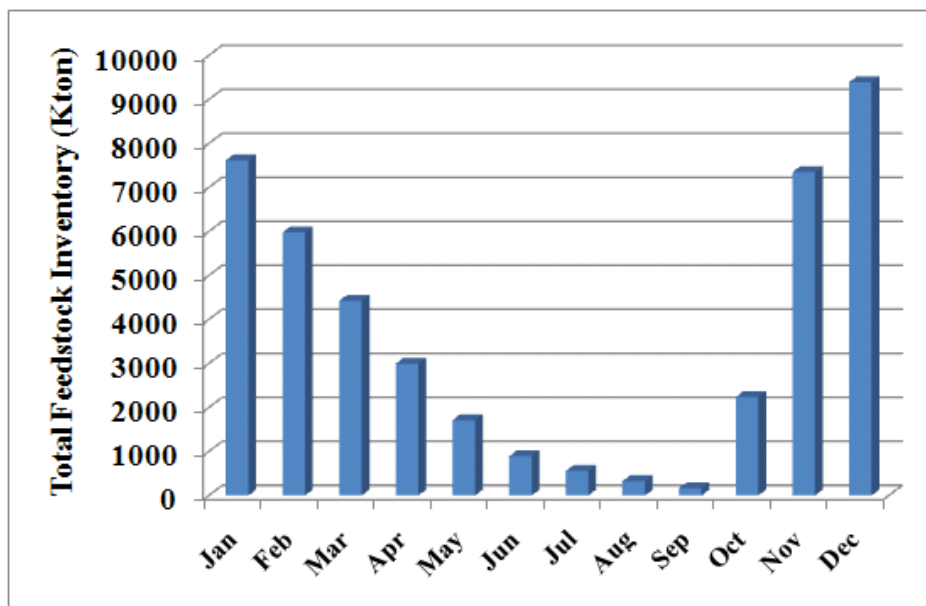


**Figure 15. Total inventory of feedstocks in each month for case study 1.**
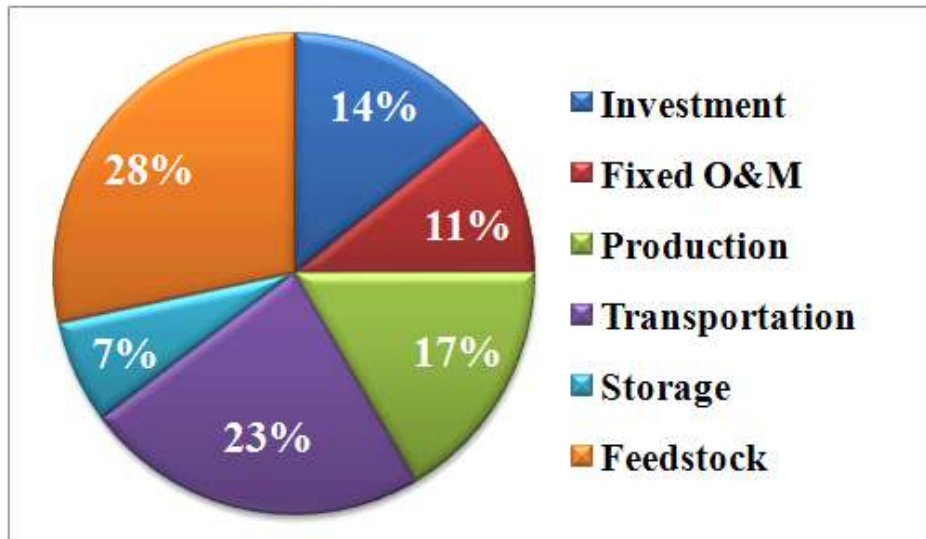
**Figure 16. Cost breakdown for case study 1.**

The total inventory level for all the feedstock biomass sources in each month for the "good choice" solution (Point B in Figure 11) is given in Figure 15. As corn stovers contribute a significant amount of the total biomass resources in Iowa, we can see there is a strong seasonality in the inventory profile. The total inventory level first increases from the minimum around 100 Kton in September to the maximum of around 9,000 Kton in December, and then decreases to the minimum in September next year. This trend is due to the harvesting season of corn stovers, which is a byproduct of corn harvesting from October to November every year. Because of the capacity limit, however, not all the feedstocks harvested from October to November can be converted to liquid transportation fuels or intermediate. Another reason is that each fuel production plant, once it is installed, should maintain a minimum production level. Thus, a significant proportion of the agricultural residues are stored in order to keep down the installation sizes of the plants and avoid supply/production disruption.

Figure 16 shows the breakdown of the total cost for the "good choice" solution (Point B in Figure 11). We can see the total capital investment (after considering incentives), fixed O&M and variable production cost contribute around 14%, 11%, and 17% of the total cost, respectively. Feedstock acquisition cost and transportation cost both contribute around a quarter of the total cost, while the cost for storage consists of only 7%. The results shown in Figure 16 suggest that conversion efficiency and equipment utilization,

contributing to 42% of the total cost, are the bottlenecks to reducing the biomass-derived liquid transportation fuel cost. It is therefore of great importance to develop advanced conversion processes to reduce both capital and variable production costs.

## 9. Conclusions

In this paper, we developed a MILP approach for the design and planning of BTL supply chains under economic and environmental criteria. A multiobjective, multiperiod MILP model was developed that takes into account the main characteristics of BTL supply chains, such as seasonality of feedstock supply, biomass deterioration with time, geographical diversity and availability of biomass resources, moisture content, diverse conversion pathways and technologies, infrastructure compatibility, demand distribution, and government incentives. The optimization model integrates decision making across multiple temporal and spatial scales and simultaneously predicts the optimal network design, facility location, technology selection, capital investment, production operations, inventory control, and logistics management decisions. In addition to the economic objective of minimizing the annualized total cost, the MILP model is integrated through a multiobjective optimization scheme to include another objective of minimizing the life-cycle GHG emissions. The multiobjective optimization problem is solved with an ε-constraint method and produces Pareto-optimal curves that reveal how the optimal annualized cost, biomass processing, and liquid fuel production network structures change with different environmental performance of the BTL supply chain. The proposed optimization approach is illustrated through two case studies for the county-level BTL supply chain for the state of Iowa. The results show that improving the conversion technologies is the key issue in overcoming the barrier of commercializing biomass-derived liquid transportation fuels.

An important future research direction is to consider the many types of uncertainty involved in the BTL supply chain, such as liquid fuel demand fluctuation, feedstock supply disruption, and changes of governmental incentives. Investigating the impacts of different types of uncertainty and risks will be important to the design and operations of robust BTL supply chains. The development of efficient decomposition-based optimization algorithms for solving large-scale instances (e.g., a nationwide, county-level

study that allows the feedstocks and liquid fuels to be transported across the state borders, or alternative discretization strategies that lead to higher geographical resolution) can be another focus of future research.

## Acknowledgment

## Nomenclature

| | |
|---|---|
| $B$ | Set of biomass feedstocks indexed by $b$ |
| $D$ | Set of demand zones indexed by $d$ |
| $G$ | Set of intermediate products (e.g., bio-oil, bio-slurry) indexed by $g$ |
| $I$ | Set of harvesting sites indexed by $i$ |
| $J$ | Set of centralized integrated biorefinery facilities indexed by $j$ |
| $K$ | Set of preconversion facilities indexed by $k$ |
| $L$ | Set of intermediate upgrading facilities indexed by $l$ |
| $M$ | Set of transportation modes indexed by $m$ |
| $P$ | Set of final products (e.g., gasoline, diesel) indexed by $p$ |
| $Q$ | Set of biomass conversion or liquid transportation fuels production technologies indexed by $q, q', q''$ |
| $R$ | Set of capacity levels of (pre)conversion facilities indexed by $r$ |
| $T$ | Set of time periods indexed by $t, t'$ |

**Parameters**

| | |
|---|---|
| $BA_{b,i,t}$ | Available amount of biomass type $b$ in harvesting site $i$ at time period $t$ |
| $CBM_{b,i,t}$ | Farm-gate cost of biomass feedstock type $b$ from harvesting site $i$ at time $t$ |
| $CFJ_{j,q}$ | Fixed annual O&M cost as the percentage of the total investment cost of integrated biorefinery $j$ with technology $q$ |
| $CFK_{k,q'}$ | Fixed annual O&M cost as the percentage of the total investment cost of preconversion facility $k$ with technology $q'$ |
| $CFL_{l,q''}$ | Fixed annual O&M cost as the percentage of the total investment cost of intermediate upgrading facility $l$ with technology $q''$ |
| $CLD_{d,p}$ | Local distribution cost of unit quantity of fuel product $p$ at demand zone $d$ |
| $CPJ_{j,q}$ | Net unit production cost per gallon of gasoline equivalent of liquid |

|  |  |
|---|---|
|  | transportation fuel in integrated biorefinery $j$ with technology $q$ (after considering charcoal credit) |
| $CPK_{k,q'}$ | Net unit production cost per dry ton of standard biomass in preconversion facility $k$ with technology $q'$ (after considering charcoal credit) |
| $CPL_{l,q''}$ | Net unit production cost per gallon of gasoline equivalent of liquid transportation fuel in intermediate upgrading facility $l$ with technology $q''$ (after considering charcoal credit) |
| $CRJ_{j,q,r}$ | Total capital investment of integrated biorefinery $j$ with technology $q$ and capacity level $r$ |
| $CRK_{k,q',r}$ | Total capital investment of preconversion facility $k$ with technology $q'$ and capacity level $r$ |
| $CRL_{l,q'',r}$ | Total capital investment of intermediate upgrading facility $l$ with technology $q''$ and capacity level $r$ |
| $DEM_{d,p,t}^{L}$ | Lower bound of the demand for fuel product $p$ at demand zones $d$ at time $t$ |
| $DEM_{d,p,t}^{U}$ | Upper bound of the demand for fuel product $p$ at demand zones $d$ at time $t$ |
| $DFCB_{b,m}$ | Distance fixed cost of biomass type $b$ with transportation mode $m$ |
| $DFCG_{g,m}$ | Distance fixed cost of intermediate type $g$ with transportation mode $m$ |
| $DFCP_{m,p}$ | Distance fixed cost of fuel product type $p$ with transportation mode $m$ |
| $DSIJ_{i,j,m}$ | Distance from harvesting site $i$ to integrated biorefinery $j$ with transportation mode $m$ |
| $DSIK_{i,k,m}$ | Distance from harvesting site $i$ to preconversion facility $k$ with transportation mode $m$ |
| $DSJD_{d,j,m}$ | Distance from integrated biorefinery $j$ to demand zones $d$ with transportation mode $m$ |
| $DSKL_{k,l,m}$ | Distance from preconversion facility $k$ to intermediate upgrading facility $l$ with transportation mode $m$ |
| $DSLD_{d,l,m}$ | Distance from intermediate upgrading facility $l$ to demand zones $d$ with transportation mode $m$ |
| $DVCB_{b,m}$ | Distance variable cost of biomass type $b$ with transportation mode $m$ |
| $DVCG_{g,m}$ | Distance variable cost of intermediate type $g$ with transportation mode $m$ |
| $DVCP_{m,p}$ | Distance variable cost of fuel product type $p$ with transportation mode $m$ |
| $EBM_{b,i,t}$ | Emission due to cultivation and acquisition of unit quantity of biomass feedstock type $b$ from harvesting site $i$ at time $t$ |
| $EHB_{b,t}$ | Unit emission of storing unit quantity of biomass type $b$ at time period $t$ |

$EHG_{g,t}$    Unit emission of storing unit quantity of intermediate type $g$ at time period $t$

$EHP_{p,t}$    Unit emission of storing unit quantity of fuel product type $p$ at time period $t$

$ELD_{d,p}$    Emission due to local distribution of fuel product type $p$ at demand zone $d$

$EPJ_{j,q}$    Emission of producing a gallon of gasoline equivalent of liquid transportation fuel in integrated biorefinery $j$ with technology $q$

$EPK_{k,q'}$    Emission of processing a dry ton of standard biomass in preconversion facility $k$ with technology $q'$

$EPL_{l,q''}$    Emission of producing a gallon of gasoline equivalent of liquid transportation fuel in intermediate upgrading facility $l$ with technology $q''$

$ESCS_{b}$    Emission credit of soil carbon sequestration due to biomass type $b$

$ETRB_{b,m}$    Emission of transporting unit amount of biomass type $b$ for unit distance with transportation mode $m$

$ETRG_{g,m}$    Emission of transporting unit amount of intermediate type $g$ for unit distance with transportation mode $m$

$ETRP_{m,p}$    Emission of transporting unit amount of fuel product type $p$ for unit distance with transportation mode $m$

$H_{t}$    Duration of time period $t$

$HBJ_{b,j,t}$    Unit inventory holding cost of biomass type $b$ in integrated biorefinery $j$ at time $t$

$HBK_{b,k,t}$    Unit inventory holding cost of biomass type $b$ in preconversion facility $k$ at time $t$

$HGK_{g,k,t}$    Unit inventory holding cost of intermediate type $g$ in preconversion facility $k$ at time $t$

$HGL_{g,l,t}$    Unit inventory holding cost of intermediate type $g$ in intermediate upgrading facility $l$ at time $t$

$HPJ_{j,p,t}$    Unit inventory holding cost of fuel product type $p$ in biorefinery $j$ at time $t$

$HPL_{l,p,t}$    Unit inventory holding cost of fuel product type $p$ at intermediate upgrading facility $l$ at time $t$

$HY$    Production time duration of a year

$INCM$    Maximum incentive that can be provided for the construction of biomass conversion facilities

$INCP$    Maximum percentage of the construction cost of biomass conversion facilities that can be covered by government incentive

$INCV_{d,p}$    Volumetric production incentive of fuel product type $p$ sold to demand zone $d$

$IR$    Discount rate

| | |
|---|---|
| $MC_b$ | Moisture content (in weight) of biomass type $b$ |
| $NJ_q$ | Maximum number of integrated biorefineries with technology $q$ that can be constructed |
| $NK_{q'}$ | Maximum number of preconversion facilities with technology $q'$ that can be constructed |
| $NL_{q''}$ | Maximum number of intermediate upgrading facilities with technology $q''$ that can be constructed |
| $NY$ | Project lifetime in terms of years |
| $PRJ_{j,q,r}$ | Upper bound of the capacity (in terms of gallons of gasoline equivalent) of integrated biorefinery $j$ with technology $q$ and capacity level $r$ |
| $PRK_{k,q',r}$ | Upper bound of the capacity (in terms of dry tons of standard biomass) of preconversion facility $k$ with technology $q'$ and capacity level $r$ |
| $PRL_{l,q'',r}$ | Upper bound of the capacity (in terms of gallons of gasoline equivalent) of intermediate upgrading facility $l$ with technology $q''$ and capacity level $r$ |
| $SJ_{j,t}$ | Safety stock inventory that should be hold to cover the production shortage in integrated biorefinery $j$ at time $t$ |
| $SK_{k,t}$ | Safety stock inventory that should be hold to cover the production shortage in preconversion facility $k$ at time $t$ |
| $SL_{l,t}$ | Safety stock inventory that should be hold to cover the production shortage in intermediate upgrading facility $l$ at time $t$ |
| $WCIJ_{i,j,m,t}$ | Weight capacity for the transportation of biomass from harvesting site $i$ to integrated biorefinery $j$ with transportation mode $m$ at time period $t$ |
| $WCIK_{i,k,m,t}$ | Weight capacity for the transportation of biomass from harvesting site $i$ to preconversion facility $k$ with transportation mode $m$ at time period $t$ |
| $MDS_{g,m,t}$ | Maximum allowable transportation distance (due to the stability) of intermediate type $g$ with transportation mode $m$ at time period $t$ |
| $\alpha_{b,p,q}$ | Yield of fuel product $p$ converted from unit quantity of biomass feedstock type $b$ at integrated biorefineries with technology $q$ |
| $\beta_{b,g,q'}$ | Yield of intermediate $g$ converted from unit quantity of biomass feedstock type $b$ at preconversion facilities with technology $q'$ |
| $\gamma_{g,p,q''}$ | Yield of fuel product $p$ converted from unit quantity of intermediate type $g$ at intermediate upgrading facilities with technology $q''$ |
| $\varepsilon_{b,t}$ | Percentage of biomass type $b$ deteriorated in storage facility at time $t$ |
| $\theta_{j,q}$ | Minimum production amount as a percentage of capacity for integrated biorefinery $j$ with conversion technology $q$ |

| | |
|---|---|
| $\eta_{l,q''}$ | Minimum production amount as a percentage of capacity for intermediate upgrading facility $l$ with technology $q''$ |
| $\varphi_p$ | Gasoline-equivalent gallons of one gallon of fuel product $p$ |
| $\rho_b$ | Mass quantity of standard dry biomass of one dry ton of biomass type $b$ |

**Integer Variables**

| | |
|---|---|
| $x_{j,q,r}$ | 0–1 variable, equal to 1 if an integrated biorefinery with technology $q$ and capacity level $r$ is located at site $j$ |
| $y_{k,q',r}$ | 0-1 variable, equal to 1 if a preconversion facility with technology $q'$ and capacity level $r$ is located at site $k$ |
| $z_{l,q'',r}$ | 0-1 variable, equal to 1 if an intermediate upgrading facility with technology $q''$ and capacity level $r$ is located at site $l$ |

**Continuous Variables (0 to $+\infty$)**

| | |
|---|---|
| $bmp_{b,i,t}$ | Amount of biomass type $b$ procured from harvesting site $i$ in time period $t$ |
| $capj_{j,q,r}$ | Annual production capacity (in terms of gallons of gasoline equivalent) of integrated biorefinery $j$ with technology $q$ and capacity level $r$ |
| $capk_{k,q',r}$ | Annual production capacity (in terms of dry tons of standard biomass) of preconversion facility $k$ with technology $q'$ and capacity level $r$ |
| $capl_{l,q'',r}$ | Annual production capacity (in terms of gallons of gasoline equivalent) of intermediate upgrading facility $l$ with technology $q''$ and capacity level $r$ |
| $fij_{b,i,j,m,t}$ | Amount of biomass type $b$ shipped from harvesting site $i$ to biorefinery $j$ with transportation mode $m$ in time $t$ |
| $fik_{b,i,k,m,t}$ | Amount of biomass type $b$ shipped from harvesting site $i$ to preconversion facility $k$ with transportation mode $m$ in time $t$ |
| $fjd_{d,j,p,m,t}$ | Amount of fuel product type $p$ shipped from biorefinery $j$ to demand zones $d$ with transportation mode $m$ in time $t$ |
| $fkl_{g,k,l,m,t}$ | Amount of intermediate type $g$ shipped from preconversion facility $k$ to intermediate upgrading facility $l$ with transportation mode $m$ in time $t$ |
| $fld_{d,l,p,m,t}$ | Amount of fuel product type $p$ shipped from intermediate upgrading facility $l$ to demand zones $d$ with transportation mode $m$ in time $t$ |
| $incj_j$ | Incentive received for the construction of integrated biorefinery $j$ |
| $inck_k$ | Incentive received for the construction of preconversion facility $k$ |
| $incl_l$ | Incentive received for the construction of intermediate upgrading facility $l$ |
| $sbj_{b,j,t}$ | Storage level of biomass type $b$ in integrated biorefinery $j$ at time $t$ |

$sbk_{b,k,t}$      Storage level of biomass type $b$ in preconversion facility $k$ at time $t$

$sgk_{g,k,t}$      Storage level of intermediate type $g$ in preconversion facility $k$ at time $t$

$sgl_{g,l,t}$      Storage level of intermediate type $g$ in intermediate upgrading facility $l$ at time $t$

$sold_{d,p,t}$      Amount of fuel product type $p$ sold to demand zones $d$ at time period $t$

$spj_{j,p,t}$      Storage level of fuel product type $p$ in biorefinery $j$ at time $t$

$spl_{l,p,t}$      Storage level of fuel product type $p$ at intermediate upgrading facility $l$ at time $t$

$tc$      Total annualized cost of operating the biofuel supply chain

$tcapj_{j}$      Total capital investment of installing integrated biorefinery $j$

$tcapk_{k}$      Total capital investment of installing preconversion facility $k$

$tcapl_{l}$      Total capital investment of installing intermediate upgrading facility $l$

$tcfpj_{j}$      Fixed annual production cost of integrated biorefinery $j$

$tcfpk_{k}$      Fixed annual production cost of preconversion facility $k$

$tcfpl_{l}$      Fixed annual production cost of intermediate upgrading facility $l$

$te$      Total GHG emission ($CO_2$-equiv/year) of operating the biofuel supply chain

$wbj_{b,j,q,t}$      Amount of biomass type $b$ used for the production of liquid transportation fuel through conversion technology $q$ in integrated biorefinery $j$ at time $t$

$wbk_{b,k,q',t}$      Amount of biomass type $b$ used for the production of biofuels through conversion technology $q'$ in preconversion facility $k$ at time $t$

$wgk_{g,k,q',t}$      Amount of intermediate type $g$ produced through conversion technology $q'$ in preconversion facility $k$ at time $t$

$wgl_{g,l,q'',t}$      Amount of intermediate type $g$ converted to liquid transportation fuel through conversion technology $q''$ in intermediate upgrading facility $l$ at time $t$

$wpj_{j,p,q,t}$      Amount of fuel product type $p$ produced through conversion technology $q$ in integrated biorefinery $j$ at time $t$

$wpl_{l,p,q'',t}$      Amount of fuel product type $p$ produced through conversion technology $q''$ in intermediate upgrading facility $l$ at time $t$

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