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Municipal Solid Waste to Liquid Transportation Fuels - Part III: An Optimization-Based Nationwide Supply Chain Management Framework

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Abstract

An optimization-based supply chain management framework for municipal solid waste (MSW) to liquid transportation fuels (WTL) processes is presented. First, a thorough analysis of landfill operations and annual amounts of MSW that are deposited across the contiguous United States is conducted and compared with similar studies. A quantitative supply chain framework that simultaneously accounts for the upstream and downstream WTL value chain operations is then presented. A large-scale mixed-integer linear optimization model that captures the interactions among MSW feedstock availabilities and locations, WTL refinery locations, and product delivery locations and demand capacities is described. The model is solved for both the nationwide and statewide WTL supply chains across numerous case studies. The results of the framework yield insights into the strategic placement of WTL refineries in the United States as well as topological information on the feedstock and product flows. The results suggest that large-scale WTL supply chains can be competitive, with breakeven oil prices ranging between $64-$77 per barrel.

1 Introduction

The development of more sustainable energy processes has received significant attention in recent decades. This attention originates from concerns regarding the environmental impacts of fossil-fuel use. In the United States, additional interest surrounding the development of energy processes utilizing domestically available energy sources has grown. This interest has been fueled by uncertainty over the future price of crude oil as well as pressure placed on the United States to reduce petroleum imports. These developments have sparked interest in applying multi-scale systems engineering tools and components, which include modeling, design, synthesis, simulation, and optimization,[1] toward the development of sustainable energy processes. Reviews on the progress of liquid transportation fuels production from hybrid energy sources and the supply chain optimization of such processes is given in [2] and [3], respectively; a current opinion article[4] highlights the benefits of biomass and fossil fuel systems. Although U.S. net imports have significantly decreased over the past few years[5], the U.S. is still a net importer of approximately 4.8 million barrels per day of petroleum products. Municipal solid waste has emerged as a potential feedstock to mitigate the aforementioned challenges because it is considered a partially renewable energy resource[6], is available in significant quantities in the United States[7, 8], and has a negative cost due to the tipping fee received from handling it[9, 10].

To gain the aforementioned benefits of using municipal solid waste, MSW-based energy processes must be studied at the reactor scale, plant scale, and network scale to ensure efficient management of upstream and downstream WTL plant operations. In recent years, we have proposed a novel stoichiometric MSW gasification model[11] that accurately captures gasifier effluents using a nonlinear parameter estimation approach. The generic gasifier model was obtained using 39 experimental data sets with an average error of 8.75% [11]. We have also studied the production of liquid transportation fuels from municipal solid waste using a global optimization-based process synthesis superstructure (see [12]) that incorporated the generic mathematical model for MSW gasification. Most recently, we have proposed a comprehensive superstructure-based approach toward the sustainable production of liquid transportation fuels, olefins, and aromatics from MSW (see [13]). In this paper, we incorporate the results obtained at the plant scale for WTL systems to accurately account for the entire waste-to-liquids value chain using an optimization-based supply chain framework.

We addressed the effect of MSW variability in our previous studies on the process scale [12] by incorporating a refuse derived fuel (RDF) facility that removes the non-combustibles and recyclables from the incoming MSW to provide a more uniform feed into the gasification section. As explained before, the generic gasifier model is able to predict the synthesis gas composition across a wide range of feeds.[11] The remaining variability that occurs on the process scale would then have a negligible effect on the network scale.

On the network scale, investigating the interactions between MSW feedstock availabilities and locations, potential WTL refinery locations, and product delivery locations and demand capacities ensures the efficient management of the integrated WTL supply chains. With optimized WTL refineries of differing capacities (i.e., 1, 2, 5, and 10 thousand barrels per day, kBD), the optimal nationwide and statewide WTL supply chains are investigated by solving a large-scale mixed-integer linear optimization (MILP) model that minimizes the total cost of fuel production. The optimization-based supply chain framework considers (i) the exact locations of MSW landfills in the United States, (ii) the exact delivery locations of the fuel products, (iii) transportation costs associated with the inputs and outputs of the WTL refineries, (iv) the material balances of the

WTL refineries, (v) the costs associated with the investment and operation of the WTL refineries, (vi) any by-product revenue associated with the WTL refineries, and (vii) water resources. The results of the supply chain optimization yields insights into (i) the strategic placement and capacity of the WTL refineries, (ii) sourcing and allocation of feedstocks in the supply chain, and (iii) distribution and destination of products, by-products, and rejects in the supply chain as well as provides a cost breakdown across various segments of the supply chain. The top 5 locations to build a WTL refinery are also investigated. The quantitative framework presented and developed allows us to, for the first time, determine the economic and operational feasibility of producing liquid transportation fuels from MSW on a large scale.

2 Literature Review

While there have been several studies in the literature that investigated biomass to bioenergy supply chains, the supply chain management of municipal solid wastes has been studied less frequently from a systems perspective. A review of the former is provided in [3] and [14]. In this section, a short review of municipal solid waste management systems is conducted.

Several papers in the literature discuss municipal solid waste management methods in different countries, including Portugal[15], India[16], and the United States [17]. Pearce and Turner discuss solid waste management in the broader context of economic and environmental policy[18]. Beigl et al. [19] reviewed published models for municipal solid waste generation and proposed guidelines for waste management decision-making. Iakovou et al.[20] discussed and reviewed the strategic, operational, and tactical decision-making process in the context of waste biomass-to-energy supply chains.

Huang et al. [21] proposed a multistage strategic planning model for the biowaste-based ethanol production in California. Chen and Fan [22] investigated uncertainties in future demand and feedstock supply of a waste-based bioethanol supply chain via a mixed-integer stochastic programming model and applied it on California biofuel production. Ghose et al. [23] developed a geographical information system routing model to trace minimum cost paths for solid wastes to landfills in a municipality in India. Zhang et al.[24] proposed a piecewise interval program that minimizes the total cost of an MSW management system. Zhang et al.[25] also proposed a multi-period chance constrained program to investigate MSW management systems.

Santibañez-Aguilar et al.[26] developed a multi-objective optimization model to simultaneously account for the economic and environmental supply chain aspects of MSW processing and demonstrated its usefulness on a case study in the west-central part of Mexico. Minciardi et al.[27] formulated a nonlinear, multi-objective model for MSW management that was demonstrated on a case study in the municipality of Genova, Italy. Costi et al.[28] developed a nonlinear, mixed-integer optimization model considering several MSW treatment options that determines the most economical MSW management system. Elia et al. investigated the nationwide coal, biomass, and natural gas [29] and hardwood biomass [30] to liquid transportation fuels energy supply chain model that included MSW using a mixed-integer linear programming model. Čuček et al. [31] presented a multi-criteria optimization model incorporating environmental, social, and economic criteria for biomass supply chain design incorporating several types of biomass, including MSW.

In this work, we continue to build upon our multi-scale systems engineering approach by integrating results obtained from the process scale to analyze the effects and feasibility of large-scale MSW conversion at the network scale.

3 WTL Refineries

The design of the WTL refineries is determined using a comprehensive global optimization-based process synthesis superstructure approach described by Niziolek et al.[12] Simultaneous heat, power, and water integration is included to convert waste heat into electricity and minimize the intake of freshwater into the refinery. The process synthesis framework for the WTL refineries[12] includes: (i) municipal solid waste gasification with/without recycle gas, (ii) syngas conversion via Fischer-Tropsch (FT) refining or methanol synthesis, (iii) methanol conversion via methanol-to-gasoline or methanol-to-olefins, (iv) hydrocarbon upgrading via ZSM-5 zeolite catalysis, olefin oligomerization, or carbon number fractionation and subsequent treatment.

A rigorous deterministic global optimization branch-and-bound strategy is utilized to minimize the overall cost of the waste-to-liquids (WTL) refinery and determine the optimal process topology. The optimization-based process synthesis framework will yield: (i) the optimal process topologies, (ii) the overall cost results, (iii) the investment costs, (iv) the material and energy balances, and (v) the carbon and greenhouse gas balances for each WTL refinery design[12]. Several of these results will serve as inputs into the optimization-based supply chain framework, thus illustrating the multi-scale nature of the work. The results at the WTL process level are described in [12].

For convenience, the main results from the process level investigation of WTL refineries are summarized in this section. At the process level, three sets of case studies producing different ratios of products at four refinery scales were investigated for a total of twelve candidate WTL refineries that can exist at the supply chain scale. The three sets of liquid fuels products investigated[12] include (a) an unrestricted fuel output, (b) the maximization of diesel product, and (c) liquid fuels production commensurate with 2014 United States demand (i.e., 67 vol% gasoline, 22 vol% diesel, 11 vol% kerosene)[32]. The production of 1, 2, 5, and 10 thousand barrels per day of gasoline equivalent (based on the lower heating value) fuels were investigated. The case studies are denoted as $N-C$, where N represents the fuel composition of the products (U - Unrestricted, D - Diesel, R - U.S. Ratios) and C represents the capacity (in kBD). Therefore, D-2 represents a WTL refinery that produces 2000 barrels per day (of gasoline equivalent) of liquid fuels that produces primarily diesel product.

The overall cost results for the twelve optimized WTL refineries are illustrated in Table 1 and are taken from [12]. The total cost includes contributions from the feedstock costs, the CO_2 sequestration cost, the investment cost, the operating and maintenance (O&M) costs, the electricity costs or revenues, and the revenues from selling byproduct liquefied petroleum gas (LPG). The break even oil price is also illustrated. These values are obtained from the solution of the deterministic global optimization of the WTL process synthesis superstructure and serve as parameters in the supply chain optimization model. Additionally, the required plant investment costs for each of the 12 WTL refineries are also shown in Table 1.

The material balances for the twelve optimized WTL refineries are illustrated in Table 2 and are taken from [12]. The material balances illustrate the amount of feedstock required, the amount of products produced, and the amount of sequestered or vented CO_2. These values also serve as parameter inputs into the supply chain optimization model.

Table 1: Overall cost results and investment costs for the 12 WTL refineries.

Contribution to Cost ($/GJ of products)	U-1	U-2	U-5	U-10	D-1	D-2	D-5	D-10	R-1	R-2	R-5	R-10
Municipal Solid Waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RDF Operation	4.80	5.23	5.73	5.73	4.46	4.35	5.47	5.28	4.33	4.33	5.14	5.59
Butane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.01	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.02
CO2 Seq.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Investment	14.95	12.76	10.00	8.39	14.36	11.21	10.02	7.90	14.05	11.19	9.76	8.51
O&M	3.95	3.37	2.64	2.21	3.79	2.96	2.65	2.09	3.71	2.95	2.58	2.25
Electricity	2.19	0.81	-0.54	-0.54	2.03	1.94	-0.85	-0.79	1.94	1.93	0.42	-0.73
LPG	-2.34	-2.34	-2.34	-2.34	0.00	0.00	0.00	0.00	0.00	0.00	-1.42	-1.42
Total ($/GJ)	23.56	19.83	15.51	13.47	24.67	20.47	17.31	14.49	24.05	20.42	16.49	14.21
Total ($/bbl)	116.90	96.38	72.61	61.36	123.01	99.90	82.52	66.99	119.58	99.61	77.98	65.45
Investment Cost												
Total (MM $)	176	301	590	989	169	264	591	932	166	264	575	1003

Table 2: Overall material balance for the 12 WTL refineries. The inputs to the WTL refinery are MSW, butane, and water, while the outputs include gasoline, diesel, kerosene, LPG, sequestered CO_2, and vented CO_2.

Material Balances	U-1	U-2	U-5	U-10	D-1	D-2	D-5	D-10	R-1	R-2	R-5	R-10
RDF (dt/hr)	16.52	35.98	98.62	197.22	15.35	29.97	94.18	181.74	14.91	29.82	88.40	192.54
Butane (kBD)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water (kBD)	0.89	1.92	5.67	11.34	1.66	1.80	7.25	11.13	0.91	1.81	4.82	11.59
Gasoline (kBD)	1.00	2.00	5.00	10.00	0.11	0.22	0.56	1.12	0.65	1.30	3.25	6.49
Diesel (kBD)	0.00	0.00	0.00	0.00	0.68	1.37	3.41	6.83	0.21	0.42	1.04	2.08
Kerosene (kBD)	0.00	0.00	0.00	0.00	0.12	0.23	0.58	1.15	0.11	0.22	0.54	1.09
LPG (kBD)	0.19	0.37	0.93	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.56	1.13
Seq. CO2 (tons/hr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vented CO2 (tons/hr)	13.93	33.46	100.15	200.26	13.50	25.59	100.69	188.76	12.80	25.59	84.46	198.91

4 MSW Feedstock Availability

Accurate information on feedstock availability is one of the key inputs for the design of optimal supply chains. This information, however, is not always assembled in one database. For the municipal solid waste supply chain optimization studies that are conducted in this paper, sources of available municipal solid waste are located in landfills across the contiguous United States. The locations of these landfills, as well as how much MSW is deposited into them yearly, is obtained from state governmental agency reports, scientific articles, or personal correspondence with state governmental agency officials. Whenever possible, we use the most recent data available for a state. Table 3 illustrates the number of MSW landfills in each state, how much MSW is landfilled per year, and the reference which is used to obtain this information. This information is carefully reviewed to ensure that only municipal solid waste or materials deposited in MSW landfills are included, which allows us to accurately determine the amount of MSW available for conversion. Landfill latitudes and longitudes are also determined using information on landfill locations.

Figure 1 illustrates the 1627 operating landfills accepting MSW that are identified in the United States. The number of landfills in each state is provided in Table 3. As Table 3 indicates, the total amount of MSW that is landfilled exceeds 278 million metric tons of MSW per year. Pennsylvania, Texas, and California are the top three landfilling states, with over 31, 30, and 22 million metric tons of waste landfilled in each, respectively. The largest landfill is located near Las Vegas, Nevada, accepting over 3 million metric tons of MSW per year.

4.1 Analysis of MSW Figures in the United States

The collection of this data also allows us to compare to other available sources that conduct a similar analysis of MSW in the U.S. The methods used by the United States Environmental Protection Agency (EPA) to characterize MSW across the nation differs from the methods used in this study. The EPA[33] characterizes the MSW stream of the entire nation, using a materials flow methodology that relies on data from industry associations and sources, key businesses, government (Department of Commerce, U.S. Census Bureau, etc.) data, and waste characterization and surveys conducted by governments, industry, or the press. The EPA also makes some assumptions[33] using imports and exports from the U.S. as well as the lifespans of products. Using this method-

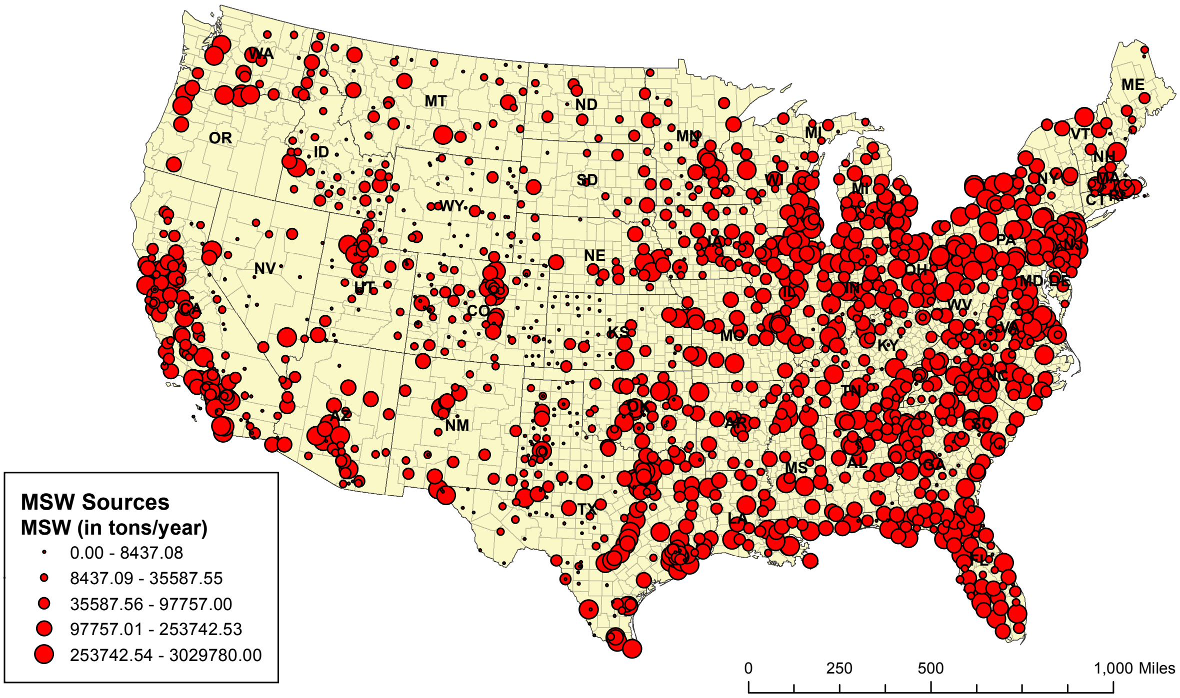

Figure 1: Operating landfills in the U.S.

ology, the U.S. EPA has estimated that 258 million short tons (234 million metric tons) of MSW were generated in the United States in 2014[7]. Of this, the U.S. EPA estimates 136 million short tons (123 million metric tons) were landfilled, 89 million short tons (81 million metric tons) were recycled and composted, and 33 million short tons (30 million metric tons) were used for energy recovery (waste to energy uses).

Our methodology relies on an analysis of operating landfills on a state level, taking care to include only municipal solid waste in our determination. We calculated that a total of 279 million metric tons of MSW are landfilled in the United States. The total figure in Table 3 is then determined by summing the contributions across the contiguous U.S. Our methodology shows that the U.S. EPA underestimates the amount of landfilled MSW in the U.S. by at least 155 million metric tons (note that we do not take into account MSW landfilled in Alaska, Hawaii, or the District of Columbia).

The results from our analysis are in greater agreement with numbers obtained by BioCycle and the Earth Engineering Center of Columbia University[8], which uses a survey-based approach that relies on responses from solid waste management departments in 50 states and the District of Columbia. An outline for their protocol and assumptions made for incomplete or otherwise missing data is provided in [8]. BioCycle and Columbia University determined that 270 million short tons (245 million metric tons) of MSW were landfilled and 389 million short tons (353 million metric tons) of MSW were generated in 2008[8]. Excluding Hawaii, Alaska, and the District of Columbia, the amount landfilled was 266 million short tons (241 million metric tons).

5 Water Resources

Water is one of the main ancillary inputs into a refinery, and as such, it is important to be conscientious of water use on both the process scale and the network scale. On the process scale, freshwater intake into the refineries is minimized by including the costs associated with freshwater use in the objective function. On the network scale, the water supply chain is considered by obtaining water use data from the United States Geological Survey (USGS) database[81]. This consideration ensures that water resources are not strained on a regional level by imposing that the freshwater requirements for the WTL plants must be satisfied within 300 miles. The USGS

Table 3: Waste to liquids supply chain optimization statistics.

State	Number of Counties	Number of Landfills	Amount of MSW landfilled (MT/year)	Reference
Alabama	67	31	4,772,756	Alabama Department of Environmental Management [34]
Arkansas	75	23	2,322,272	Arkansas Department of Environmental Quality [35]
Arizona	15	39	6,471,054	Arizona Department of Environmental Quality [36]
California	58	119	22,036,642	California Department of Resources Recycling and Recovery [37]
Colorado	64	75	5,253,646	Colorado Department of Public Health and Environment [38]
Connecticut	8	1	13,425	Connecticut Department of Energy and Environmental Protection [39]
Delaware	3	3	440,841	Delaware Division of Waste and Hazardous Substances [40]
Florida	67	67[1]	14,859,083	Florida Department of Environmental Protection [41]
Georgia	159	50	11,322,589	Georgia Department of Community Affairs [42]
Idaho	44	44[2]	1,518,406	The State of Garbage in America [8]
Illinois	102	39	13,394,965	Illinois Environmental Protection Agency [43]
Indiana	92	33	10,687,317	Indiana Department of Environmental Management [44]
Iowa	99	43	2,542,003	Iowa Department of Natural Resources [45]
Kansas	105	42	2,820,267	Kansas Department of Health and Environmental Waste Management [46]
Kentucky	120	26	1,479,689	Kentucky Department for Environmental Protection [47]
Louisiana	64	25	5,336,745	Louisiana Department of Environmental Quality [48]
Maine	16	8	211,831	Maine Department of Environmental Protection [49]
Maryland	23	24	1,605,425	Maryland Department of the Environment [50]
Massachusetts	14	15	1,650,744	Massachusetts Energy and Environmental Affairs [51]
Michigan	83	47	9,248,267	Michigan Department of Environmental Quality [52]
Minnesota	87	31	2,638,248	Minnesota Pollution Control Agency [53]
Mississippi	82	19	3,313,434	Mississippi Department of Environmental Quality [54]
Missouri	114	18	3,960,119	Missouri Department of Natural Resources [55]
Montana	56	30	1,558,060	Personal Correspondence: Montana Department of Environmental Quality [56]
Nebraska	93	22	2,091,658	Nebraska Department of Environmental Quality [57]
Nevada	16	22	5,022,420	Nevada Division of Environmental Protection [58]
New Hampshire	10	6	760,440	Personal Correspondence: New Hampshire Department of Environmental Services [59]
New Jersey	21	21[1]	5,656,431	New Jersey Department of Environmental Protection [60]
New Mexico	33	26	2,394,956	New Mexico Recycling Coalition [61]
New York	62	26	8,147,808	New York State Department of Environmental Conservation [62]
North Carolina	100	40	7,439,609	North Carolina Department of Environmental Quality [63]
North Dakota	53	13	702,057	North Dakota Solid Waste and Recycling Association [64]
Ohio	88	39	10,915,979	Ohio Environmental Protection Agency [65]
Oklahoma	77	39	4,832,155	Oklahoma Department of Environmental Quality [66]
Oregon	36	8	3,467,695	State of Oregon Department of Environmental Quality [67]
Pennsylvania	67	44	31,040,100	Pennsylvania Department of Environmental Protection [68]
Rhode Island	5	2	939,638	Rhode Island Department of Environmental Management [69]
South Carolina	46	23	5,119,718	South Carolina Department of Health and Environmental Control [70]
South Dakota	66	15	592,483	Personal Correspondence: South Dakota Department of Environment and Natural Resources [71]
Tennessee	95	34	6,785,975	Tennessee Department of Environment and Conservation [72]
Texas	254	197	30,569,741	Texas Commission on Environmental Quality [73]
Utah	29	40	2,391,329	Utah Department of Environmental Quality [74]
Vermont	14	1	351,392	Vermont Department of Environmental Conservation [75]
Virginia	95	50	9,748,777	Virginia Department of Environmental Quality [76]
Washington	39	14	3,402,296	Department of Ecology State of Washington [77]
West Virginia	55	18	2,218,368	West Virginia Solid Waste Management Board [78]
Wisconsin	72	31	3,977,291	Wisconsin Department of Natural Resources [79]
Wyoming	23	44	501,759	Wyoming Department of Environmental Quality [80]
Total:	3066	1627	278,527,901	

1. Amount of MSW landfilled is available on a county basis - assumed landfill located at county centroid
2. Amount of MSW landfilled taken from [8] - assumed landfill located at county centroid with MSW amount proportional to county population

database provides the daily amount of industrial freshwater withdrawn and the total freshwater withdrawn on a county basis. In order to prevent strain on water resources, it is assumed that the non-zero minimum between the industrial freshwater withdrawn and 15% of the total freshwater withdrawn is available for the WTL refineries.

6 Candidate WTL Refinery Locations

Candidate locations of the optimized WTL refineries are an important input in the supply chain optimization framework. Candidate WTL refinery locations are chosen as county centroids. The locations for the candidate WTL refineries are obtained from the United States Census Bureau[82, 83]. All 3066 contiguous county locations serve as potential locations for the placement of a WTL refinery, and the number of counties in each state is illustrated in Table 3. The candidate locations for the WTL refineries are illustrated in Figure 2. The optimization model imposes a maximum distance of 100 miles for MSW to be delivered to a WTL refinery and for products/rejects to be delivered to their end destinations from a WTL refinery.

7 MSW Rejects Delivery Locations

As explained in Niziolek et al.[12], there are undesired components in municipal solid waste, such as glasses, metals, and incombustibles, that must be separated out prior to gasification. The RDF facility[12] at the WTL refinery is responsible for this separation step. The refuse derived fuel (RDF) exiting the RDF facility has a more consistent quality, composition, and moisture. In [12], it was assumed that the rejected material is 20% of the incoming MSW feed. These rejects are directed back to the landfills (Figure 1) and as such, it is important to account for this added transportation cost in the WTL supply chain network. The MSW landfills described previously are considered end destinations for the MSW rejects. In the supply chain case studies, the operating capacity of the landfills is expanded by 20% relative to the MSW production determined in Section 4.

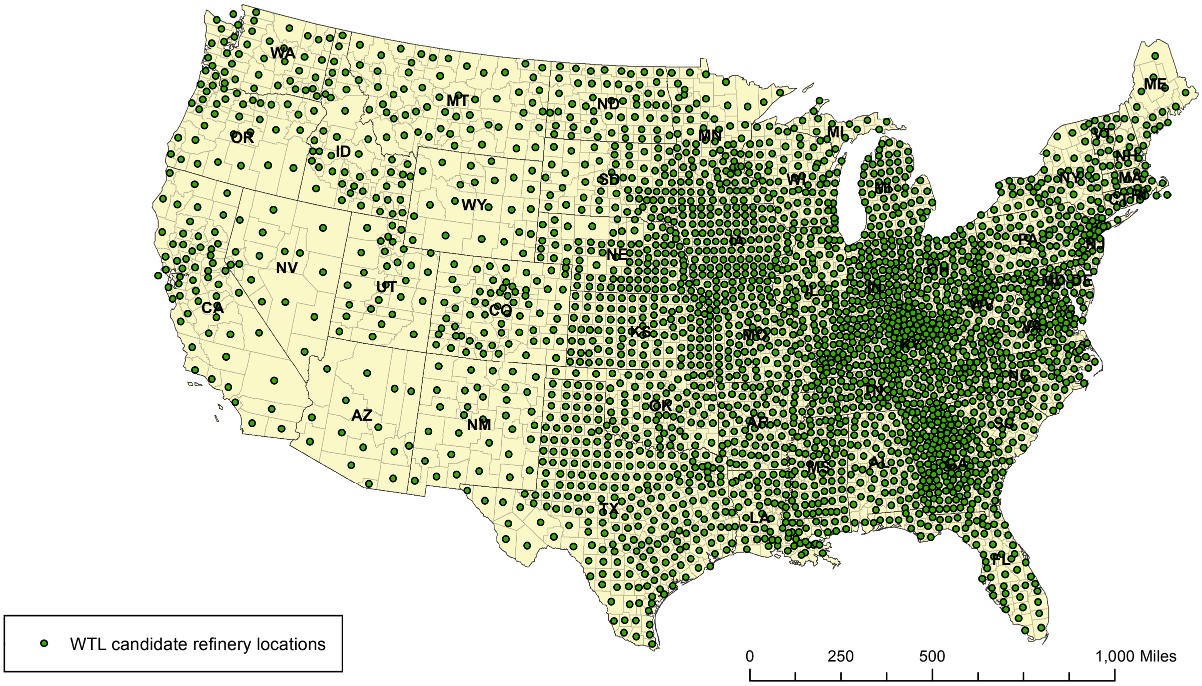

Figure 2: Candidate refinery locations in U.S. counties.

8 Liquid Fuels Delivery Locations

The end destinations for the liquid fuels are operating petroleum refineries in the contiguous United States. The EIA provides information[84] on the capacity for all operating and idle petroleum refineries. The liquid fuels produced from the WTL refineries are delivered to these petroleum refineries, and it assumed that the amount delivered cannot exceed the operating capacity of the petroleum refineries. By utilizing the petroleum refineries as end destinations, the WTL supply chain can take advantage of the current hydrocarbon infrastructure within the United States. The latitudes and longitudes of the end destinations are determined using the 2015 refinery capacity data[84].

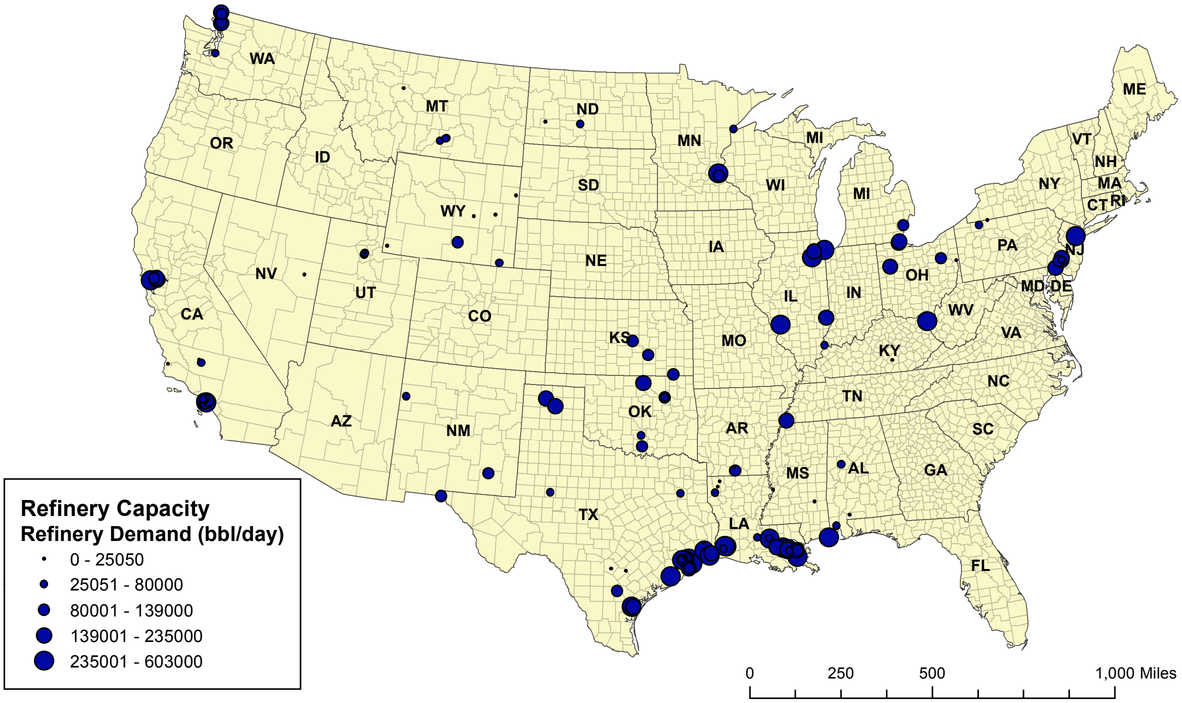

Figure 3: Liquid fuels delivery locations in the U.S.

9 Transportation Costs

In the supply chain framework, MSW, MSW rejects, and the products are transported by truck, while water is transported by pipeline. Transportation costs are calculated using Equation 1, where DFC is the distance fixed cost, DVC is the distance variable cost, $Distance$ is the distance traveled, and DM is the distance multiplier. $Distance$ is calculated between two points given their longitudes and latitudes using the Haversine formula. DM is introduced to account for path curvatures and the DM value is assumed to be 1.1. For fuel products transportation by truck, the DFC value is \$3.318/bbl and the DVC value is \$0.124/bbl-mi; for MSW and MSW rejects transportation by truck, the DFC value is assumed to be \$4.839/metric ton and the DVC value is \$0.213/metric ton-mi; and for water transportation by pipeline, the DFC value is \$0.0003/kg and the DVC value is \$5E-6/kg-mi.[29, 85]

$$\text{Transportation Cost} = DFC + DVC \cdot Distance \cdot DM \tag{1}$$

It is important to accurately estimate costs associated with MSW and MSW rejects transportation for those cases where landfills are assumed to be located at the county centroids. Because candidate WTL refineries are also located at these county centroids, neglecting this would allow some connections in the WTL supply chain to have a “zero” distance. For the three states (see Table 3 - Florida, Idaho, New Jersey) where the assumption is made that landfills exist at the country centroid, only connections between county centroids are allowed. That is, intracounty connections are disallowed to avoid the “zero” distance value. The same assumption is applied for the water transportation connections.

In [12], it was assumed that the transportation costs associated with delivering the MSW to the plant gate are equal to the tipping fee received from handling the MSW (hence why the cost for municipal solid waste in Table 1 is zero). It was also assumed the MSW is transported a distance of 50 miles. Using this information, together with the DFC and DVC parameters for MSW transportation by truck, the tipping fee per mass basis for MSW can be computed. The MSW tipping fee in [12] comes out to be \$19.35/metric ton of MSW. Note that only the tipping fee from MSW that is ultimately converted into product is considered as additional revenue in the WTL refinery, the MSW rejects from the RDF facility are directed to the landfills and the tipping fee from that portion of feedstock is not considered. The tipping fee from MSW is therefore assumed to be \$19.35/metric ton in the supply chain case studies illustrated in this paper.

10 MSW Energy Supply Chain Optimization Model

The parameter inputs into the supply chain optimization model were described in the previous subsections. These parameter inputs include (i) the locations and availabilities of MSW feedstocks, (ii) the transportation costs of MSW, water, products, and MSW rejects, (iii) input/output data for the optimized WTL refineries (e.g., the investment and operational costs, by-product revenues, tipping fee revenues, feedstock requirements, fuel product amounts, water costs, and electricity costs or sales, etc.), and (iv) the locations and demand capacities of product destinations (i.e., operating petroleum refineries). The large-scale mixed-integer supply chain optimization model will yield (i) the strategic placement and capacity of the WTL refineries, (ii) topological information surrounding feedstocks, products, and rejects, and (iii) a cost breakdown across various segments of the WTL supply chain.

The generic supply chain optimization model is described below and is based on the model developed by Elia et al.[29, 85, 86] The mathematical nomenclature used for the supply chain optimization is illustrated in Table 4. Equation 2 restricts the existence of at most one WTL refinery at each candidate location. Equation 3 imposes a maximum number of overall WTL refineries in the supply chain network; whereas Equations 4 and 5 imposes a maximum and minimum number of WTL refineries of a certain capacity in the supply chain network.

$$\sum_{(f,t,q)} y_{f,l,t,q} \leq 1 \qquad \forall l \in L^F \tag{2}$$

$$\sum_{(f,l,t,q)} y_{f,l,t,q} \leq N \tag{3}$$

$$\sum_{(f,l,q)} y_{f,l,t,q} \leq N_t^{max} \quad \forall t \in T \tag{4}$$

$$\sum_{(f,l,q)} y_{f,l,t,q} \geq N_t^{min} \quad \forall t \in T \tag{5}$$

The required levelized investment cost of a refinery ($Cost_l^I$) at a location is determined from the levelized investment costs of the candidate facilities ($LC_{f,t,q}$) using Equation 6. Equation 7 specifies the required levelized electricity costs/revenues ($Cost_l^E$) at a location from the levelized costs/revenues of the candidate facilities ($EC_{f,t,q}$). The required levelized O&M costs, LPG sales, and RDF operation costs of a refinery at a location are determined from the levelized O&M costs, LPG sales, and RDF operation costs of the candidate facilities using Equations 8 - 10, respectively.

$$\sum_{(f,t,q,p),p\in P^{GDK}} \frac{y_{f,l,t,q} LC_{f,t,q} PR_{p,t,q}}{TotalFuel} = Cost_l^I \qquad \forall l \in L^F \tag{6}$$

$$\sum_{(f,t,q,p),p\in P^{GDK}} \frac{y_{f,l,t,q} EC_{f,t,q} PR_{p,t,q}}{TotalFuel} = Cost_l^E \qquad \forall l \in L^F \tag{7}$$

$$\sum_{(f,t,q,p),p\in P^{GDK}} \frac{y_{f,l,t,q} OMC_{f,t,q} PR_{p,t,q}}{TotalFuel} = Cost_l^{OM} \qquad \forall l \in L^F \tag{8}$$

$$\sum_{(f,t,q,p),p\in P^{GDK}} \frac{y_{f,l,t,q} LPGS_{f,t,q} PR_{p,t,q}}{TotalFuel} = Sales_l^{LPG} \qquad \forall l \in L^F \tag{9}$$

$$\sum_{(f,t,q,p),p\in P^{GDK}} \frac{y_{f,l,t,q} RDFC_{f,t,q} PR_{p,t,q}}{TotalFuel} = Cost_l^{RDF} \qquad \forall l \in L^F \tag{10}$$

Equation 11 specifies the refinery feedstock requirement ($FR_{f,l}$) of a location from the feedstock requirements of the candidate facilities ($FR_{f,t,q}^{MSW}$). Equations 12 restricts the total feedstock flow from source (which are landfills) c to location l via mode of transportation m to be less than feedstock availability at source c ($FA_{f,c}$). The total feedstock flow must fulfill the requirements at location l, as imposed by Equation 13.

The flow of liquid products from each refinery location l to demand location d is determined by the production capacity and product ratios, as shown in Equation 14. Equation 15 constrains the total product flow to each demand location d to be less than or equal to known operating capacities. Equation 16 constrains the total gasoline, diesel, and kerosene must meet predetermined demand amounts.

$$FR_{f,l} = \sum_{(t,q)} FR^{MSW}_{f,t,q} y_{f,l,t,q} \qquad \forall f \in F, l \in L^F \tag{11}$$

$$\sum_{(l,m)} x_{f,c,l,m} \leq FA_{f,c} \qquad \forall f \in F, c \in C \tag{12}$$

$$\sum_{(c,m)} x_{f,c,l,m} = FR_{f,l} \qquad \forall f \in F, l \in L^F \tag{13}$$

$$\sum_{(d,m)} z_{p,l,d,m} = \sum_{(f,t,q)} y_{f,l,t,q} PR_{p,t,q} \qquad \forall l \in L^F, p \in P \tag{14}$$

$$\sum_{(l,m)} z_{p,l,d,m} \leq DM_{p,d} \qquad \forall p \in P, d \in D \tag{15}$$

$$\sum_{(p,l,d,m), p \in P^{GDK}} z_{p,l,d,m} = TotalFuel \tag{16}$$

Equation 17 specifies the refinery water requirement (WF_l) of a location from the water requirements of the candidate facilities ($FW_{f,t,q}$). Equations 18 restricts the total water flow from source l' to location l to be less than feedstock availability at source l' ($WA_{l'}$). The total freshwater flow must fulfill the requirements at location l, as imposed by Equation 19. Since both freshwater sources and candidate refinery locations are located at county centroids, all $w_{l,l}$ are constrained to be zero.

$$\sum_{(f,t,q)} y_{f,l,t,q} FW_{f,t,q} = WF_l \quad \forall l \in L^F \tag{17}$$

$$\sum_{l} w_{l',l} \leq WA_{l'} \qquad \forall l' \in L^W \tag{18}$$

$$WF_l = \sum_{l'} w_{l',l} \qquad \forall l \in L^F \tag{19}$$

The flow of MSW rejects from each refinery location l back to the landfill c is determined by the production capacity and product ratios (since not all similar capacity plants input the same amount of MSW), as shown in Equation 20. Equation 21 constrains the total MSW rejects flow to each landfill c to be less than or equal to known expanded landfill capacities.

$$\sum_{(c,m)} r_{f,l,c,m} = \sum_{(t,q)} y_{f,l,t,q} RE_{f,t,q} \quad \forall f \in F, l \in L^F \tag{20}$$

$$\sum_{(l,m)} r_{f,l,c,m} \leq CAP_{f,c} \qquad \forall f \in F, c \in C \tag{21}$$

The objective function for the waste-to-liquids energy supply chain network is shown in Equation 22 and represents the total cost of the network. Equation 22 includes contributions from the (i) the investment costs associated with the new WTL refineries, (ii) the electricity costs or sales, (iii) the operating and maintenance costs associated with the new WTL refineries, (iv) the revenues from any by-product LPG sales, (v) the costs associated with the RDF facility, (vi) feedstock purchase and transportation costs, (vii) rejects transportation costs, (viii) product transportation costs, and (ix) freshwater purchase and transportation costs. Note that the objective function is normalized with respect to the total energy of liquid fuels produced.

$$\begin{aligned} MIN \quad & \sum_{l \in L^F} Cost_l^I + Cost_l^E + Cost_l^{OM} - Sales_l^{LPG} + Cost_l^{RDF} \\ & + \Bigg(\sum_{(f,c,l,m)} x_{f,c,l,m} (Cost_f^F + Cost_{f,c,l,m}^{FT}) \\ & + \sum_{(f,l,c,m)} r_{f,l,c,m} Cost_{f,l,c,m}^{RT} \\ & + \sum_{(p,l,d,m)} z_{p,l,d,m} Cost_{p,l,d,m}^{PT} \\ & + \sum_{(l',l)} w_{l',l} (Cost^{WP} + Cost_{l',l}^{WT}) \Bigg) \Bigg/ (TotalFuel \cdot LHV_{Fuel}) \end{aligned} \tag{22}$$

10.1 Alternate optimal solutions

In the case studies that are illustrated in this paper, an additional constraint(s) is imposed to subsequently find alternative optimal solutions. Let the set of all binary variables be Y. In the most recent optimization solution, let N be the subset of Y such that $y^*_{f,t,l,q} = 1$ for all (f,t,l,q) in N.

Table 4: Mathematical supply chain optimization model nomenclature.

Symbol	Definition
	Indices
f	Feedstock index
t	Capacity index
l	Location index
q	Fuel product ratio index
c	Feed source index
m	Transportation mode index
d	Demand location index
p	Product index
	Sets
F	Feedstock (MSW)
L^F	Candidate refinery locations
C	Source (landfill) locations
D	Demand locations
C_P	Product-demand location pairs
P	Products
P^{GDK}	Gasoline, diesel, and kerosene products
L^W	Freshwater availability locations
T	Refinery capacities (i.e., 1, 2, 5, 10 kBD)
	Parameters
N	Maximum number of WTL refineries built in the U.S.
N_t^{max}	Maximum number of WTL refineries for capacity t
N_t^{min}	Minimum number of WTL refineries for capacity t
$FR_{f,t,q}^{MSW}$	WTL MSW requirement for capacity t and fuel ratio q
$LC_{f,t,q}$	WTL investment cost for feed f, capacity t, and fuel ratio q
$EC_{f,t,q}$	WTL electricity cost/revenue for feed f, capacity t, and fuel ratio q
$OMC_{f,t,q}$	WTL O&M cost for feed f, capacity t, and fuel ratio q
$LPGS_{f,t,q}$	WTL LPG revenue for feed f, capacity t, and fuel ratio q
$RDFC_{f,t,q}$	WTL RDF operation cost for feed f, capacity t, and fuel ratio q
$FA_{f,c}$	Feedstock availability at source c
$PR_{p,t,q}$	Amount of product p at capacity t and fuel ratio q
$DM_{p,d}$	Demand of product p in demand location d
$TotalFuel$	Predetermined amount of gasoline, diesel, and kerosene produced in the U.S.
$FW_{f,t,q}$	WTL freshwater requirement for capacity t and fuel ratio q
$WA_{l'}$	Water availability in location l'
$Cost_f^F$	Feedstock purchase cost f
$Cost_{f,c,l,m}^{FT}$	Cost of transporting feedstock f from source c to location l using mode m
$Cost_{p,l,d,m}^{PT}$	Cost of transporting product p from location l to destination d using mode m
$Cost^{WP}$	Freshwater purchase cost
$Cost_{l',l}^{WT}$	Cost of transporting freshwater by pipeline from location l' to location l
$RE_{f,t,q}$	Amount of feedstock rejects f at capacity t and fuel ratio q
$CAP_{f,c}$	Capacity of source (landfill) c for feedstock f
$Cost_{f,l,c,m}^{RT}$	Cost of transporting feedstock rejects f from location l to source (landfill) c using mode m
	Binary Variables
$y_{f,t,l,q}$	WTL refinery binary variable with feedstock f, location l, capacity t, and fuel ratio q
	Continuous Variables
$FR_{f,l}$	Amount of feedstock f required at location l
$Cost_l^I$	Levelized investment cost of refinery at l
$Cost_l^E$	Levelized electricity cost/revenue of refinery at l
$Cost_l^{OM}$	Levelized O&M costs of refinery at l
$Sales_l^{LPG}$	Levelized LPG sales of refinery at l
$Cost_l^{RDF}$	Levelized RDF operation costs of refinery at l
$x_{f,c,l,m}$	Feedstock flow f from source c to location l using transportation mode m
$z_{p,l,d,m}$	Flow of product p from location l to demand location d using transportation mode m
WF_l	Amount of freshwater required at location l
$w_{l',l}$	Freshwater flow from location l' to location l
$r_{f,l,c,m}$	Feedstock rejects flow f from location l to source (landfill) c using mode of transportation m

Then an integer cut (Equation 23) is added to exclude the previous optimal solution and the optimization model is solved again.

$$\sum_{(f,t,l,q)\in N} y_{f,t,l,q} - \sum_{(f,t,l,q)\in Y\setminus N} y_{f,l,t,q} \leq |N| - 1 \tag{23}$$

This process is repeated to find the third-best, fourth-best, etc. solution.

11 Energy Supply Chain Optimization Model Statistics

Equations 2 - 23 represent a large-scale mixed-integer linear optimization model which contains 49,380 equations, 1,259,071 continuous variables, and 36,792 binary variables for the nationwide case. The size of the model changes with geographical scope. The MILP model is solved using CPLEX using 16 processors.[87] The relative stopping tolerance, *epgap*, and absolute stopping tolerance, *epagap*, were both set to 0.00001 for the model. All case studies investigated are solved in under 2 hours.

12 Nationwide WTL Supply Chain Optimization Case Studies

The WTL supply chain optimization model is solved for the (i) nationwide and (ii) statewide supply chain networks. For the nationwide WTL supply chain networks, two sets of case studies are investigated that (i) restrict (R) the production of diesel to be at least 40% by volume relative to the total amount of liquid transportation fuels (gasoline, diesel, and kerosene) produced and (ii) only allow unrestricted (U) refineries to exist (since they have the lowest cost of liquid fuels production) [12]. The restricted set of case studies allows the existence of three different types of WTL refineries: unrestricted, maximization of diesel, and U.S. ratios restricted (commensurate with 2014 United States demand - i.e. 67 vol% gasoline, 22 vol% diesel, 11 vol% kerosene)[12]. Each set of case studies will examine the production of two levels of liquid transportation fuels: 100 kBD and 500 kBD of gasoline equivalent (based on lower heating value) liquid transportation fuels. Since the U.S. transportation sector consumed 8.924 million barrels of motor gasoline per

Table 5: Labeling Conventions for Case Studies.

					Lower Bounds (N_t^{min}) Capacity			
Case Study	Scope	Capacity (kBD)	Type of WTL refineries allowed	Minimum Capacity Restriction	1 kBD	2 kBD	5 kBD	10 kBD
R-USA-100kBD-MC	USA	100	All	Y	10	5	5	0
R-USA-100kBD-NMC	USA	100	All	N	0	0	0	0
R-USA-500kBD-MC	USA	500	All	Y	20	10	10	0
R-USA-500kBD-NMC	USA	500	All	N	0	0	0	0
U-USA-100kBD-MC	USA	100	Unrestricted only	Y	10	5	5	0
U-USA-100kBD-NMC	USA	100	Unrestricted only	N	0	0	0	0
U-USA-500kBD-MC	USA	500	Unrestricted only	Y	20	10	10	0
U-USA-500kBD-NMC	USA	500	Unrestricted only	N	0	0	0	0

day (MMBD), 2.892 MMBD of diesel, and 1.614 MMBD of jet fuel in 2016 [88], these two production levels represent approximately 0.7% and 3.7% of petroleum-based fuels substituted by MSW. Furthermore, the two levels of liquid transportation fuels production will examine two distinct runs characterized by the lower bounds (N_t^{min}) on the number of WTL refineries of capacity t allowed to exist within the supply chain network. One set places no restriction on a minimum number of WTL refineries (*NMC* case studies) of a certain capacity, while the other (*MC* case studies) does. The latter set represents the scenario where smaller capacity pilot plants (i.e., 1 kBD and 2 kBD) are initially built to minimize the risk associated with larger capacity WTL refineries (e.g., 10 kBD). In total, eight case studies are investigated. The labeling conventions for the case studies are illustrated in Table 5.

The overall cost results for the nationwide restricted and unrestricted WTL supply chains are illustrated in Tables 6 and 7. The overall cost takes the (i) transportation costs of the MSW feedstock, MSW rejects, and products (liquid fuels and LPG), (ii) the investment, operating and maintenance, and RDF operating costs, (iii) electricity costs or revenues, (iv) LPG revenues, (v) tipping fees from handling MSW, and (vi) freshwater transportation and refinery costs into account. The break-even oil price (BEOP) is also calculated by subtracting the refiner's margin from the total cost for all liquid transportation fuels produced and dividing by the volume of liquid transportation fuels produced. The BEOP represents the price at which the WTL supply chain becomes competitive with petroleum-based processes. Tables 6 and 7 also illustrate the type of refineries selected, the type and quantity of products produced per day, and how much MSW is utilized (equivalent to the RDF processed in the WTL plant[12]) per year.

12.1 Restricted WTL Supply Chains

The summary of results for the restricted WTL supply chains that are constrained to produce a minimum amount of diesel is illustrated in Table 6. As Table 6 shows, the cost of the WTL supply chains are lower when no restriction is placed on the type of refineries to be built (*NMC* case studies). This is because the *NMC* case studies select larger capacity WTL refineries (i.e., 10 kBD plants) to be built that have a lower levelized investment cost and operating/maintenance costs. However, the *MC* case studies, which constrain a minimum number of WTL refineries at each capacity to be built, have lower transportation costs due to the existence of more refineries that are placed strategically closer to landfills and product destination locations.

The R-USA-100kBD-NMC supply chain network has a break even oil price of \$64.84/bbl, which is almost \$12.00/bbl less expensive than the R-USA-100kBD-MC supply chain network that has a break even oil price \$76.66/bbl. The R-USA-100kBD-NMC supply chain network has a required investment cost of \$9.746 billion dollars, compared with \$11.352 billion required for the R-USA-100kBD-MC supply chain network. The types of WTL refineries that exist within the WTL supply chain networks are also illustrated in Table 6. The R-USA-100kBD-MC supply chain selects a total of 6 unrestricted refineries, 18 max. diesel refineries, and 2 restricted refineries; the R-USA-100kBD-NMC only selects 4 diesel refineries and 6 restricted refineries. The breakdown of the capacities of the selected WTL refineries are shown in Table 6. The two WTL supply chains that produce 100 kBD of liquid fuels utilize over 20 million metric tons of MSW per year. The R-USA-100kBD-NMC supply chain network is illustrated in Figure 4 and the R-USA-100kBD-MC supply chain network is shown in Figure 5. Figures 4 and 5 illustrate the types and locations of the WTL refineries, the locations of selected landfills that supply the feedstock to these WTL refineries, and end destinations for the products.

At the 500 kBD level, the R-USA-500kBD-MC WTL supply chain network has a total cost of \$15.73/GJ (BEOP: \$73.78/bbl) and the R-USA-500kBD-NMC WTL supply chain has a total cost of \$15.08/GJ (BEOP: \$70.22/bbl). The lower cost of the R-USA-500kBD-NMC WTL supply chain is due to lower capital and operating costs. The R-USA-500kBD-NMC supply chain network has a required investment cost of \$48.872 billion dollars, compared with \$51.892 billion required for the R-USA-500kBD-MC supply chain network. The R-USA-500kBD-MC supply

Table 6: Summary of Results for the Nationwide Restricted WTL Supply Chain Case Studies.

Contribution to Cost ($/GJ)	R-USA-100kBD-MC	R-USA-100kBD-NMC	R-USA-500kBD-MC	R-USA-500kBD-NMC
MSW Transportation Costs	1.15	1.34	1.70	1.91
MSW Rejects Transportation Costs	0.20	0.21	0.23	0.23
Product Transportation Costs	0.80	0.83	1.19	1.26
Investment Costs	9.63	8.27	8.80	8.29
RDF Costs	5.30	5.47	5.40	5.48
OM Costs	2.54	2.19	2.33	2.19
Electricity Costs or Sales	-0.29	-1.17	-0.85	-1.19
LPG Sales	-0.99	-0.85	-0.93	-0.91
Tipping Fee Sales	-2.14	-2.20	-2.18	-2.21
Water Transportation Costs	0.01	0.01	0.01	0.01
Water Refinery Costs	0.02	0.02	0.02	0.02
Total Cost of Supply Chain ($/GJ)	16.25	14.10	15.73	15.08
Break even oil price ($/bbl)	76.66	64.84	73.78	70.22
Investment Cost				
Total (MM $)	11352	9746	51892	48872
Refinery Selection				
Unrestricted Refineries				
1 kBD refineries	0	0	0	0
2 kBD refineries	0	0	0	0
5 kBD refineries	6	0	9	0
10 kBD refineries	0	0	0	0
Diesel Refineries				
1 kBD refineries	10	0	20	0
2 kBD refineries	5	0	10	0
5 kBD refineries	0	0	0	0
10 kBD refineries	3	4	16	18
U.S. Ratios Restricted Refineries				
1 kBD refineries	0	0	0	0
2 kBD refineries	0	0	0	0
5 kBD refineries	0	0	1	0
10 kBD refineries	2	6	25	32
Product Composition (kBD)				
Gasoline	48.54	43.42	232.82	227.84
Diesel	38.30	39.80	189.62	189.50
Kerosene	7.98	11.14	50.89	55.58
LPG	7.84	6.78	37.18	36.16
MSW Utilized (MT/year)	20,079,059	20,704,208	102,344,207	103,758,595

chain includes 9 unrestricted refineries, 46 diesel refineries, and 26 restricted refineries, while the R-USA-500kBD-NMC supply chain includes 18 diesel refineries and 32 restricted refineries. Over 100 million metric tons of MSW are utilized per year in both case studies. The R-USA-500kBD-NMC supply chain network is illustrated in Figure 6 and the R-USA-500kBD-MC supply chain network is shown in Figure 7.

12.2 Unrestricted WTL Supply Chains

The summary of results for the WTL supply chains that only allow unrestricted WTL refineries to exist is illustrated in Table 7. The case studies that place no restriction on a minimum number of WTL refineries (*NMC* case studies) have a lower total cost for the supply chain. This is because these case studies select larger WTL refineries (plant scales: 5 kBD and 10 kBD) to be built that have a lower levelized investment cost due to economies of scale.[12] However, the case studies

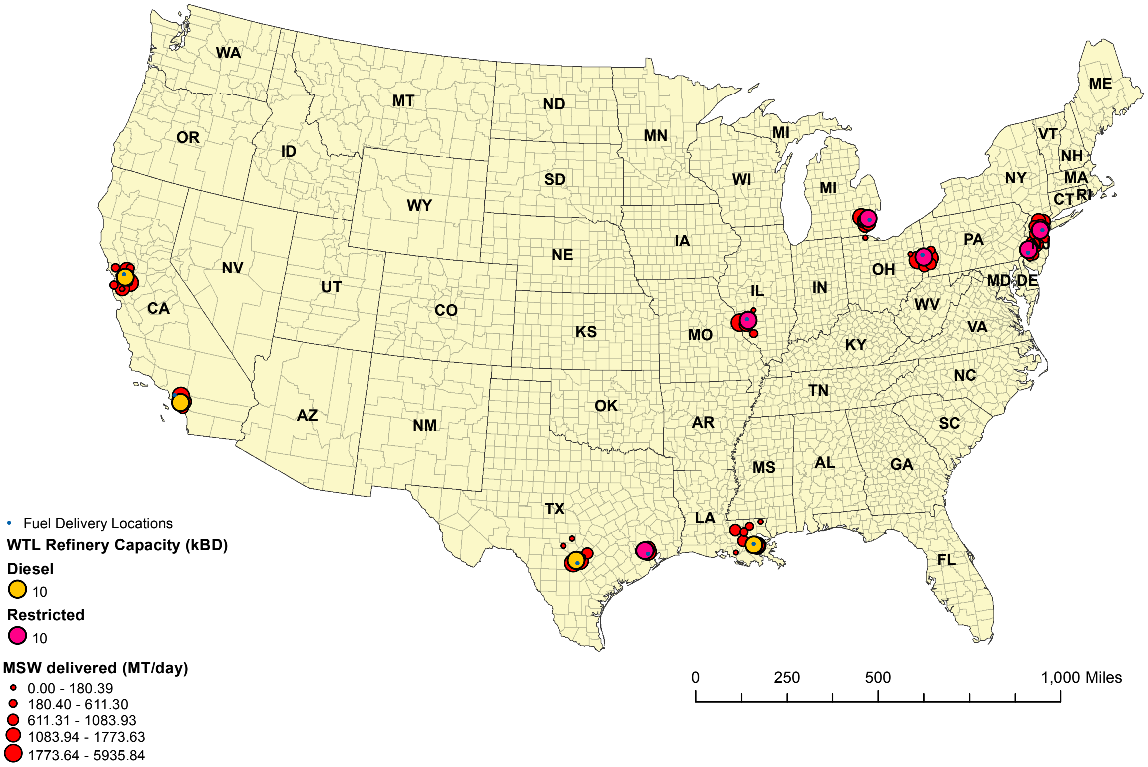

Figure 4: Optimal WTL supply chain network for the R-USA-100kBD-NMC case study.

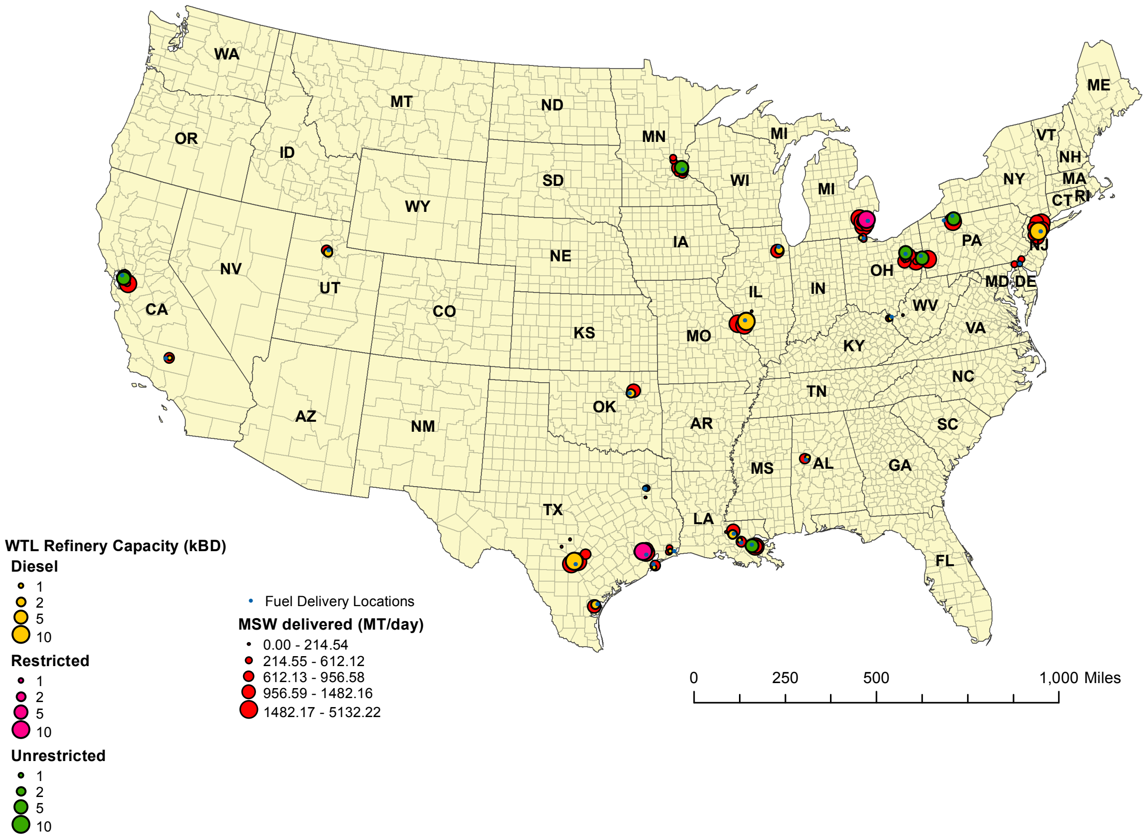

Figure 5: Optimal WTL supply chain network for the R-USA-100kBD-MC case study.

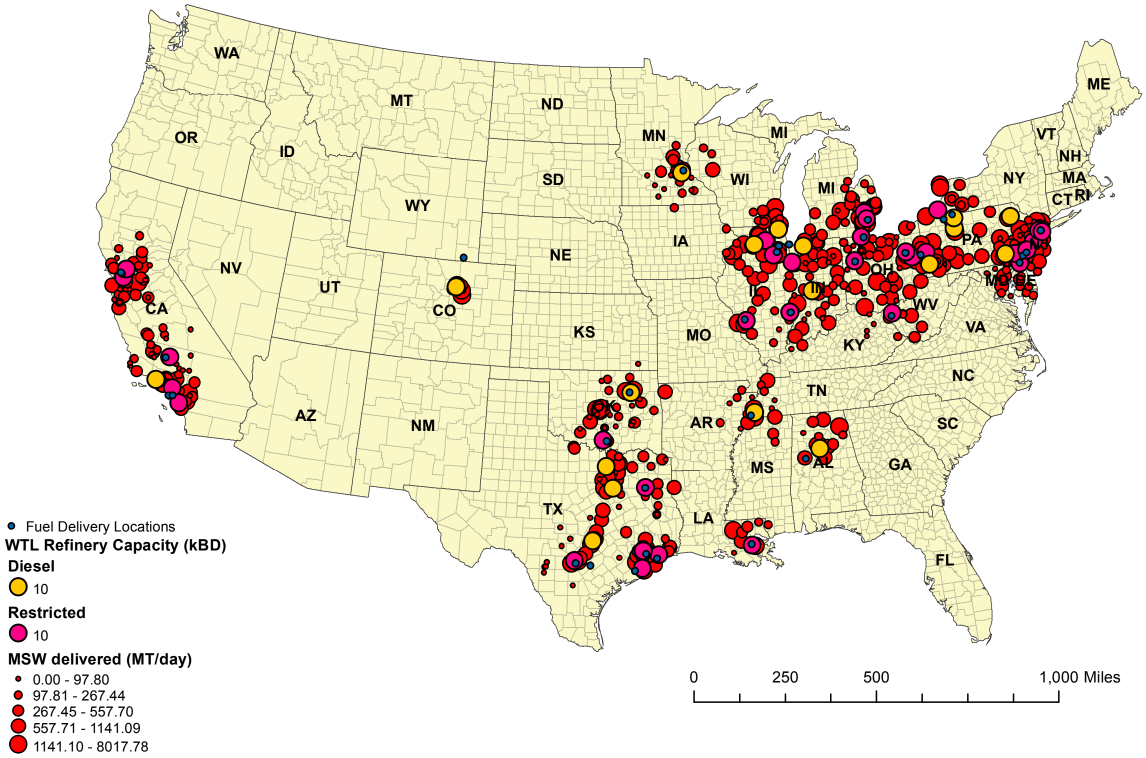

Figure 6: Optimal WTL supply chain network for the R-USA-500kBD-NMC case study.

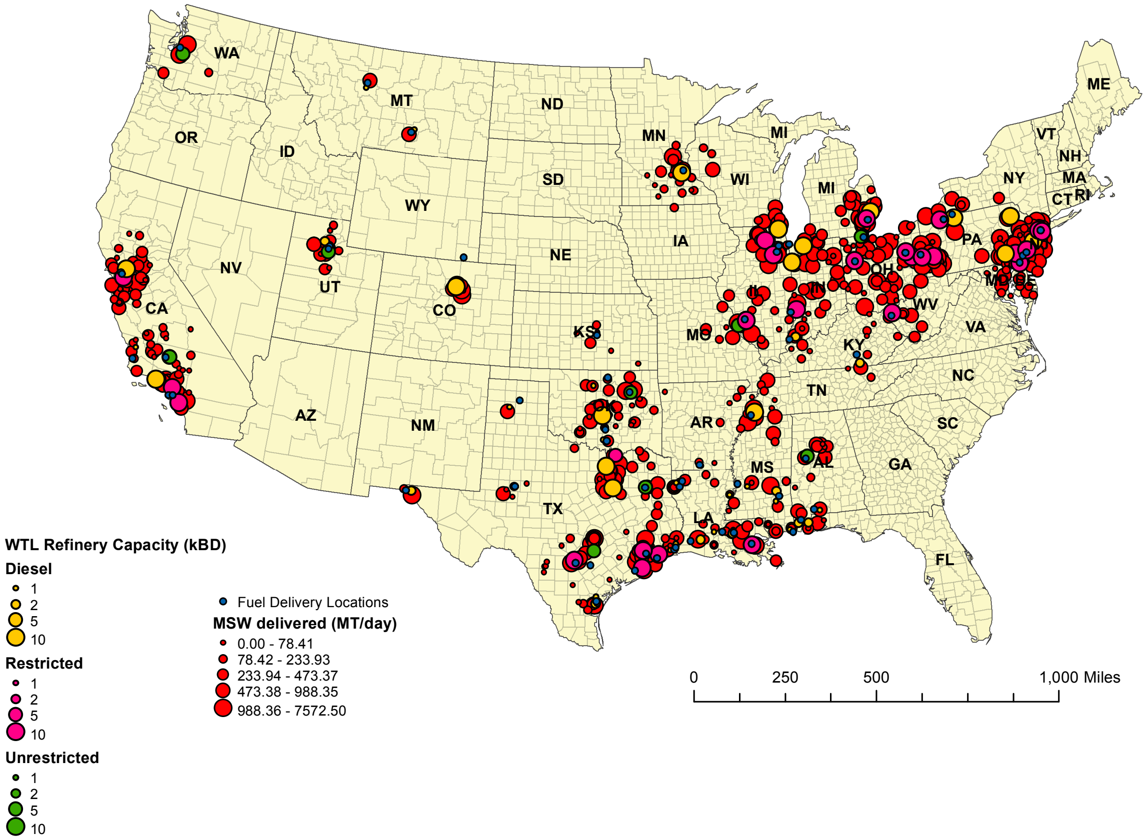

Figure 7: Optimal WTL supply chain network for the R-USA-500kBD-MC case study.

that place a restriction on the minimum number of WTL refineries (*MC* case studies) have lower transportation costs because a larger number of plants are built at strategic locations that minimize the transportation distance for the feedstocks, rejects, and products.

The U-USA-100kBD-NMC case study has a lower total cost of the WTL supply chain network (\$13.81/GJ) than the U-USA-100kBD-MC (\$15.85/GJ) case study because of significantly lower capital and operating costs. The largest contributing factor to the overall cost is the investment cost associated with building these WTL refineries. The investment cost for the U-USA-100kBD-NMC supply chain network is \$9.890 billion dollars and \$11.750 billion dollars for the U-USA-100kBD-MC supply chain network. The BEOP for the U-USA-100kBD-NMC case study is \$63.22/bbl and \$74.48/bbl for the U-USA-100kBD-MC case study.

At the 500 kBD level, once again the U-USA-500kBD-NMC case study has a lower total cost (\$15.04/GJ) than the U-USA-500kBD-MC (\$15.58/GJ) because of the lower capital and operating costs. The U-USA-500kBD-NMC and U-USA-500kBD-MC case studies have required investment costs of \$49.832 and \$52.979 billion dollars, respectively. The BEOP for the U-USA-500kBD-NMC case study is \$70.02/bbl and \$72.96/bbl for the U-USA-500kBD-MC case study.

At the 500 kBD level, the levelized transportation costs for the feedstocks, rejects, and products are higher than at the 100 kBD level. This is due to the fact that more landfills need to be utilized to transport more MSW for conversion into liquid fuels, and these landfills are further away from the candidate refinery locations that are selected. The average distance the feedstocks, rejects, and products have to travel further is larger. Figures 8 - Figure 11 illustrate the locations of the WTL refineries, the landfills that deliver the feedstock to the refineries, and the petroleum refineries that serve as end destinations for the products that are selected from the supply chain optimization for the nationwide unrestricted WTL case studies.

12.3 Nationwide WTL Location Ranking

The supply chain optimization framework can be used to determine the top five most economical locations to build a WTL refinery. Equation(s) 23 is used to determine these locations for the four capacities (1 kBD, 2 kBD, 5 kBD, and 10 kBD) examined in this work. The top five most economical locations for the 1 kBD, 2 kBD, 5 kBD, and 10 kBD WTL unrestricted refineries in

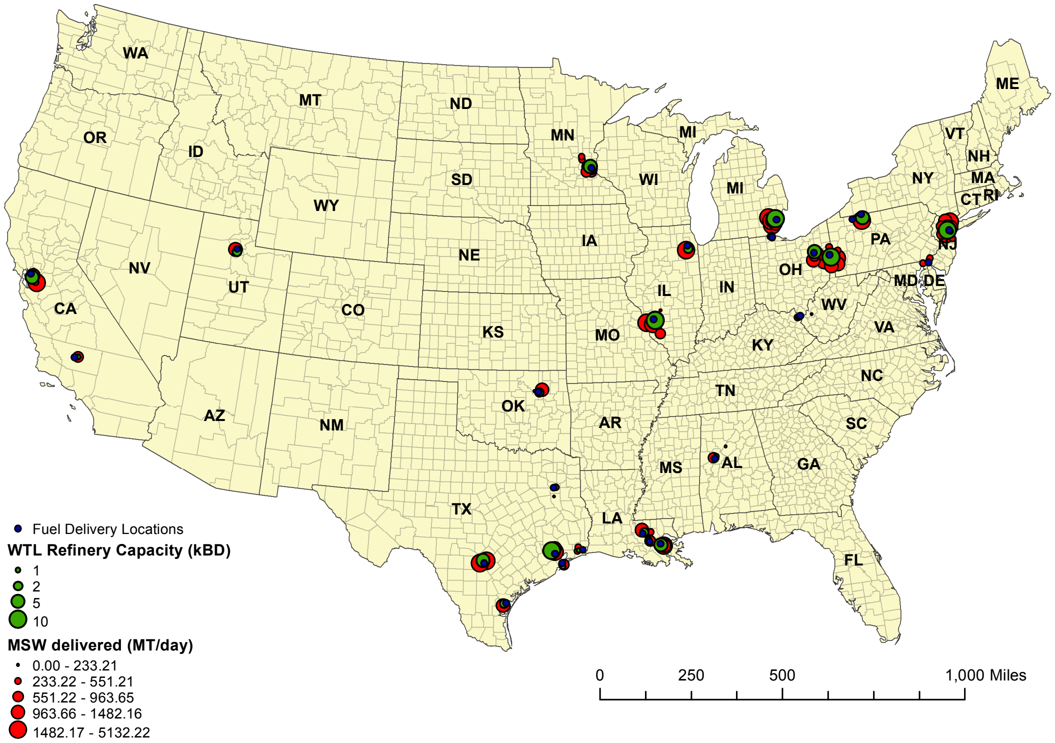

Figure 8: Optimal WTL supply chain network for the U-USA-100kBD-MC case study.

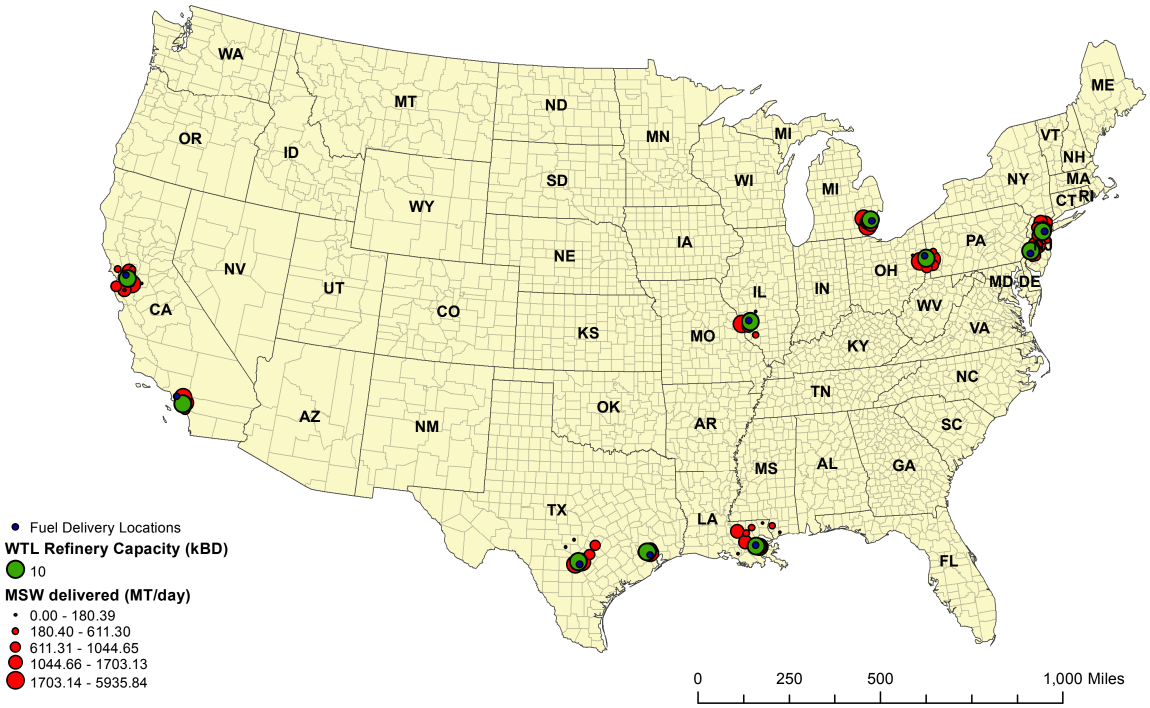

Figure 9: Optimal WTL supply chain network for the U-USA-100kBD-NMC case study.

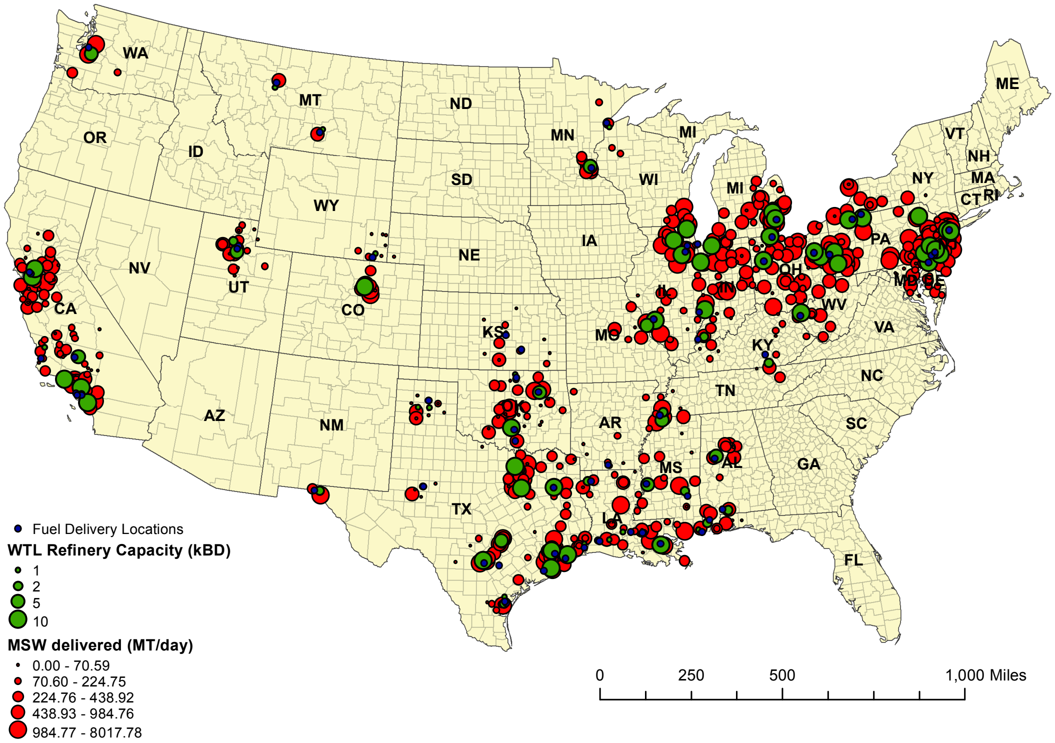

Figure 10: Optimal WTL supply chain network for the U-USA-500kBD-MC case study.

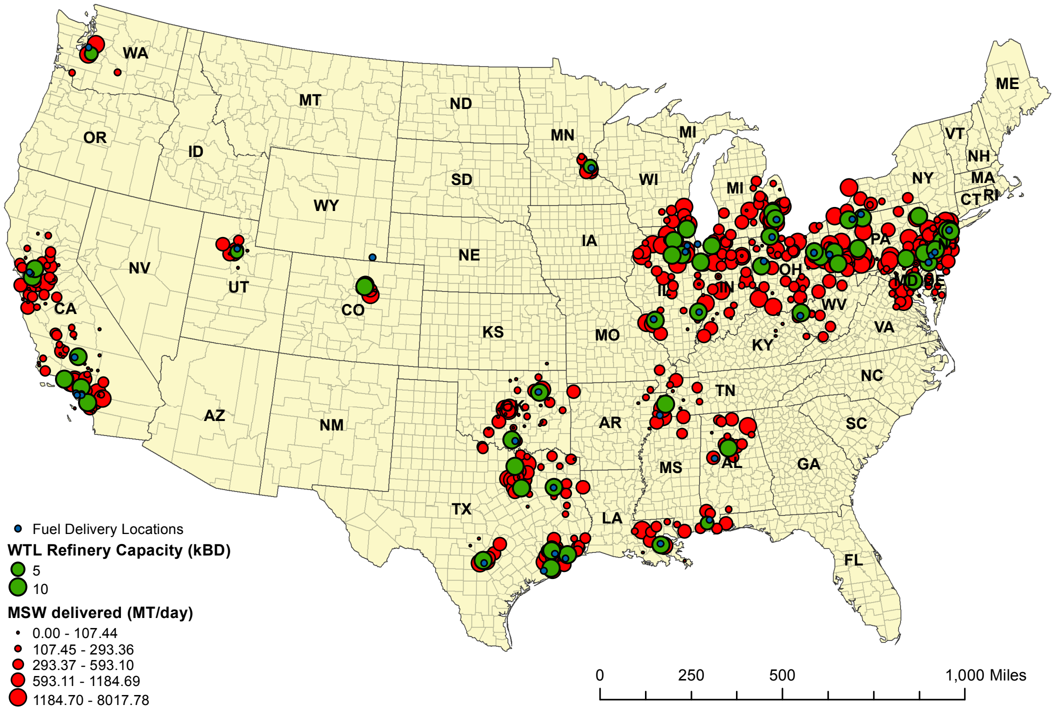

Figure 11: Optimal WTL supply chain network for the U-USA-500kBD-NMC case study.

Table 7: Summary of Results for the Nationwide Unrestricted WTL Supply Chain Case Studies.

Contribution to Cost ($/GJ)	U-USA-100kBD-MC	U-USA-100kBD-NMC	U-USA-500kBD-MC	U-USA-500kBD-NMC
MSW Transportation Costs	1.23	1.44	1.91	2.04
MSW Rejects Transportation Costs	0.21	0.23	0.24	0.25
Product Transportation Costs	0.92	0.97	1.36	1.50
Investment Costs	9.97	8.39	8.99	8.45
RDF Costs	5.59	5.73	5.67	5.73
O&M Costs	2.63	2.21	2.37	2.23
Electricity Costs or Sales	-0.13	-0.54	-0.38	-0.54
LPG Sales	-2.34	-2.34	-2.34	-2.34
MSW Tipping Fee Sales	-2.25	-2.31	-2.29	-2.31
Water Transportation Costs	0.01	0.01	0.01	0.01
Water Refinery Costs	0.02	0.02	0.02	0.02
Total Cost of Supply Chain ($/GJ)	15.85	13.81	15.58	15.04
Break-even oil price, BEOP ($/bbl)	74.48	63.22	72.96	70.02
Investment Cost				
Total (MM $)	11750	9890	52979	49832
Refinery Selection				
Unrestricted Refineries				
1 kBD refineries	10	0	20	0
2 kBD refineries	5	0	10	0
5 kBD refineries	6	0	10	4
10 kBD refineries	5	10	41	48
Product Composition (kBD)				
Gasoline	100.00	100.00	500.00	500.00
Diesel	0.00	0.00	0.00	0.00
Kerosene	0.00	0.00	0.00	0.00
LPG	18.63	18.60	93.06	93.00
MSW Utilized (MT/year)	21,152,118	21,694,208	107,386,607	108,471,409

the U.S. are shown in Figures 12, 13, 14, and 15, respectively. The summary of results for the location ranking is also shown in Table 8. Since the results shown in Table 8 use exact distances for transportation instead of assumptions for this distance (as in [12]), they are more indicative of the expected costs of building a WTL refinery and corroborate the necessity of developing supply chain frameworks at the network scale.

Table 8 shows that at every capacity investigated, the top location to build a WTL refinery is in Madison County, IL. However, as Figures 12-15 and Table 8 show, rankings 2-5 change significantly as the plant capacity changes due to the availability of feedstocks and distances necessary to transport the feedstocks, rejects, and products.

13 Statewide WTL Supply Chain Optimization Case Studies

The supply chain optimization model presented previously can be adapted to investigate statewide WTL supply chains. We investigate the production of 50 kBD of fuels in Texas with no restriction on the capacity of plants (case study: U-TX-50kBD-NMC). We also investigate the top 5 economical locations to build a 10 kBD plant in Texas. Both case studies investigate unrestricted WTL

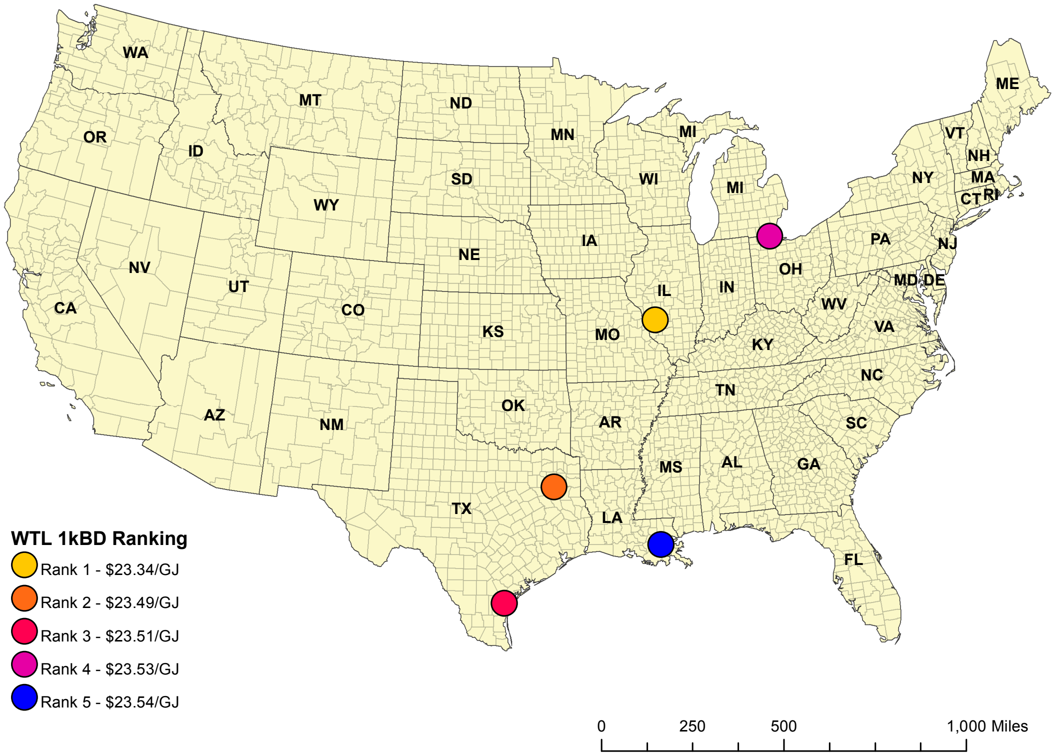

Figure 12: Top 5 most economical locations to build a 1 kBD unrestricted WTL refinery in the U.S.

Table 8: Summary of Results for the Location Ranking of U.S. Unrestricted WTL Refineries.

1 kBD WTL Refineries				2 kBD WTL Refineries			
Rank	Location	Cost ($/GJ)	BEOP ($/bbl)	Rank	Location	Cost ($/GJ)	BEOP ($/bbl)
1	Madison County, IL	23.34	115.71	1	Madison County, IL	19.52	94.68
2	Smith County, TX	23.49	116.51	2	Nueces County, TX	19.73	95.82
3	Nueces County, TX	23.51	116.62	3	St. Charles Parish, LA	19.74	95.86
4	Lucas County, OH	23.53	116.73	4	Will County, IL	19.80	96.19
5	St. Charles Parish, LA	23.54	116.77	5	Ramsey County, MN	19.80	96.20
5 kBD WTL Refineries				10 kBD WTL Refineries			
Rank	Location	Cost ($/GJ)	BEOP ($/bbl)	Rank	Location	Cost ($/GJ)	BEOP ($/bbl)
1	Madison County, IL	15.21	70.95	1	Madison County, IL	13.52	61.66
2	St. Charles Parish, LA	15.33	71.60	2	Harris County, TX	13.60	62.09
3	Jefferson Parish, LA	15.47	72.34	3	Wayne County, MI	13.64	62.29
4	Bexar County, TX	15.54	72.74	4	Union County, NJ	13.71	62.66
5	Union County, NJ	15.57	72.91	5	Richmond County, NY	13.73	62.80

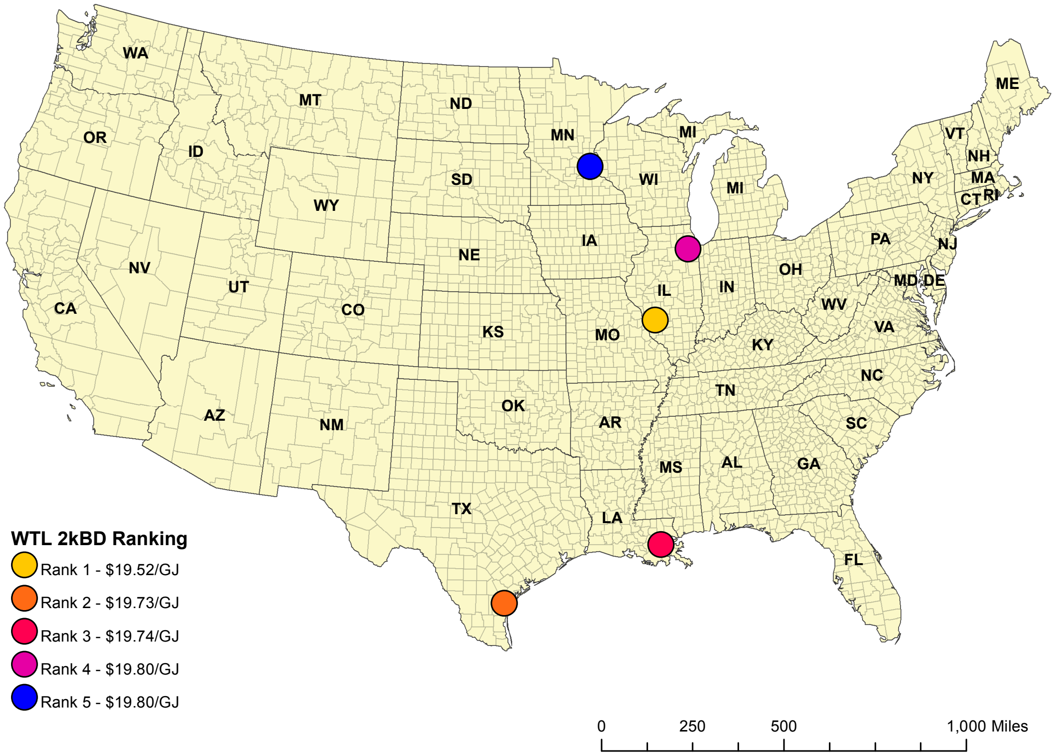

Figure 13: Top 5 most economical locations to build a 2 kBD unrestricted WTL refinery in the U.S.

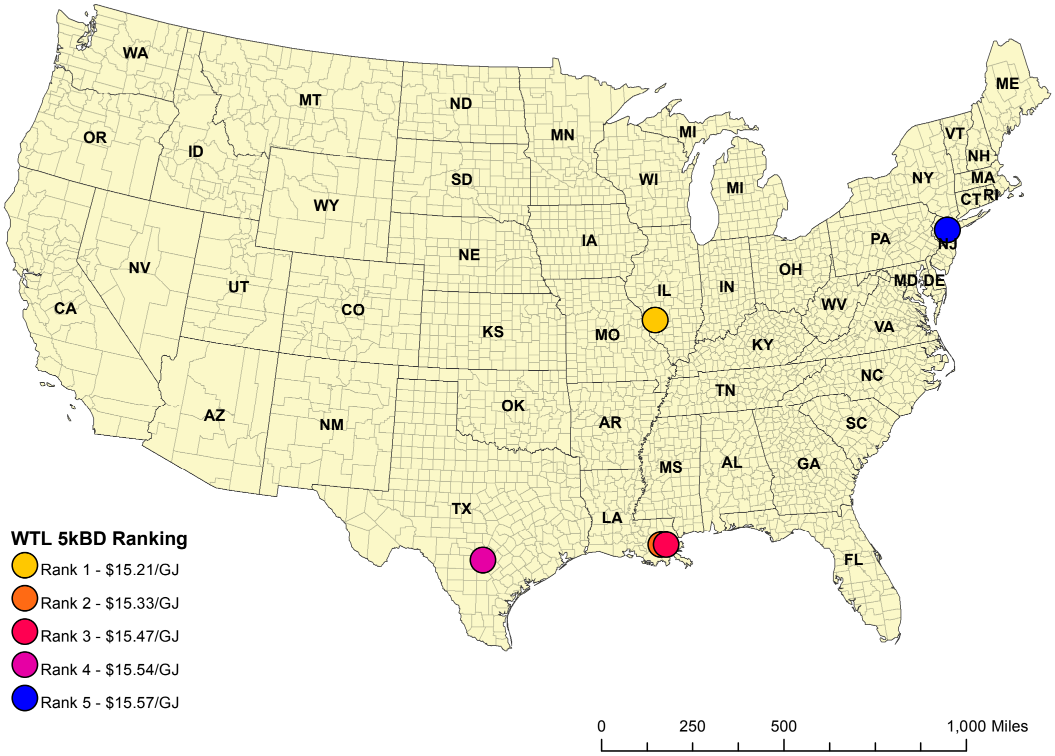

Figure 14: Top 5 most economical locations to build a 5 kBD unrestricted WTL refinery in the U.S.

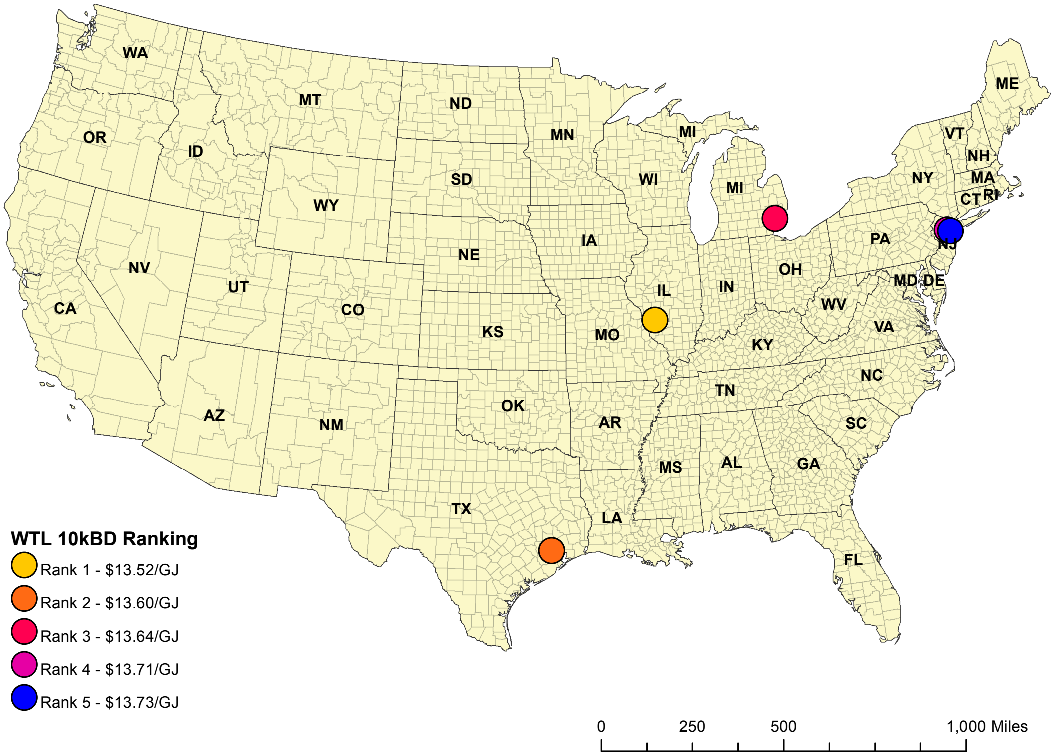

Figure 15: Top 5 most economical locations to build a 10 kBD unrestricted WTL refinery in the U.S.

refineries.

Figure 16 illustrates the top five economical locations to build a 10 kBD WTL refinery in Texas. One refinery is located below the center of the state, while four are clustered around the southeastern portion of Texas. The top location in Texas (which also corresponds to the second most economical location in the nation - see Table 8) has an overall cost of \$13.60/GJ. Together, these top five locations produce a cumulative total of 50 kBD, which poses the question of whether these top five locations would also be selected in a WTL supply chain network producing 50 kBD of liquid fuels.

Figure 17 illustrates the locations of the WTL refineries, the landfills that deliver the feedstock to the refineries, and the petroleum refineries that serve as end destinations for the products that are selected from the supply chain optimization for the Texas WTL 50 kBD network. As is evident from Figures 16 and 17, the top 5 most economical locations to build a 10 kBD WTL refinery in Texas are not all selected for a network that produces 50 kBD. This is primarily due to the feedstock availability in the southeastern portion of Texas. As Table 10 shows, Smith County is included in the WTL 50 kBD network, but is not one of the top 5 most economical locations to build a WTL refinery. This comparison illustrates the need to be conscientious of these factors during a planning phase for refinery construction.

Table 9 shows the breakdown for the total cost of the Texas supply chain producing 50 kBD. The total cost of the Texas supply chain is \$14.36/GJ, with a BEOP of \$66.26/bbl and required investment cost of \$4.945 billion dollars. The total MSW utilized for a network of this size surpasses 10 MM metric tons/year.

14 Conclusions

An optimization-based supply chain framework is proposed and solved for the efficient management of waste to liquid systems in the United States. The framework incorporates optimized WTL refineries and integrates across the entire WTL value chain to yield the strategic placement of WTL refineries at the lowest cost. The operational and static input and output data of the refineries, together with locations of MSW landfills, locations of end destinations for the products, candidate refinery locations, and water resources are considered. The economic and operational tradeoffs

Table 9: Summary of Results for the Texas WTL Supply Chain Case Study.

Contribution to Cost ($/GJ)	U-TX-50kBD-NMC
MSW Transportation Costs	1.90
MSW Rejects Transportation Costs	0.25
Liquid Fuels Transportation Costs	1.04
Investment Costs	8.39
RDF Costs	5.73
OM Costs	2.21
Electricity Costs or Sales	-0.54
LPG Sales	-2.34
Tipping Fee Sales	-2.31
Water Transportation Costs	0.02
Water Refinery Costs	0.02
Total Cost of Supply Chain ($/GJ)	14.36
Break even oil price ($/bbl)	66.26
Investment Cost	
Total (MM $)	4945
Refinery Selection	
1 kBD refineries	0
2 kBD refineries	0
5 kBD refineries	0
10 kBD refineries	5
MSW Utilized (MT/year)	10,847,097

Table 10: Summary of Results for the Location Ranking of Texas Unrestricted WTL Refineries and Comparison with 50 kBD Network.

10 kBD Texas WTL Refineries Ranking				U-TX-50kBD-NMC
Rank	Location	Cost ($/GJ)	BEOP ($/bbl)	Location
1	Harris County	13.60	62.09	Harris County
2	Bexar County	13.79	63.10	Bexar County
3	Brazoria County	14.22	65.46	Brazoria County
4	Galveston County	14.25	65.65	Smith County
5	Chambers County	14.48	66.89	Chambers County

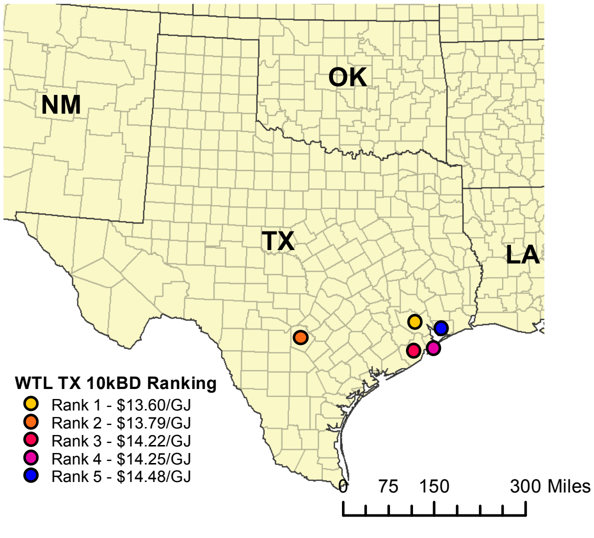

Figure 16: Top 5 most economical locations to build a 10 kBD WTL refinery in Texas.

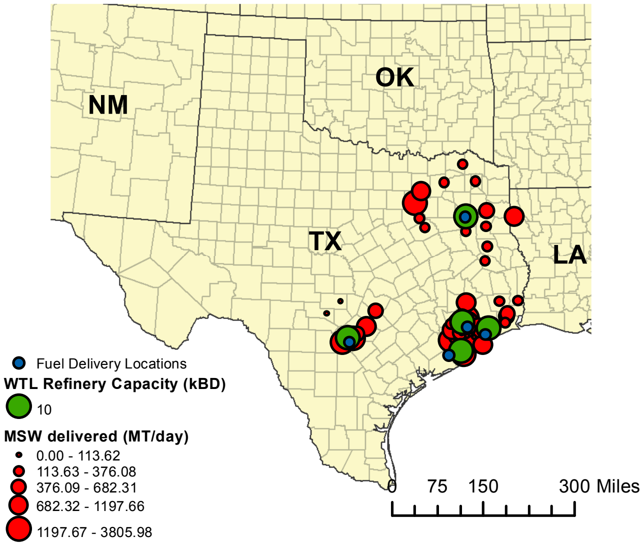

Figure 17: Optimal WTL supply chain network for the U-TX-50kBD-NMC case study.

for nationwide and statewide WTL supply chains are investigated. The mathematical optimization model is also adapted to determine the top 5 most economical locations to build WTL refineries.

Two sets of nationwide case studies are investigated. The first set, which imposes a minimum amount of diesel to be produced, has BEOPs that range between \$64 - \$77/bbl. The second set, which only allows unrestricted WTL refineries to exist, has BEOPs ranging between \$63.22/bbl to \$74.48/bbl. The Texas statewide supply chain has a BEOP of \$66.26/bbl. For the nationwide location ranking case studies, Madison County, IL was consistently the top location to build a WTL refinery across all plant capacities investigated. The optimal results indicate that building a large-scale system of WTL refineries that produces 500 kBD of liquid transportation fuels poses no logistical constraints with regards to MSW availability and can reduce the amount of MSW landfilled by over 107 MM metric tons per year.

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Appendix A

Table 11 displays the general abbreviations present throughout the manuscript.

Table 11: General abbreviations

Symbol	Definition
MSW	Municipal solid waste
WTL	Waste to liquids
kBD	Thousand barrels per day
$MILP$	Mixed-integer linear optimization
$epgap$	relative stopping tolerance
$epagap$	absolute stopping tolerance
$O\&M$	Operating and maintenance
RDF	Refuse derived fuel
LPG	Liquefied petroleum gas
GJ	Gigajoule
CO_2	Carbon dioxide
EPA	Environmental Protection Agency
DFC	Distance fixed cost
DVC	Distance variable cost
DM	Distance multiplier
N	Fuel composition of the products for plant
C	Capacity of plant

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Manuscript highlights:

1 A comprehensive nationwide municipal solid waste to liquid fuels supply chain management framework is introduced

2 The optimal topological feedstock and product flows are determined via a mixed-integer linear optimization model

3 A comprehensive analysis of the amount and locations of landfilled MSW in the U.S. are described

4 The supply chain optimization framework is used to determine the location ranking of WTL facilities across the U.S.

5 The capabilities of the framework are illustrated for nationwide and statewide case studies