Overview of the Regional Bio-Economy Model (RBEM)

Daniel Inman,[1] Steve Peterson,[2] and Emily Newes[1]

1 The National Renewable Energy Laboratory
2 Steven O. Peterson, Consultant

NREL is a national laboratory of the U.S. Department of Energy
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15013 Denver West Parkway
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List of Acronyms

A4A	Airlines for America
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet fuel
BETO	Bioenergy Technology Office
BSM	Biomass Scenario Model
DOE	U.S. Department of Energy
EE	elementary effects
FCI	fixed capital investment
FOG	fats, oils, and greases
FT	Fischer-Tropsch
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
GGE	gasoline-gallon equivalent
GHG	greenhouse gas
GPY	gallons per year
HEFA	hydrotreated esters and fatty acids
HSF-SIP	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins
HTL	hydrothermal liquefaction
MFSP	minimum fuel selling price
NREL	National Renewable Energy Laboratory
NPV	net present value
ORD	Chicago O'Hare International Airport
POTW	publicly owned treatment works
RBEM	Regional Bioeconomy Model
SAF	sustainable aviation fuels
USD	U.S. dollars

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1 Introduction

To better understand possible regional evolution scenarios for the sustainable aviation fuel (SAF) supply chain, we have developed the Regional Bioeconomy Model (RBEM). RBEM is a dynamic model that can be used to create potential development scenarios for bioenergy fuels within a defined region. The current version of the model is focused on the development of SAF in the region surrounding Chicago O'Hare International Airport (ORD). However, the model can be adapted to address other regions and other fuel mixes. RBEM is intended to gain insight into key questions related to the development of the SAF industry. Specifically, what could spur/accelerate SAF development and what are the distinguishing features of the SAF market scale-up.

Recent decarbonization goals and market pressures, within the United States and globally, have led airlines to commit to aggressive strategies to reduce carbon emissions in their fleets. For example, U.S. airlines, through the trade group Airlines for America (A4A), have committed to a three-pronged approach to reduce carbon emissions. This approach includes the following: (1) limit net carbon emissions to 2019 levels; (2) invest SAF technological development to enable 2 billion gallons of cost-competitive SAF (~ 8% of 2019 aviation fuel) to be produced by 2030; (3) reduce net carbon emissions to zero by 2050 (Airlines for America 2021). To encourage development of SAF, A4A supports a suite of policy incentives (Table 1).

Table 1. Proposed SAF Incentives Supported by Airlines for America (Airlines for America 2021)

Incentive Type	Description
SAF Blender's Tax Credit	Federal approval of a 10-year performance-based SAF blender's tax credit, at $1.50/gallon for SAF that achieves a 50% life cycle greenhouse gas (GHG) emissions benefit and additional credit up to $2/gallon for SAF with GHG emissions savings above 50%. Note that the this proposed tax credit pre-dates the Inflation Reduction Act of 2022 (IRA) and the proposed level of credit is greater than what is in the IRA. (Congress 2022)
SAF Production Tax Credit	Establish a tax credit for the annual production of SAF, in addition to an SAF blender's tax credit, akin to the credit in Internal Revenue Code Section 40(b)(6) for the production of second-generation biofuels, or the credit in Section 40A(b)(4) for the production of small agri-biodiesel quantities, or the credit in Section 45H for the production by small business refiners of low-sulfur diesel fuel (Code 2011).
Capital Grants and Loan Guarantees	Enable SAF producers to construct facilities and establish or scale up operations by creating a new U.S. Department of Transportation / Federal Aviation Administration competitive grant program and a new loan guarantee program specific to SAF producers.
SAF Research and Development	Interagency review and update of the 2016 Federal Alternative Jet Fuels Research and Development Strategy to prioritize and accelerate federal research and development initiatives to address key scientific and technical challenges that inhibit the development,

Incentive Type	Description
	widescale production and use of economically viable SAF (International Air Transport Association 2020); enhanced federal support for FAA's SAF research and development work, with at least $30 million in annual appropriations for at least 5 fiscal years.
U.S. Department of Energy (DOE) Support	Provide additional financial support for SAF production/manufacturing (and/or SAF research and development) through DOE's Bioenergy Technologies Office, with the goal of ensuring aviation and SAF are not disfavored vis-à-vis on-road vehicles and alternative fuels used in ground transportation.
ASTM International Support	Support the ASTM International Review and Approval Process for SAF Pathways; direct funding assistance for the FAA-established ASTM D4054 Clearinghouse, which seeks to increase the efficiency of the SAF qualification process (ASCENT 2019).

The aviation fuel market is markedly different from that of ground transportation fuels in its supply and distribution network and demand centers. For example, the 2019 market for aviation fuel in the United States was 26 billion gallons per year (Airlines for America 2021), which is approximately one-seventh the size of the ground transportation market for the same year (DOE Office of Energy Efficiency and Renewable Energy 2020). Before the COVID-19 pandemic, passenger demand was expected to double by 2040. Recent projections of passenger demand are less bullish; U.S. airline passenger demand is expected to recover to 2019 levels by 2023 and grow at an annual rate of ~2% (International Air Transport Association 2021). Aviation fuel is primarily purchased via long-term purchasing agreements with suppliers; fuel moves in large batches from the point of production to point of use through pipelines or via barges. Fuel costs comprise up to 30% of an airline's annual operating expenses, which leaves airlines exposed to price fluctuations. Although airlines are sensitive to fuel price fluctuations, customers may be willing to pay a premium for SAF, which could help offset any additional costs incurred in its production. A recent DOE report suggests that demand for SAF could be less elastic than for petroleum-based aviation fuels because airline passengers have demonstrated a willingness to pay additional costs to support SAF usage (DOE Office of Energy Efficiency and Renewable Energy 2020).

In 2022, SAF comprised < 0.1% (15.8 million gallons) of the total aviation fuel market (Airlines for America 2021) (GAO 2023). DOE has recently begun to invest heavily in research and development efforts to make SAF more competitive with conventionally produced aviation fuels. Significant work remains in terms of investment in, and at-scale deployment of, SAF. The current market price for SAF is high compared to conventional aviation fuel (Kohlman 2020) (Figure 1). Such price differences are to be expected for developing technologies when compared to commercially mature incumbent technologies. Industrial scale-up and the associated learning dynamics may compensate for this gap between the price for incumbent aviation fuel technologies and the current market price for SAF. Understanding the system behaviors that lead to broad SAF investment and market penetration could inform the development of strategies that more effectively lead to SAF deployment.

Because of the structure of the aviation fuel market, the SAF industry will likely develop regionally, with the largest airports being the first movers. Insight into how the SAF industry develops at the regional level will provide stakeholders with regionally specific information on the key barriers and synergies for a given region.

In the following sections, we provide a brief description of the analytic framework and modeling approach used to develop the model. This description is followed by a top-down view into the model's structure, beginning with an overview of the RBEM supply chain and then drilling down into the modules that represent specific supply chain elements.

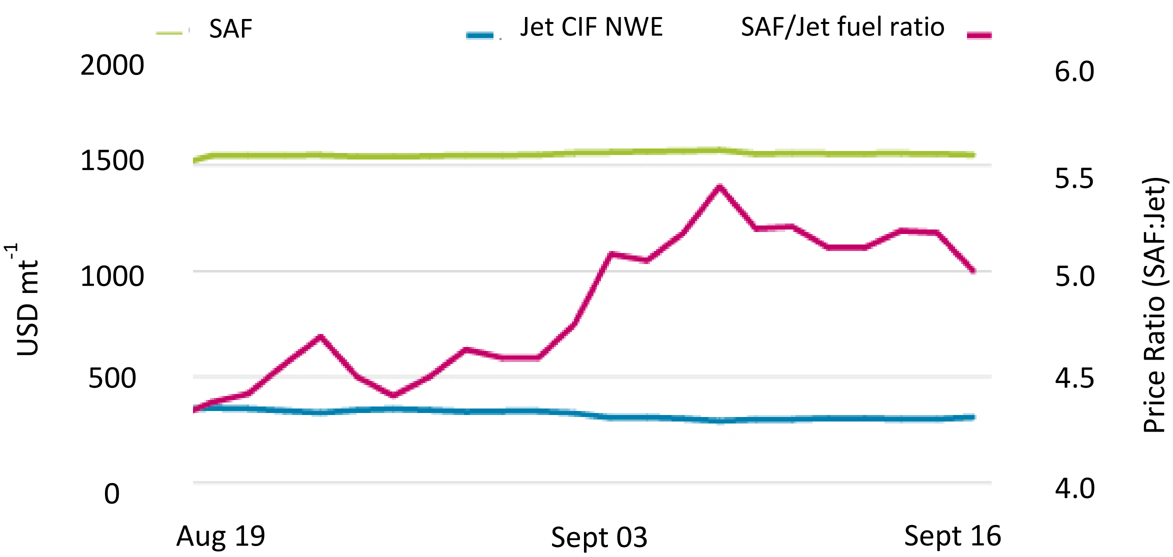

Figure 1. Price comparison of SAF and conventional aviation fuel for the period 08/19/2020–09/16/2020. The left axis is USD per metric ton (mt) of aviation fuel; the right axis is the price ratio of SAF to conventional jet fuel, based on the delivered price of jet fuel in Western Europe.

CIF NWE = cost, insurance, and freight charges for shipping products in Northwestern Europe.

Figure is modified from (Kohlman 2020).

2 Analytic Framework and Modeling Approach

To develop the current version of RBEM (GitHub commit 725d892), we adapted tools from the system dynamics toolset using agile development approaches. The system dynamics approach has been used extensively at the National Renewable Energy Laboratory (NREL) and elsewhere to develop models of energy supply chains (NREL 2022). In the RBEM model, we make extensive use of the stock-and-flow organizing framework from the system dynamics toolset. Stocks represent accumulations such as inventories or production capacities. Flows represent activities, such as producing, consuming, or investing, that cause accumulations to grow or decline over time. Sterman (2006) provides more detail on the system dynamics approach.

The model was developed with the Stella software (isee systems 2010). In creating the model, we used the following practices:

- **Sprints**. The team worked in an intensive, week-long sprint to develop the initial prototype model version of the model. Subsequent sprints were used to evolve the model to its current form and to conduct an initial analysis with the model.
- **Reuse/adaptation of structures from existing models**. Many of the structural components of the RBEM were developed originally in the context of other bioenergy models at NREL. In particular, the investment and production logic found within the RBEM's conversion module is adapted from work originally developed in the context of NREL's Biomass Scenario Model (BSM) project (NREL 2022).

2.1 Model Overview

RBEM aims to improve understanding related to the development of supply/value changes for bioenergy fuels within a defined region. While the model can be adapted to other regions, the current version of the model focuses on the region surrounding ORD. The model addresses the potential for SAF produced by one of four separate feedstock-conversion pathways. Three of these pathways have been certified by ASTM International for use in aviation fuel (Table 2).

Table 2. Feedstocks and Associated Conversion Processes Represented in RBEM

Feedstock	Conversion Process	ASTM Certified
Soybean oil Distiller corn oil Fats, oils, greases (FOG)	Hydroprocessed esters and fatty acids (HEFA)	Yes
Sludge from publicly owned treatment works (POTWs)	Hydrothermal liquefaction (HTL)	No
Corn stover	Alcohol-to-jet (ATJ)	Yes
Woody forest residues	Fischer-Tropsch (FT)	Yes

RBEM is constructed in a top-down fashion, using modules to represent the different aspects of the supply chain (Figure 2). At the left side of Figure 2 are feedstock modules. These modules contain supply and price estimates, along with an allocation logic for each feedstock represented in RBEM. For each feedstock module, we represent feedstock availability as a set of discrete quantities, prices, and transport costs at 0–50-, 50–100-, and 100–200-mile radial distances from

ORD. These static supply/price/cost combinations form a set of tranches from which feedstock demand is satisfied. The conversion module captures the buildout of conversion operations within the region, incorporating calculations of investment, production, and industrial learning for each of the conversion processes represented. Investment in conversion facilities can be specified to operate endogenously, determined by the potential financial feasibility of the prospective investment. Alternately, economic viability of an investment can be simulated in response to an exogenously specified decision to invest in a conversion facility. At the right side of Figure 2 is the end-use module, which contains scenarios related to oil prices, as well as logic related to potential policy initiatives such as carbon taxes and low-carbon fuel standards. The end-use module also accounts for displaced petroleum from SAF.

Overall, the model serves as a framework to account for potential impacts of SAF development within a region, given scenarios around feedstock cost and availability in the context of petroleum price scenarios and policy settings. The model is solved numerically at a sub-monthly level and typically reports output for the time frame of 2020 to 2040.

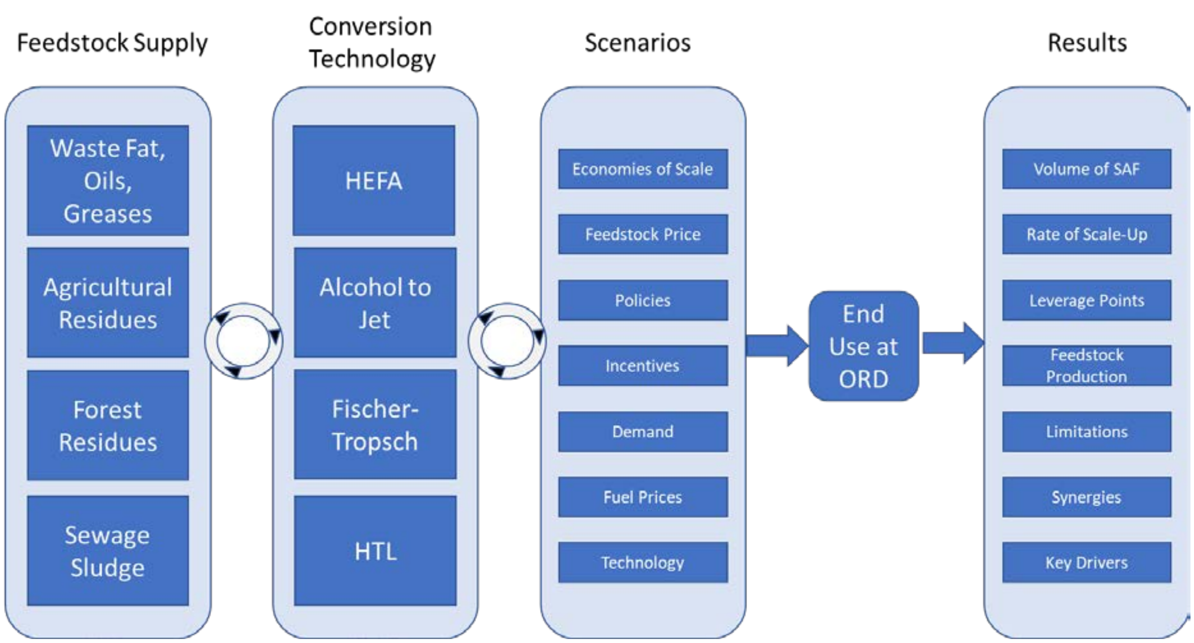

Figure 2. Schematic of RBEM. Modules and key attributes are shown for reference.

2.2 RBEM Modules

The modules within RBEM correspond to feedstock supply, conversion processes, and end uses. In this section, we provide a brief description of each module.

2.2.1 FOG FS

The FOG FS module tracks the supply and demand of FOG in response to demand from the conversion module. FOG feedstocks are associated with the HEFA conversion process. We represented FOG feedstock availability as a set of discrete quantities, prices, and transport costs at 0–50-, 50–100-, and 100–200-mile radial distances from ORD. These static supply/price/cost combinations form a set of tranches from which feedstock demand is satisfied. Quantity and price data are derived from Milbrandt (2020); transport costs are developed based on Dickerson and Rubin (2009) Table 3.

A logit allocation mechanism, based on the price of feedstock delivered to the biorefinery, is used to apportion feedstock demand among the different feedstock supply tranches. The default mechanism favors lower-cost feedstocks before higher-cost feedstocks; this default configuration can be modified such that feedstock demand is met by a broader portfolio of feedstock tranches. The HEFA biorefinery is assumed to be located adjacent to ORD.

The FOG FS module tracks the supply and demand of FOG in response to demand from the conversion module. FOG feedstocks are associated with the HEFA conversion process. The price represents the feedstock price at the gate of the conversion facility and includes transport costs. Quantity and price data are derived from Milbrandt (2020); transport costs are developed based on Dickerson and Rubin (2009) Table 3.

Table 3. FOG Quantities, Prices, and Transport Costs at Different Radial Distances from ORD.

Distance from ORD (mi)	Quantity (ton/yr)	Price (USD/ton)	Transport to ORD (USD/ton)
0–50	99,543	466	4.5
50–100	430,017	466	9
100–200	2,542,865	466	18

A logit allocation mechanism, based on the price of feedstock delivered to the biorefinery, is used to apportion feedstock demand among the different feedstock supply tranches. The default mechanism favors lower-cost feedstocks before higher-cost feedstocks; this default configuration can be modified such that feedstock demand is met by a broader portfolio of feedstock tranches.

2.2.2 Stover FS

Corn stover feedstocks are used for cellulosic ATJ conversion in RBEM. Stover feedstock is modeled in three tranches (based on collection area), with static quantities, prices, and transport costs at 0–50-, 50–100-, and 100–200-mile radial distances from ORD. Stover supplies are based on source data from the Billion-Ton Study (DOE 2016). Raw supply data from the Billion-Ton Study were processed using the geopandas package in Python (Kelsey Jordahl 2020), while using ORD as the centroid.

Table 4. Stover Quantities, Prices, and Transport Costs at Different Radial Distances from ORD

Distance from ORD (mi)	Quantity (ton/yr)	Price (USD/ton)	Transport to ORD (USD/ton)
0–50	1,895,799	48	16.08
50–100	7,259,591	48	16.08
100–200	17,510,764	48	16.08

A logit allocation mechanism, based on the price of feedstock delivered to the biorefinery, apportions feedstock demand among the different feedstock supply tranches. The default mechanism configuration is to consume lower-cost feedstocks before higher-cost feedstocks; this default configuration can be modified such that feedstock demand is met by a broader portfolio of feedstock tranches. The ATJ biorefinery is assumed to be adjacent to ORD.

2.2.3 Woody FS

In RBEM, woody feedstocks consist of forest residues and are associated with Fischer-Tropsch (FT) conversion. We use three supply tranches to capture static quantities, prices, and transport costs at 0–50-, 50–100-, and 100–200-mile radial distances from ORD. These static feedstock supplies are based on source data from the Billion-Ton Study (DOE 2016). Raw supply data from the Billion-Ton Study were processed using the geopandas package in Python (Kelsey Jordahl 2020), while using ORD as the centroid.

Table 5. Forest Residue Quantities, Prices, and Transport Costs at Different Radial Distances from ORD

Distance from ORD (mi)	Quantity (ton/yr)	Price (USD/ton)	Transport to ORD (USD/ton)
0–50	143,338	60	17.80
50–100	493,633	60	17.80
100–200	1,789,656	60	17.80

As with other feedstocks, a logit allocation mechanism is used to apportion feedstock demand among the different feedstock supply tranches. The mechanism is configured in the default to consume lower-cost feedstocks before higher-cost feedstocks; this default configuration can be modified such that feedstock demand is met by a broader portfolio of feedstock tranches. The FT biorefinery is assumed to be adjacent to ORD.

2.2.4 Sludge FS

Sludge feedstocks in RBEM consist of sewage sludge from POTWs. RBEM associates sludge feedstock with HTL conversion. Sludge feedstock availability is represented as a set of discrete quantities, prices, and transport costs at 0–50-, 50–100-, and 100–200-mile radial distances from ORD. Sludge supplies are estimated using source data from Seiple, Coleman, and Skaggs (2017).

Table 6. Sludge Quantities, Prices, and Transport Costs at Different Radial Distances from ORD

Distance from ORD (mi)	Quantity (ton/yr)	Price (USD/ton)	Transport to ORD (USD/ton)
0–50	841,763	0	5.5
50–100	441,173	5.36	11
100–200	940,497	6.45	22

As with other feedstocks, a logit allocation mechanism apportions feedstock demand among the different feedstock supply tranches based on delivered costs at the biorefinery. The mechanism is configured in the default to consume lower-cost feedstocks before higher-cost feedstocks; this default configuration can be modified such that feedstock demand is met by a broader portfolio of feedstock tranches. Rather than co-locating the biorefinery at POTWs, the HTL biorefinery is assumed to be adjacent to ORD.

2.2.5 Feedstock Transportation Costs

Transportation costs for the SAF feedstocks identified in this document are uncertain because there is yet to be a large-scale market and supply chain developed. The costs assumed for transportation are based on a combination of literature review and interviews with waste management companies and consultants. The feedstocks that are included in RBEM vary widely in their physical characteristics, from dried agricultural and forestry residues to liquid sewage sludge and waste FOG.

Due to these uncertainties, the only transportation costs that are assumed to make plant-gate price vary with distance are those for FOG. The distance-based variation in transportation costs and plant-gate prices are shown in Table 6. These effects are based on the quantities shown in Table 7.

Table 7. Costs for Truck and Pipeline Transportation of Sewage Sludge, FOG, and Bio-Oil

Mode	Capacity	Feedstock	Solids (%)	Costs (USD/mile)	Notes
Truck	30 M^3	Sewage sludge	20	0.51	Owned
Truck	40 M^3	Sewage sludge	20	0.72	Owned
Truck	30 M^3	Sewage sludge	20	4.56	Rental
Truck	40 M^3	Sewage sludge	20	4.76	Rental
Pipeline	150 M^3 d^{-1}	Sewage sludge	5	1.3555	4"-diameter pipe
Pipeline	200 M^3 d^{-1}	Sewage sludge	5	0.956	4"-diameter pipe
Pipeline	350 M^3 d^{-1}	Sewage sludge	5	1.1911	6"-diameter pipe
Pipeline	450 M^3 d^{-1}	Sewage sludge	5	0.8723	6"-diameter pipe
Pipeline	550 M^3 d^{-1}	Sewage sludge	5	1.012	7"-diameter pipe
Pipeline	700 M^3 d^{-1}	Sewage sludge	5	1.0145	8"-diameter pipe
Pipeline	800 M^3 d^{-1}	Sewage sludge	5	0.8315	8"-diameter pipe
Pipeline	1,000 M^3 d^{-1}	Sewage sludge	5	0.8908	9"-diameter pipe
Truck	46,000 lb	FOG	n/a	2.08	Owned
Truck	46,000 lb	FOG	n/a	4.0	Rental
Truck	30 M^3	Bio-oil	n/a	0.035*	USD per gallon-mile
Truck	60 M^3	Bio-oil	n/a	0.035*	USD per gallon-mile
Truck	n/a	Green wastes	n/a	2.77*	USD per sh.ton

Costs are based on a combination of literature review and consultation with providers. Truck and pipeline costs are from Marufuzzaman, Eksioglu and Hernandez (2015), FOG transportation costs are from Greasehauler (2022) and Greasezilla (2022), bio-oil costs are from Pootakham and Kumar (2010), and green waste costs by truck are from CalRecycle (2019).

2.2.6 Conversion

The conversion module is used to simulate the investment and operation and utilization dynamics for multiple potential SAF production pathways:

- HEFA using FOG as feedstock.
- Cellulosic ATJ using stover from corn.
- FT using woody forest and urban residues.
- HTL using sewage sludge from POTWs.

Key features of this module include:

- Techno-economics estimates for each process.
- Investment in new facilities
- Operation of on-line facilities determinants of production and feedstock demand
- Accounting for financial performance of the SAF conversion operation(s) at ORD.
- Technologies are not competed against each other but are instead simulated in isolation.

2.2.6.1 Techno-Economics

Techno-economic inputs to the conversion module consist of attributes such as throughput capacity, fixed capital investment, process yield, and operating costs. Table 8 summarizes key inputs used in the conversion module (Tao 2022).

Table 8. Key Techno-Economic Inputs

Attribute	Fog-HEFA	Stover-ATJ	Woody-FT	Sludge-HTL
Throughput capacity (ton/yr)	89,586	1,105,492	1,505,447	36,300
Fixed Capital Investment (FCI) (USD)	135,210,506	59,6731,061	897,593,634	58,964,886
Fixed operating cost (USD/yr)	7,919,958	15,881,169	39,688,677	3,467,260
Other variable operating costs (USD/yr)	8,643,931	35,706,458	13,329,780	791,897
Power sales (USD/yr)	0	3,379,519	6,564,891	0
Coproduct sales (USD/yr)	2,021,105	44,270,811	39,980,459	0
Process yield (gal/ton)	284.9	45.6	64.6	97.27

2.2.6.2 Investment in New Facilities

The conversion module can be configured to simulate the implications of investment in a single facility that is “forced” into the system, or to *endogenously* invest in facilities based on a minimum fuel selling price (MFSP) metric (Figure 4). Single-facility investment begins in simulated year 2024.

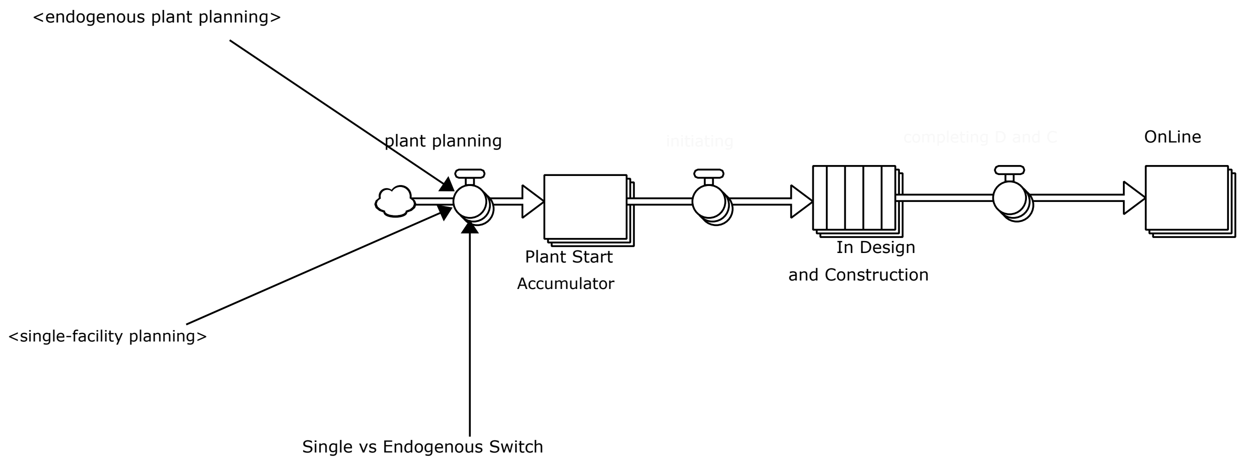

Figure 3. Simplified representation of the conversion facility development process. Based on switch setting, single facility vs. endogenous planning logic is active. The plant start accumulator translates a continuous signal into a batch signal, which then moves through the design-construction phase to come online.

On the other hand, endogenous investment is based on an MFSP metric. These MFSP-based simulations internally generate an investment signal when the calculated minimum SAF selling price, after accounting for incentives, is lower than the prevailing petroleum-based aviation fuel price that comes from the end-use module and is based on U.S. Energy Information Administration (EIA) projections or user-defined scenarios. The model limits endogenous investment to a single facility by default (this constraint can be relaxed if desired).

The calculation for MFSP is based on a discounted cash flow analysis, and then a "goal-seeking" function is used to determine the MFSP—the product price that results in a net present value (NVP) of zero for the proposed investment. The conversion module accomplishes this goal-seeking process by embedding the MFSP calculation within a feedback loop (Figure 5).

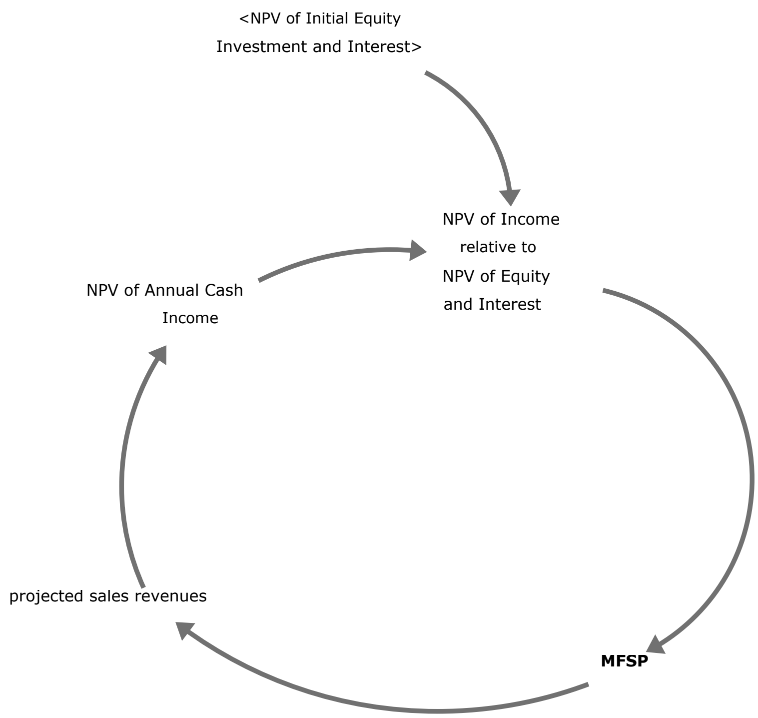

Figure 4. Simplified view of feedback structure used to estimate the MFSP. Changes in the MFSP are highly responsive to imbalances between the NPV of cash income and the NPV of initial equity investment, resulting in rapid convergence.

Note that the MFSP calculation within the conversion occurs over simulated time. Given an initial seed value for the MFSP metric, the model uses the initial years of the simulation to converge on an MFSP that balances the NPV of annual cash income against the NPV of the initial equity investment and interest payments.

2.2.6.3 Operation of Existing Facilities

Once the a facility exists (whether through endogenous investment or single-facility planning), operation of existing facilities is derived from logic developed for the BSM project (NREL 2022). The module uses techno-economic inputs related to facility operation, along with feedstock availability and price, to determine utilization. Annual production from the facility is determined by its thruput, process yield, and utilization rate (hours operating vs. hours it could operate) (Figure 6).

For each conversion process represented in the model, feedstock demand is determined primarily by output capacity, process yield, and facility utilization. The current version of RBEM does not include feedstock inventories; feedstock is assumed to be available at the conversion facility on a "just in time" basis.

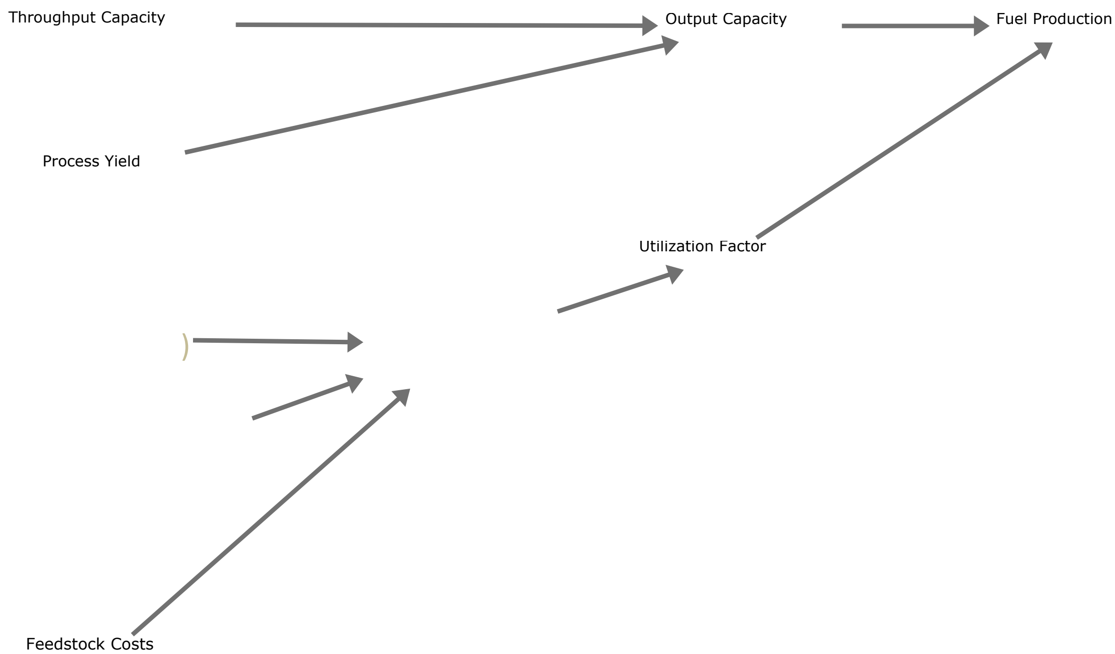

Figure 5. Simplified representation of operations: production capacity, determinants of utilization, and fuel production.

2.2.6.4 Economic Scorekeeping

One way to gauge the economic viability of SAF at ORD is to *simulate* the economic implications of an investment. This simulation can be accomplished through a set of "what-if" scenarios in which a facility operates under a range of different financial conditions relating to petroleum-based fuel prices and other financial considerations. The conversion module includes tracking nominal cash flow over the course of the simulation. These cash flows are discounted as the simulation progresses. The resulting NPV metric can track the overall financial attractiveness of the project. Its final value indicates the NPV of the potential investment. The time that the NPV becomes positive indicates the number of years before the investment would be a attractive one (Figure 7).

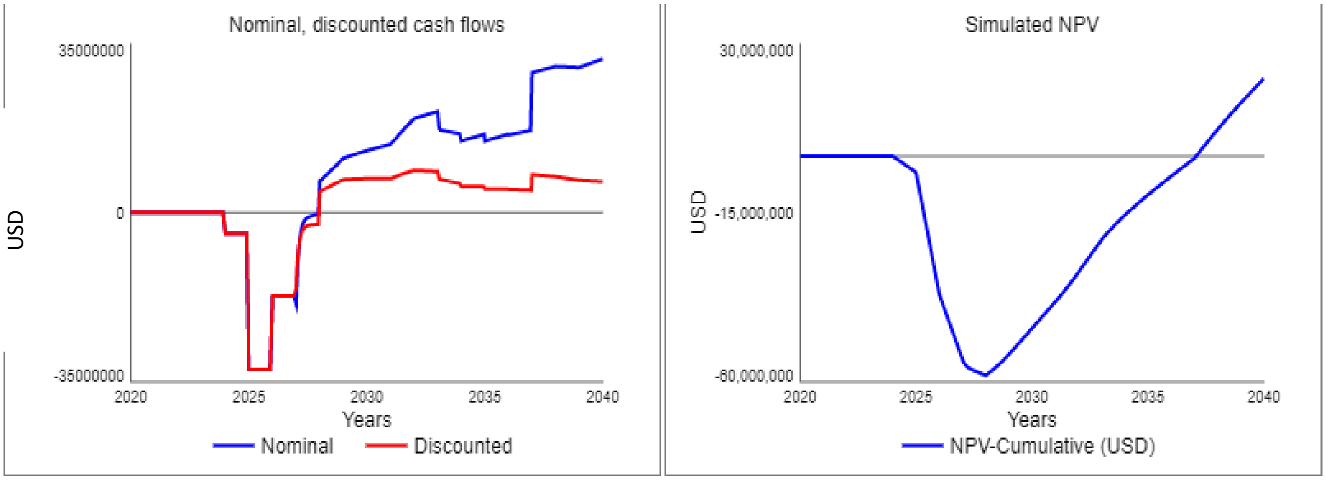

Figure 6. Illustration of financial accounting. The left panel shows nominal and discounted cash flows. Right panel shows NPV from accumulation of discounted cash flows. Investment begins in 2024. Cash flows become positive in ~2028.

This cash flow accounting is most useful when the model is configured to force investment in a single facility.

2.2.7 End Use

The end-use module incorporates logic for petroleum-based fuel prices, for carbon tax scenarios, and for initiatives analogous to California's Low Carbon Fuel Standard (LCFS). Petroleum-based fuel prices are represented as scenarios based on EIA projections from the 2020 annual energy outlook (EIA 2020). LCFS logic is taken from NREL's BSM (NREL 2022). Additionally, the module can account for SAF displacement of petroleum fuels at ORD.

3 Sensitivity Analysis

The sensitivity results presented below are focused on ORD and the surrounding region (Figure 8. Model results are presented for the 2020–2040 time frame. As mentioned previously, feedstocks considered are waste FOG; forest residues; agricultural residues (corn stover); and municipal sewage sludge for 50-, 100-, and 200-mile radii from ORD. Fuel conversion technologies considered are:

- ATJ via Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP) (ASTM D7566) (International Air Transport Association 2020)
- FT Synthetic Paraffinic Kerosene (FT-SPK) (ASTM D7566)
- HEFA (ASTM D7566)
- HTL (Snowden-Swan, et al. 2020).

Feedstock and conversion technology combinations used are shown in Table 9. We assume constant aviation fuel demand at ORD of 1,000,000,000 gallons per year (GPY) and a blending ratio for SAF of 10%, creating a maximum SAF blend stock demand of 100,000,000 GPY (Davidson, et al. 2014).

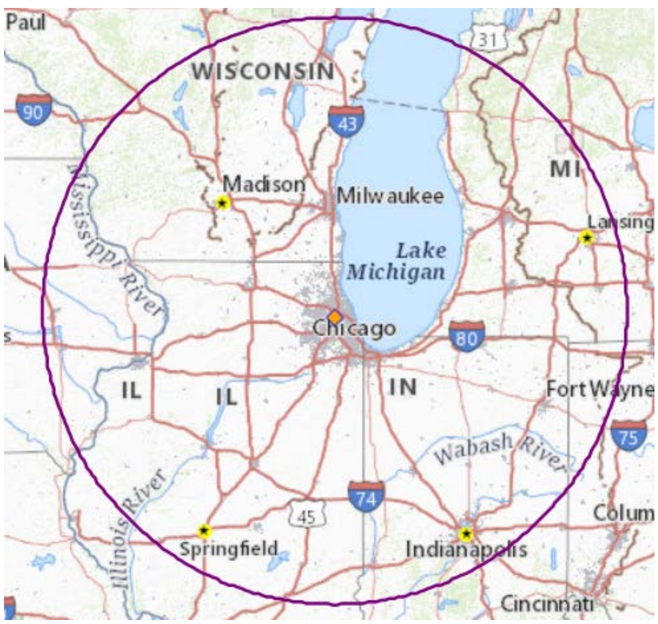

Figure 7. Area of study. The feedstock resource collection radii considered in this study are 50-, 100-, and 200-mile radii from ORD.

Table 9. SAF Conversion Technology, Feedstock, and Collection Radii Used in This Study

Conversion Technology	Feedstock	Feedstock Supply Radii (miles)
HTL	POTW Sludge	50, 100, 200
HEFA	Waste FOG	50, 100, 200
FT-SPK	Forest residues	50, 100, 200
HFS-SIP	Corn stover	50, 100, 200

Sources: HTL (Snowden-Swan, et al. 2020); HEFA (ASTM D7566); FT-SPK (ASTM D7566); HFS-SIP (ASTM D7566) (International Air Transport Association 2020).

3.1 Analysis Approach

We performed an elementary effects (EE) sensitivity of the model to determine what variables are most important regarding annual SAF production from each pathway (Morris 1991). The study design was developed by varying model inputs across their assumed value ranges, as shown in Table 10; each study design consisted of between 1,100 and 2,400 runs, depending on how many inputs were varied. The study design was created and the results were analyzed using the SALib Python library (Herman, et al. 2017).

Annual SAF production results from the EE study for each pathway evaluated are shown in Figure 9. Each line in the figure represents the production from one SAF facility. All SAF pathways assessed had some degree of facility takeoff, where takeoff is defined as non-zero SAF production between 2020 and 2040, given the factor settings used in the study designs (Table 10).

Both the ATJ and FT pathways experienced takeoff in all sensitivity runs evaluated, while the HEFA and HTL pathways had varying degrees of industry takeoff. The HEFA pathway exhibited takeoff in 98% of all runs evaluated, while the HTL pathway exhibited takeoff for fewer than 10% of the runs evaluated. The greatest amount of simulated annual SAF production is attributed to the FT pathway, which met 100% of the potential demand assumed for SAF in this study. This result is most likely because of feedstock costs and availability. Forest residues are readily available at a low cost within the region evaluated, which allowed the FT facility to use all available feedstock (200-mile radius) and scale accordingly.

Similarly, the ATJ pathway exhibited substantial takeoff (~50% of the maximum potential demand), which can also be attributed to feedstock costs and availability. The ATJ pathway was able to use feedstocks within 100 miles, but sourcing feedstock beyond 100 miles and scaling the facility was not financially attractive given the range of conditions tested in this study. In contrast to FT and ATJ, the HEFA pathway met approximately 25% of the maximum demand for SAF assumed in this study. This lower value is likely a result of the feedstock transportation and feedstock costs assumed for FOG feedstocks. The assumed transportation costs for FOG are an order of magnitude greater than the costs assumed for corn stover and woody feedstocks (Table 10). Likewise, the assumed costs for FOG are also an order of magnitude greater than the costs assumed for herbaceous and woody feedstocks. Although the HEFA pathway does take off, using FOG from within a 50-mile radius, the combined costs of procurement and transportation make it untenable to source feedstock beyond 50 miles, which would be required to scale the facility to meet 100% of the assumed demand.

The HTL pathway exhibited very little takeoff, both in terms of the number of simulations that produced non-zero results and the percentage of assumed SAF demand that the pathway can meet. The HTL pathway is not as technologically mature as the other pathways assessed and is assumed to use POTW sludge as feedstock. Like FOG, POTW sludge is expensive to procure and transport. In addition, for POTW sludge to be transported distances greater than a few miles from the source, it should be dewatered, which adds substantial costs to the feedstock production and logistics stages.

Results of the EE sensitivity suggest that, in most cases (HEFA, ATJ, FT), the price of the feedstock is the most influential factor in terms of annual SAF output for the pathways evaluated. Second to the price of feedstock is the production subsidy level While the price of feedstock is an isolated variable in the model, the point-of-production cost is composed of numerous techno-economic factors that suggest, at a high level, further technology development is needed to bring costs down. Unlike the other pathways evaluated, HTL production is most sensitive to the dewatering costs. Again, the cost to dewater POTW sludge for transportation adds substantial costs to the feedstock.

Table 10. Input Settings Used for the Elementary Effects Study Design

RBEM Variable	Default	Min	Max	Units	Variable Description
Conversion.Background Subs [Price]	0	0	1	USD/GGE	Point-of-production subsidy applied to the refinery
Conversion.Background Subs [Feedstock]	0	0	1	USD/Ton	Feedstock subsidy applied to the refinery
Conversion.Background Subs [FCI]	0	0	1	Unitless	Fraction of FCI grant applied to the refinery
Conversion.Background Subs [Loan]	0	0	1	Unitless	Proportion of the loan guaranteed to the refinery
Conversion.Startup Subs [Price]	0	0	1	USD/GGE	Point-of-production subsidy applied to the refinery
Conversion.Startup Subs [Feedstock]	0	0	1	USD/Ton	Feedstock subsidy applied to the refinery
Conversion.Startup Subs [FCI]	0	0	1	Unitless	Fraction of FCI grant applied to the refinery
Conversion.Startup Subs [Loan]	0	0	1	Unitless	Proportion of the loan guaranteed to the refinery
Conversion.Initial Indices of Commercial Maturity [HEFA]	1	0	1	Unitless	Starting point for the technological maturity
Conversion.Initial Indices of Commercial Maturity [HTL]	1	0	1	Unitless	Starting point for the technological maturity
Conversion.Initial Indices of Commercial Maturity [ATJ]	1	0	1	Unitless	Starting point for the technological maturity
Conversion.Initial Indices of Commercial Maturity [FT]	1	0	1	Unitless	Starting point for the technological maturity
Conversion.Progress Ratios Commercial [HEFA]	0.75	0.7	0.8	Unitless	Rate of industrial learning applied to the technology
Conversion.Progress Ratios Commercial [HTL]	0.75	0.7	0.8	Unitless	Rate of industrial learning applied to the technology
Conversion.Progress Ratios Commercial [ATJ]	0.75	0.7	0.8	Unitless	Rate of industrial learning applied to the technology
Conversion.Progress Ratios Commercial [FT]	0.75	0.7	0.8	Unitless	Rate of industrial learning applied to the technology
FOG FS.FOG Price Multiplier	1	5	1.5	Unitless	Multiplier applied to the cost of FOG feedstock
FOG FS.FOG Supply Multiplier	1	5	1.5	Unitless	Multiplier applied to the annual supply of FOG

RBEM Variable	Default	Min	Max	Units	Variable Description
FOG FS.transport cost source to plantgate [near]	100	75	125	USD/Ton	Transportation costs for FOG within 50 miles
FOG FS.transport cost source to plantgate [medium]	200	150	250	USD/Ton	Transportation costs for FOG within 100 miles
FOG FS.transport cost source to plantgate [far]	400	300	500	USD/Ton	Transportation costs for FOG within 200 miles
Sludge FS.dewatering cost [Swine]	400	300	500	USD/Ton	Cost to remove water from POTW sludge
Sludge FS.Price Multiplier	1	0.5	1.5	Unitless	Multiplier applied to the cost of POTW sludge feedstock
Sludge FS.transport cost farmgate plantgate [near]	100	75	125	USD/Ton	Transportation costs for POTW sludge within 50 miles
Sludge FS.transport cost farmgate plantgate [medium]	200	150	250	USD/Ton	Transportation costs for POTW sludge within 100 miles
Sludge FS.transport cost farmgate plantgate [far]	400	300	500	USD/Ton	Transportation costs for POTW sludge within 200 miles
Stover FS.Stover Price Multiplier	1	0.5	1.5	Unitless	Multiplier applied to the cost of stover feedstock
Stover FS.Stover Supply Multiplier	1	0.5	1.5	Unitless	Multiplier applied to the annual supply of stover
Stover FS.transport cost farmgate plantgate [near]	16.08	12.06	20.1	USD/Ton	Transportation costs for stover within 50 miles
Stover FS.transport cost farmgate plantgate [medium]	16.08	12.06	20.1	USD/Ton	Transportation costs for stover within 100 miles
Stover FS.transport cost farmgate plantgate [far]	16.08	12.06	20.1	USD/Ton	Transportation costs for stover within 200 miles
Woody FS.Woody Price Multiplier	1	0.5	1.5	Unitless	Multiplier applied to the cost of woody feedstock
Woody FS.Woody Supply Multiplier	1	0.5	1.5	Unitless	Multiplier applied to the annual supply of woody feedstock
Woody FS.transport cost farmgate plantgate [near]	17.8	13.35	22.25	USD/Ton	Transportation costs for woody feedstock within 50 miles

RBEM Variable	Default	Min	Max	Units	Variable Description
Woody FS.transport cost farmgate plantgate [medium]	17.8	13.35	22.25	USD/Ton	Transportation costs for woody feedstock within 100 miles
Woody FS.transport cost farmgate plantgate [far]	17.8	13.35	22.25	USD/Ton	Transportation costs for wood feedstock within 200 miles

The variable name, model default value, minimum, maximum, units, and descriptions for the inputs are shown.

GGE = gasoline-gallon equivalent.

Sources: HTL (Snowden-Swan, et al. 2020); HEFA (ASTM D7566); FT-SPK (ASTM D7566); ATJ via HFS-SIP (ASTM D7566) (International Air Transport Association 2020).

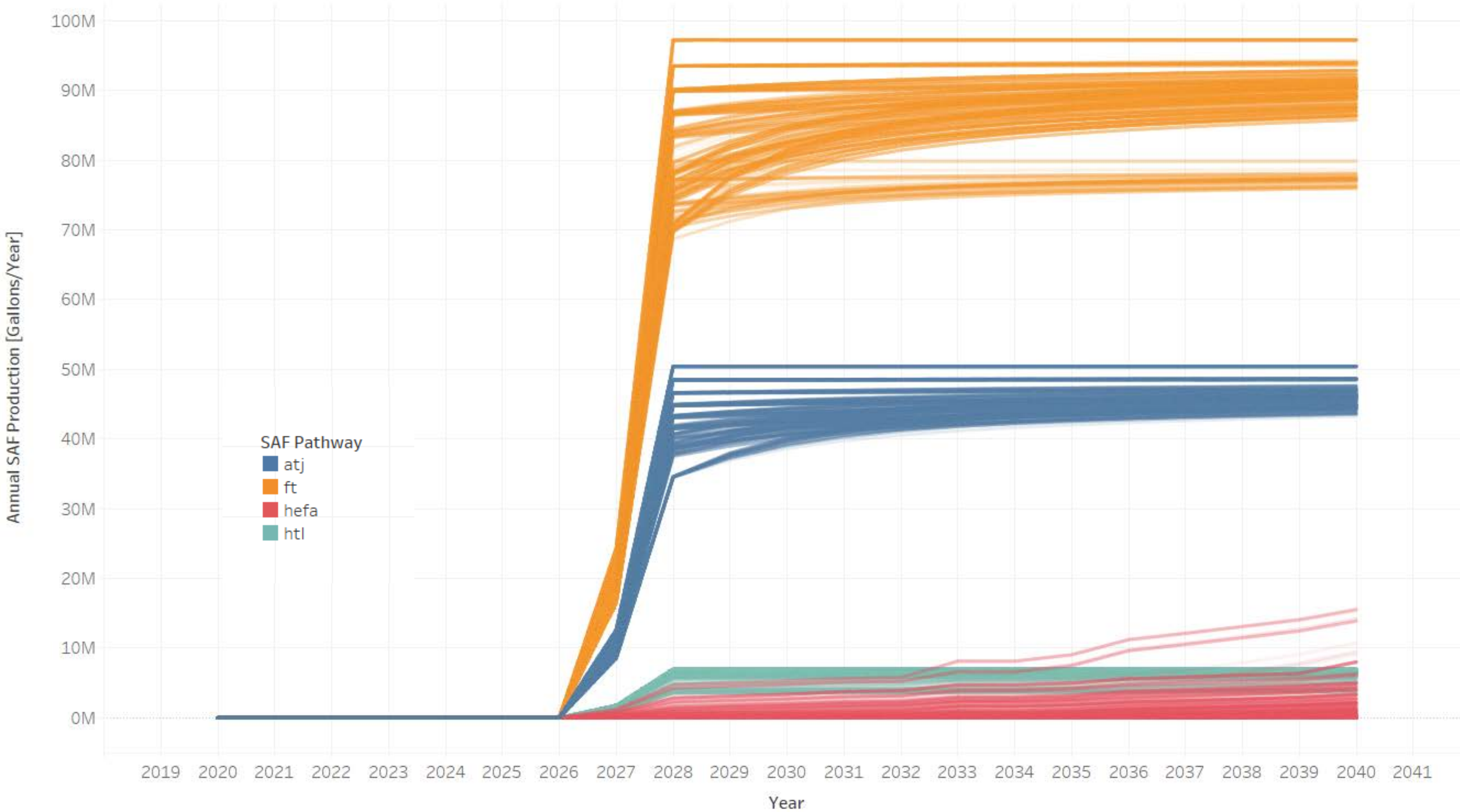

Figure 8. Annual SAF production results from the EE study design. Results are shown for 2020–2040 for four SAF production pathways: HEFA, HTL, ATJ, and FT. Each line represents the simulated production from a single facility.

Each line represents a single model simulation; there were between 1,100 and 2,400 runs for each SAF technology evaluated. Note that the maximum production of SAF was assumed to be 100,000,000 million gallons per year.

4 Conclusions

Based on our initial analysis using RBEM to assess four SAF pathways for the region surrounding ORD, a SAF market could develop in the region sufficiently to meet the demand for SAF under certain conditions. Our findings suggest that the largest barrier for SAF in this region is the feedstock price at the plant gate.

In this study, technologies that use herbaceous and woody feedstocks have the greatest potential for investment and takeoff as compared to technologies that use waste materials (FOG and POTW sludge). The lower-cost feedstock allows the facility to use more distant sources that enable economies of scale. This conclusion would not hold if the relative costs of the feedstocks were reversed, either through lower costs of long-distance transport of wet feedstocks (FOG and POTW sludge), or through higher costs of herbaceous and woody feedstocks. The data for long-distance transport of wet feedstocks and dewatering of POTW sludge are particularly scarce and uncertain. The assumptions used in RBEM for these inputs are based on a review of literature and have not been verified with vendors or suppliers.

Based on the data and assumptions used in this study, for wet feedstock-based technologies to be considered cost-effective for SAF production in the ORD region, transportation and processing costs need to be considerably lower. Financial attractiveness and process economics have long been shown to be highly sensitive to feedstock prices. Feedstock price is largely driven by agricultural markets that are somewhat separate from the refinery and fuel markets, reducing the uncertainty around this cost should be a focus for any prospective SAF facility.

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