Sustainable Aviation Fuel for the Future: What Does Iowa Have to Gain?

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Prepared For:

Iowa Renewable Fuels Association

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Inadvertent errors and omissions related to data collection, data summarization, and visual display of data.

Table 1. Acronyms

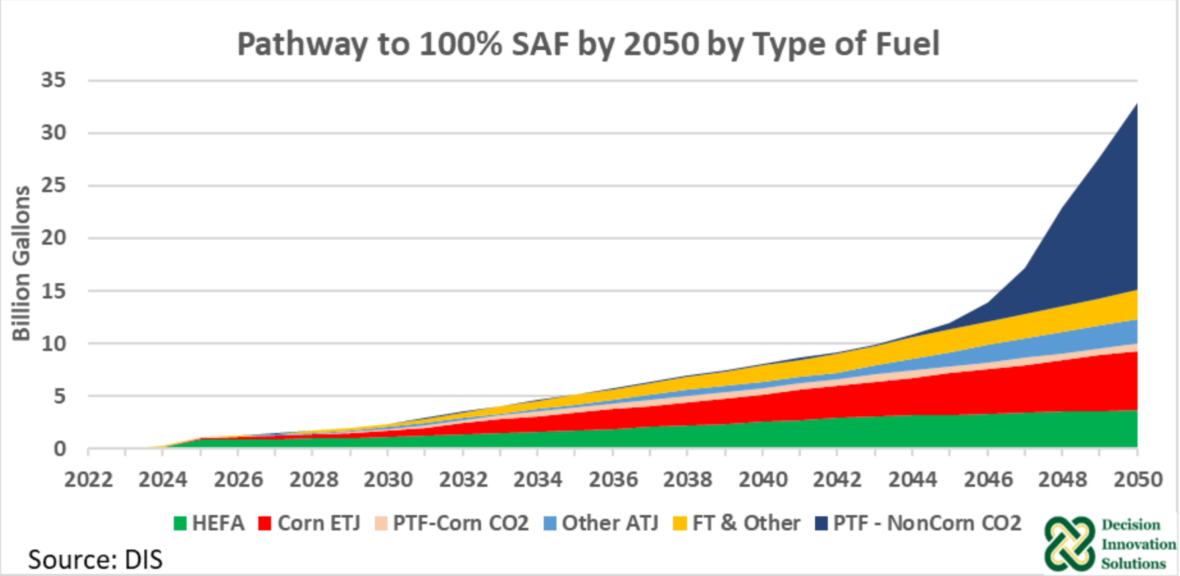
Acronym	Description
ANL	Argonne National Laboratory
ASCENT	Center of Excellence for Alternative Jet Fuels and Environment
ASTM	American Society for Testing and Materials
ATJ	alcohol to jet
BD	Biodiesel
BEA	Bureau of Economic Analysis
BLS	Bureau of Land Statistics
Bpd	barrels per day
BTC	blenders tax credit
BtL	biomass to liquid
CANO	canola oil
CAPEX	capital expenditure
CCS	carbon capture and sequestration
CCUS	carbon capture, utilization and storage
CI	carbon intensity
DAC	direct air capture
DCO	distillers corn oil
DIS	Decision Innovation Solutions
DOE	Department of Energy
DOT	Department of Transportation
EDCO	enhanced distillers corn oil
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
ETJ	ethanol to jet
EY	end of year
FAA	Federal Aviation Administration
FECM	Office of Fossil Energy and Carbon Management
FOG	fats, oils, greases
FT	Fischer-Tropsch
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HEFA	hydroprocessed esters and fatty acids
IRA	Inflation Reduction Act
MSW	municipal solid waste
mmt	million metric ton
MT	metric ton
MWh	megawatt hours
NG	natural gas
NGO	nongovernmental organization
OPEX	operating expenses
OTT	Office of Technology Transitions
PTF	power to fuel
PtL	power to liquid jet
RD	renewable diesel
RFS	Renewable Fuel Standard

Acronym	Description
RG	renewable gasoline
RIN	Renewable Identification Number
ROW	right of way
SAF	sustainable aviation fuel
SBO	soybean oil
SPD	synthetic paraffinic diesel
SPK	synthetic paraffinic kerosene
TCF	Technology Commercialization Fund
UCO	used cooking oil
U.S.	United States
USDA	United States Department of Agriculture
USDA-ARS	Agricultural Research Service
USDA-FS	Forest Service
USDA-NIFA	National Institute of Food and Agriculture
USDA-PSD	Production, Supply, and Distribution Database

1 Executive Summary

Sustainable Aviation Fuel (SAF) production provides a substantial opportunity for Iowa, Iowa's farmers, and Iowa's renewable fuel producers to prosper in the coming years if the SAF Grand Challenge comes to fruition and Iowa takes steps to be active participants in making the Roadmap come to life. The pathway that DIS estimates most likely to be realized has HEFA-based SAF and ethanol-to-jet (ETJ) being the two most prominent pathways for SAF production at least for the next 20 years. SAF from HEFA, ETJ, and PTF-corn CO2 are expected to be more than 90% of SAF production in 2026, around 80% of SAF production in 2030, and still more than 70% of SAF production in 2043 before the eventual development of PTF-SAF from direct air capture and renewable hydrogen kick in for the final push to 100% SAF adoption by 2050.

But, this potential cannot be fully realized without Carbon Capture and Sequestration (CCS) for ethanol. And, without the potential new use for corn for ETJ-SAF, Iowa's corn supply and the U.S. corn supply are and will continue to grow at a pace that outstrips demand. Either stocks will build, and prices will decline, or a significant amount of corn acreage will need to be pulled out of production. Furthermore, the urgency of facilitation of CCS for ethanol becomes even greater if Electric Vehicle (EV) adoption happens more rapidly than projected by the current Energy Information Administration (EIA) baseline. Time is of the essence and the clock is ticking.



Source: DIS

HEFA-based SAF will lead the way in early development with more than 1.1 billion gallons of SAF being produced from HEFA feedstocks by 2030. Iowa is well positioned to capture new HEFA-SAF production which could be co-located with new soybean processing capacity that is coming online and is expected to increase into the future.

ETJ will begin to become more prominent as ethanol plants that are located over geological formations that can support on-site sequestration of CO2 produce feedstock for ETJ-SAF plants. But to fully realize the potential for SAF production, there is an opportunity to develop 12 billion gallons of additional ethanol production with more than 90 percent of that new production in the Midwest to go along with the current ethanol production capacity that supports domestic ethanol blending (more than 14.8 billion gallons projected by EIA to be blended for light vehicle use in 2050). If Iowa enables carbon capture and sequestration, Iowa has the potential to capture 2.2 billion gallons (17%) of the new ethanol production that could come online in the Midwest and support ETJ-SAF production. In addition, Iowa has the potential to capture 20% of the new ETJ-SAF production.

The construction of new ethanol production capacity (modeled as 11 new 200 mgy ethanol plants) is expected to generate $3.3 billion in new output, along with $1.5 billion of new output from the construction of 5 ETJ-SAF production facilities, $1 billion from 3 new HEFA-SAF facilities and eventually even more economic activity from 8 new Power-to-Fuel production facilities. It is expected that more than 35,000 jobs will result from the construction of this new industry, providing nearly $2.3 billion in labor income and more than $3 billion in value-added activities. These construction activities are expected to occur over the next 25 years and since there is new capacity projected to be developed nearly every year the impacts in the Iowa economy should be relatively consistent with more than 1,400 steady construction jobs every year, $90 million in labor or household income, and $123 million of additional Gross Domestic Product (GDP) that comes from the value-added activities. The following table is a summary of the direct, indirect, and induced impacts of the construction activities associated with the construction of 11 new ethanol plants, 5 new ETJ-SAF plants, 3 new HEFA-SAF plants, and 8 new PTF plants that would use CO2 from ethanol plants that produce for the light-vehicle fuel market.

Iowa Construction Impact Summary

Event	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
New Ethanol Production	20,432	$ 1,286.6	$ 1,744.4	$ 3,333.1
SAF from ETJ	9,175	$ 587.9	$ 806.1	$ 1,532.5
SAF from HEFA	6,069	$ 389.6	$ 535.3	$ 1,016.8
Total	**35,676**	**$ 2,264.1**	**$ 3,085.9**	**$ 5,882.4**

By 2050, annual operations of the new ethanol and SAF production facilities within Iowa are expected to generate $11.9 billion per year in additional annual output compared to today's ethanol and SAF production, 22,169 more employment, $954 million in annual labor income, and $2.7 billion in value-added activity expanding the GDP of Iowa. The 5 new ETJ-SAF production plants are each projected to use 426 million gallons of ethanol annually. In addition, 3 new HEFA-SAF plants are projected to be built and operating in Iowa by 2050 producing more than 500 million gallons of SAF. And as the industry develops, CO2 captured from the ethanol plants that are producing ethanol for light-vehicle fuel blending can be converted to SAF at the 8 new PTF-SAF plants that would use the CO2 from those ethanol plants. The following table shows the total impacts (direct, indirect, and induced impacts.

Iowa Operations Impact Summary (Direct, Indirect, and Induced Impacts)

Event	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
New Ethanol Production	18,018	$ 709.1	$ 1,738.7	$ 7,897.9
SAF from ETJ	2,574	$ 128.9	$ 4.3	$ 492.7
SAF from HEFA	1,577	$ 115.5	$ 977.9	$ 3,508.7
Total	**22,169**	**$ 953.6**	**$ 2,721.0**	**$ 11,899.3**

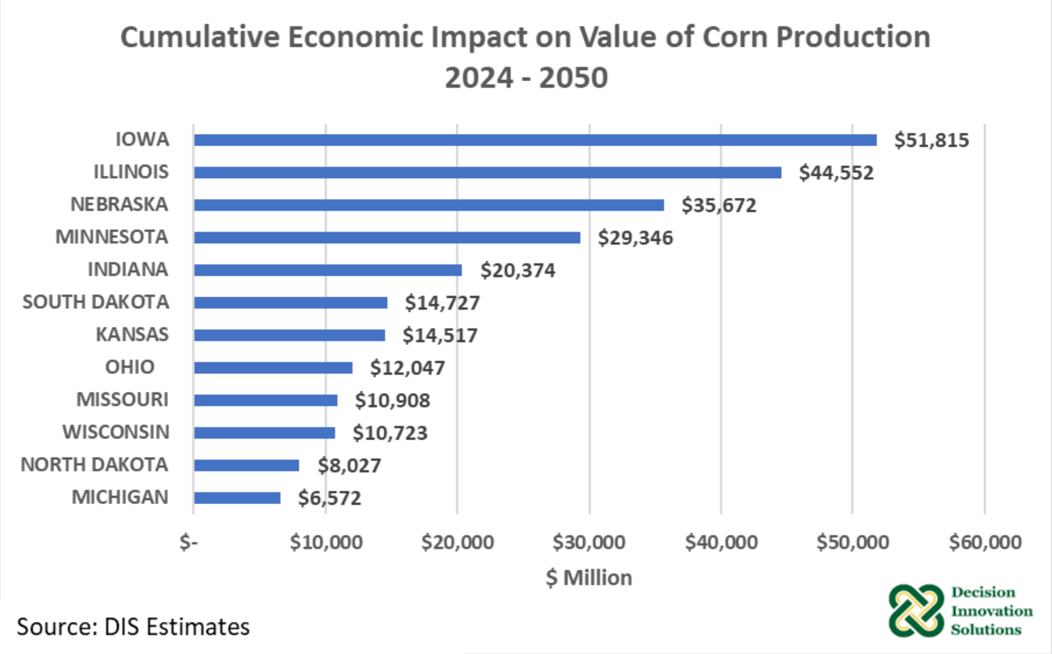
The following table breaks out and highlights the direct impacts that are included in the prior summary table. As indicated by the difference between them, this new industry will support a lot of indirect and induced jobs, labor income, value added and an increase in overall output, but just the direct economic impacts are impressive. If enabled to take advantage of the new opportunities provided by the developing SAF market, Iowa's biofuels industry could increase their contribution to Iowa's economy by more than $7 billion per year, providing more than 2,400 new, high paying jobs spread across the Iowa landscape which would produce more than $130 million in labor and household income.

Iowa Operations Direct Impact Summary

Event	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
New Ethanol Production	924	$ 44.9	$ 367.9	$ 4,014.1
SAF from ETJ	945	$ 62.6	$ (143.3)	$ 195.0
SAF from HEFA	603	$ 23.1	$ 768.0	$ 2,851.2
Total	**2,472**	**$ 130.7**	**$ 992.5**	**$ 7,060.2**

One measure of the economic impact of facilitating corn use for ETJ is the difference in the value of corn production with ETJ demand and without ETJ demand. Using a "stable price" of $4.67 per bushel, the lost value of corn production was calculated in today's dollars. For the Midwestern states in total, the difference in value of production of the corn crop with ETJ versus the scenario of no significant new corn demand is $259.3 billion across the 2024-2050 period. **This is nearly $10 billion per year, on average.**

If that $10 billion per year impact is spread across the current 83 million acres of corn, then it would amount to $120 per acre of corn and for a 1,000-acre farm with 50/50 corn-soybeans, it would amount to $60,240 per year less revenue, on average over the next 25 years. Clearly, the annual impacts would be greater further out in the future than they would be near-term, but strong upward trends in production need to be accompanied with strong upward trends in utilization or as has been experienced in the past, sharp, painful adjustments to both price and acreage will develop. As shown in the following graph, farmers in Iowa, as the leading corn production state, have the most at stake (nearly $52 billion) from this new opportunity (or the failure to take advantage of the new opportunity).



Source: DIS Estimates

Across Iowa, the new ethanol plants, each using approximately 70 million bushels of corn annually with an estimated average basis premium of 10 cents per bushel, would add $77 million of additional income to farmers who merchandise corn to these ethanol plants. And this is beyond the economic impact of standard returns for producing those 770 million bushels of additional corn beyond what is being produced in 2023. For a 1,000-acre farm with 50/50 corn and soybeans and trendline national yields, this would mean $11,760 more income in 2050. Since Iowa yields are typically 11% higher than national yields, the impacts for a 1,000-acre Iowa farm with 500 acres of corn would likely be more than $13,000 per year.

Trendline production nationally is increasing by 210 million bushels per year due to trendline yields which are increasing by 1.9 bushels per acre per year and without expanded demand for this new production, either acres in corn production need to decline or price will plummet in response to corn production outpacing the 55 million bushels per year trendline increase in all other uses of corn beyond ethanol production. Trendline corn production in Iowa is increasing at a rate of 32.5 million bushels per year driven by yield increases of 2.31 bushels per acre per year.

As of the writing of this report, there are three CO2 pipelines still under active development in the Midwest. Wolf Carbon Solutions is still working on their pipeline through eastern Iowa and Illinois. Summit Carbon Solutions is still working on a CO2 pipeline that would cross parts of five Midwestern states (IA, MN, NE, SD, and ND) and TallGrass Energy is converting a natural gas pipeline in Nebraska for transport of CO2 to a sequestration point in Wyoming. The exact number of facilities that will capture CO2 is unknown, although a prior-released analysis was conducted that included 31 collection facilities. If regulatory approval for the main trunk line, pumping stations and the sequestration site facilities is eventually approved, it is likely that other facilities in Iowa that were considering carbon sequestration via pipeline could be added to the Summit Carbon pipeline or the Wolf Carbon Solutions pipeline.

Building out CO2 capture and sequestration via pipeline could have substantial positive impacts across the Midwest. While the trunkline and 31 connected plants are estimated to generate $5.1 billion in construction impacts, the eventual addition of 33 more plants to that trunkline are estimated to add another $2.58 billion in construction impact. Gross economic impact of capital output relative to capital expenditures is estimated to be $5.4 billion for the combined set of CO2 sequestration construction and capital outlays. Construction employment is estimated to be 4,697 jobs and total federal, state, and local taxes from construction activities and capital outlays is estimated to be $559 million.

Annual operations of the combined carbon collection and sequestration activities are estimated to be $256 million with gross economic output of $568 million with 3,499 jobs and $146 in annual federal, state and local taxes being generated.

Iowa's ethanol plants account for approximately two-thirds of the ethanol plants that could eventually be a part of a Midwestern carbon capture network with access to pipelines.

2 Introduction

Carbon capture and sequestration (CCS) holds great potential for allowing Iowa produced renewable fuels to move from reduced carbon fuels to securing a position as a producer of very low carbon fuels. The capturing of carbon dioxide at ethanol plants, power plants, and other manufacturing facilities that currently emit carbon dioxide as a result of fuel consumption or as a byproduct of a manufacturing process is technically feasible and is becoming more economically feasible, especially when combined with pipeline transport of the captured carbon dioxide to permanent terrestrial storage.

In December 2022, the Administration through the U.S. Department of Energy announced the launch of four programs that are designed to accelerate private-sector investment and spur advancements in carbon management technologies. The new efforts from the Bipartisan Infrastructure Law are:

- **Direct Air Capture Commercial and Pre-Commercial Prize** –support and prize awards totaling $115 million to promote diverse approaches to direct air capture. The Direct Air Capture Pre-Commercial Prize provides up to $15 million in prizes to incubate and accelerate research and development of breakthrough direct air capture technologies. The Direct Air Capture Commercial Prize provides up to $100 million in prizes to qualified direct air capture facilities for capturing CO2 from the atmosphere.
- **Regional Direct Air Capture Hubs** – DOE will invest $3.5 billion to develop four domestic regional direct air capture hubs, each of which will demonstrate a direct air capture technology or suite of technologies at commercial scale with the potential for capturing at least 1 million metric tons of CO2 annually from the atmosphere and storing that CO2 permanently in a geologic formation or through its conversion into products.
- **Carbon Utilization Procurement Grants** – which will provide grants to states, local governments, and public utilities to support the commercialization of technologies that reduce carbon emissions while also procuring and using commercial or industrial products developed from captured carbon emissions.
- **Bipartisan Infrastructure Law Technology Commercialization Fund (TCF)** – DOE's Office of Technology Transitions (OTT), in partnership with FECM, will issue a Lab Call to accelerate commercialization of carbon dioxide removal technologies, including direct air capture, by advancing measurement, reporting, and verification best practices and capabilities. OTT anticipates awarding $15 million to projects led by DOE National Laboratories, plants, and sites, and supported by diverse industry partnerships spanning the emerging carbon dioxide removal sector.

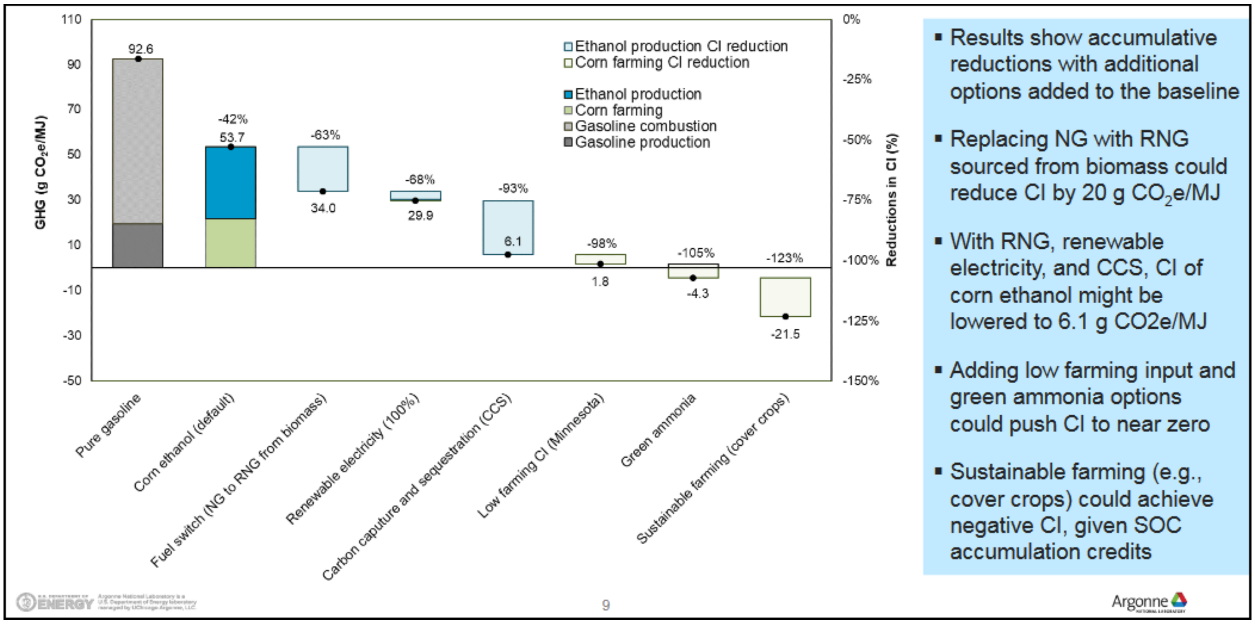
In addition to these new programs the Inflation Reduction Act enhanced the tax credits provided by Section 45Q of the tax code and initiated a new set of tax credits in Section 45Z that have the potential to stimulate carbon-reducing activities all along the supply chain of renewable fuels and greatly enhance the role of carbon capture and sequestration in the effort to reduce the carbon Intensity (CI) scores of ethanol and other advanced biofuels such as Sustainable Aviation Fuel (SAF).

First introduced in 2008, Section 45Q of the Unites States Internal Revenue Code provides a tax credit for CO2 storage. The policy is intended to incentivize deployment of carbon capture, utilization and storage (CCUS), and a variety of project types are eligible. Under Section 45Q, captured carbon dioxide must be either stored underground in secure geologic formations, used for carbon dioxide-enhanced oil recovery or utilized in other projects that permanently sequester carbon dioxide.

The 2022 changes to 45Q provide up to $85 per metric ton of CO2 permanently stored and $60 per metric ton of CO2 used for enhanced oil recovery (EOR) or other industrial uses of CO2, provided emissions reductions can be clearly demonstrated. The credit amount significantly increases for direct air capture (DAC) projects to $180 per metric ton of CO2 permanently stored and $130 per metric ton for used CO2. In addition, the 2022 changes reduce the capacity requirements for eligible projects: 18,750 metric tons per year for power plants (provided at least 75% of the CO2 is captured), 12,000 metric tons per year for other facilities, and 1,000 metric tons per year for DAC facilities. Finally, the 2022 changes include a seven-year extension to qualify for the tax credit, meaning that projects have until January 2033 to begin construction.

In Part 2 of Subtitle D of the Inflation Reduction Act, tax credits for clean fuel production are contained in section 45Z. This credit applies to clean fuels produced after 2024 and generally sold before 2028. It is a new general business credit for clean transportation fuel that is produced at a qualifying facility and sells for qualifying purposes. These fuels must meet certain emissions standards. For ethanol the credit-per-gallon base amount is $0.20 (non-aviation fuel) and the credit amount increases to $1.00 per gallon (non-aviation fuel) if wage and apprenticeship requirements are met and are based on the fuel's carbon intensity score with a CI score of 50 kgCO2e/mmbtu (based on the GREET model) being the trigger point, and the credit potential increasing as the CI score declines toward zero. So, essentially, each reduction in the CI score of the fuel below 50 generates a 2 cents per gallon production tax credit with the tax credit being maximized at $1.00 per gallon if the CI score is zero.

No credit under the 45Z tax credit is allowed at a facility that includes property for which a credit is taken under sections 45Q, 45X, or section 48 ITC for clean hydrogen production facilities during the taxable year.



- Results show accumulative reductions with additional options added to the baseline
- Replacing NG with RNG sourced from biomass could reduce CI by 20 g CO_2e/MJ
- With RNG, renewable electricity, and CCS, CI of corn ethanol might be lowered to 6.1 g CO2e/MJ
- Adding low farming input and green ammonia options could push CI to near zero
- Sustainable farming (e.g., cover crops) could achieve negative CI, given SOC accumulation credits

Figure 1. Ways to Reduce CI Score of Ethanol

Currently, most of the corn-starch-based ethanol production in Iowa has CI scores between 55 – 65 based on the GREET model. There are a number of production techniques and methodologies that can be implemented to incrementally reduce the carbon emissions of ethanol production, but the use of CCUS is the most effective means of dramatically reducing the carbon emissions of ethanol production from corn with the implementation of CCUS estimated to typically reduce the CI score of an ethanol facility by approximately 30 CI points. In addition to the changes to the processes at the ethanol plants there are changes to production practices that corn producers can make which can also reduce the CI score of ethanol by reducing the CI score of the corn production process (Figure 1).

2.1 SAF Grand Challenge Roadmap Overview

An interagency team led by DOE, DOT, and USDA worked with EPA, other government agencies, and stakeholders from national labs, universities, nongovernmental organizations (NGOs), and the aviation, agricultural, and energy industries to develop the SAF Grand Challenge Roadmap which was released in September 2022. The Roadmap outlines a whole-of-government approach with coordinated policies and specific activities that should be undertaken by the federal agencies to support achievement of both the 2030 and 2050 goals of the SAF Grand Challenge. The roadmap is designed to ensure alignment of government and industry actions and coordinate government policies to achieve the goals of the SAF Grand Challenge. This includes coordination in the formation and execution of plans in research, development, demonstration, and deployment such as modeling and analysis to ensure sharing of approaches, tools, assumptions, and insights across agencies' research centers at the DOE national laboratories, FAA's Center of Excellence for Alternative Jet Fuels and Environment (ASCENT), and USDA's Agricultural Research Service (USDA-ARS), Forest Service (USDA-FS), and USDA's National Institute of Food and Agriculture (USDA-NIFA).

The Roadmap lays out six action areas detailing all activities with the potential to impact SAF Grand Challenge objectives of (1) expanding SAF supply and end use, (2) reducing the cost of SAF, and (3) enhancing the sustainability of SAF. The six action areas are:

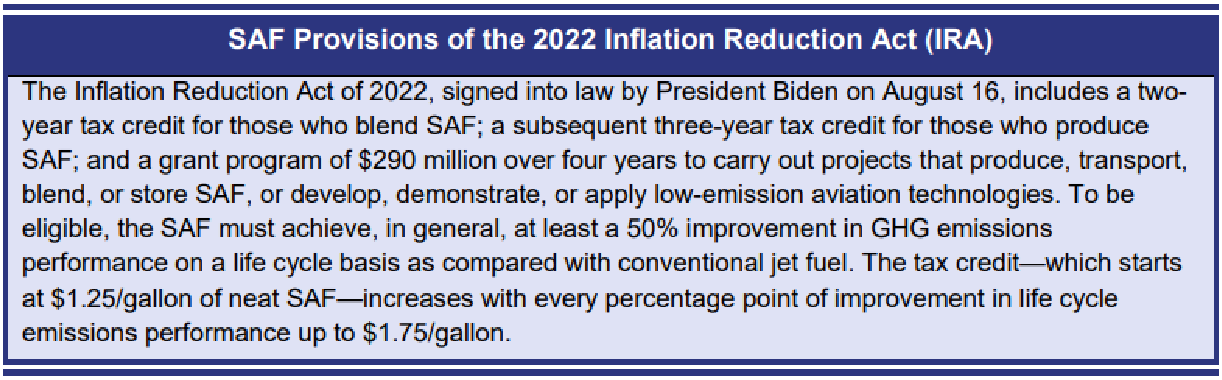
- Feedstock Innovation
- Conversion Technology Innovation
- Building Supply Chains
- Policy and Valuation Analysis
- Enabling End Use
- Communicating Progress and Building Support

Within the SAF Grand Challenge, two primary goals for the U.S. have been established:

- 3 billion gallons of SAF production and use per year by 2030
- 35 billion gallons of SAF production and use per year by 2050

These goals account for about one-third of the global targets for the SAF market which are likely 100 million gallons or more. Just as the U.S. is an exporter of ethanol and other fuels, there will likely be opportunities for the U.S. to be exporters of SAF.

While there are many specific policy statements, actions and activities that have been put in place or are being put in place to support these goals, several provisions were contained within the 2022 Inflation Reduction Act (IRA) that were specifically targeted at supporting the 2030 objectives of the SAF Grand Challenge Roadmap. As cited in the Roadmap, these provisions are:



SAF Provisions of the 2022 Inflation Reduction Act (IRA)

The Inflation Reduction Act of 2022, signed into law by President Biden on August 16, includes a two-year tax credit for those who blend SAF; a subsequent three-year tax credit for those who produce SAF; and a grant program of $290 million over four years to carry out projects that produce, transport, blend, or store SAF, or develop, demonstrate, or apply low-emission aviation technologies. To be eligible, the SAF must achieve, in general, at least a 50% improvement in GHG emissions performance on a life cycle basis as compared with conventional jet fuel. The tax credit—which starts at $1.25/gallon of neat SAF—increases with every percentage point of improvement in life cycle emissions performance up to $1.75/gallon.

2.2 Summary: What is Needed to Achieve 100% SAF Use by 2050?

The factors that characterize what is needed to achieve 100% SAF use in the U.S. by 2050 are:

- Increased production of feedstocks
- Reduced cost of transformation processes
- Demand drivers
- Enabling policy
- Public support

The early development of SAF will require increased production of feedstocks, primarily those feedstocks that are used in HEFA-SAF pathways and the use of low-carbon ethanol for ETJ. Increased availability of HEFA feedstocks can come about through technological advancements such as increased Distillers Corn Oil (DCO) recovery, increased recovery of used cooking oil (UCO), and increased vegetable oil yields on a per-acre basis of both soybean oil and canola oil[1]. Increased low-carbon ethanol as a feedstock will become increasingly available from ethanol facilities that can do direct sequestration of CO2 onsite, but the real ramp-up in availability of low-carbon ethanol will come from capture and sequestration via pipeline for the ethanol produced in Iowa, Minnesota, Nebraska, South Dakota, and North Dakota.

Transformation processes for cellulosic ethanol, some Fischer-Tropsch (FT) gasification pathways, and for transformation of direct air capture CO2 to SAF all are relatively expensive at present. Technological breakthroughs are needed to reduce the cost of these pathways. Cellulosic ethanol has a very attractive CI score, but the feedstock gathering costs tend to be high, materials handling can be difficult, and the cost of transformation of cellulosic materials into alcohols is generally more expensive than using starch-based materials such as corn. According to (Zang et.al, 2021) one of the key issues with use of the FT process for liquid fuel production from hydrogen and CO2 is the cost of hydrogen production as well as the cost of electrical generation which can result in FT liquid fuels costing 75% to 100% more than petroleum-based fuels. Most Power-to-Fuel (PTF) processes that use captured CO2 and renewable hydrogen, while technically feasible, are very expensive to produce.

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[1] A substantial amount of research is currently underway for oilseed cover crops that may provide additional, low-carbon feedstocks for HEFA, but the research has not progressed far enough at this time to be included in this study.

Typically, replacement of one fuel source with another comes from within a market that takes into account the costs and benefits of the newer fuel. In the case of SAF, the demand drivers are very likely to be based in government policy as it relates to carbon emissions and the desire to de-carbonize the air travel industry. Demand driven by this consideration will likely need substantial incentives to mobilize the private sector investments that will be needed to build the next generation of low carbon fuel production facilities. Airlines, themselves, will need to be very involved in the early stages of the transformation of fuel supplies to SAF. Offtake contracts and other instruments that will provide sufficient stability for long-term investments in SAF production will likely be common to get SAF production capacity up to a critical mass where market economics can become more of the driver of full adoption.

Public policy needs to be enabling of the early investments in SAF production and consumption. Federal tax policies as contained in the Inflation Reduction Act of 2022 will play influential roles in both feedstock development and production as well as SAF production itself. But these public incentives need to be evaluated on regular basis to make sure that the policies are not creating their own barriers to SAF development such as the seemingly advantage that renewable diesel has over SAF production when all tax and renewable energy credits are taken into account. For the 100% SAF goal to be achieved in 2050, such disparities will need to be addressed.

And then there is public support. Production of SAF requires low-carbon feedstocks. And one of the most promising low-carbon feedstocks can be corn-based ethanol with the carbon sequestered. Some ethanol plants have the potential to do on-site sequestration of CO2. But most plants in Iowa, Minnesota, Nebraska, South Dakota, and Nort Dakota will need to move the CO2 captured at their ethanol plants to sequestration sites that may be several hundred miles away and the most economical and efficient way to transport such CO2 is via pipeline. But pipelines face vocal public opposition in some areas. Getting public buy-in to the whole process will be an essential element of unleashing the potential economic value that can accrue to the Midwest through SAF production.

And, the potential for SAF adoption will depend on the extent to which low-carbon air transport is demanded by the public. SAF is likely to cost more than petroleum-based jet fuels. And this extra cost will, at least to some degree, be borne by those who utilize air travel. Engaging the public and eliciting public support will be a very important aspect of the future of SAF production.

3 SAF Production Pathways

There are multiple technology pathways to produce fuels approved by ASTM and blending limitations based on these pathways. ASTM D7566 *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons* dictates fuel quality standards for non-petroleum-based jet fuel and outlines approved SAF-based fuels and the percent allowable in a blend with Jet A. ASTM D1655 *Standard Specification for Aviation Turbine Fuels* allows co-processing of biomass feedstocks at a petroleum refinery in blends up to 5%. Both ASTM standards are continuously updated to allow for advancements in technology to produce SAF. DOE's Sustainable Aviation Fuel Review of Technical Pathways provides details on various SAF production pathways.

The pathways below represent only those currently approved by ASTM. Processes and tests exist for the approval of other feedstocks, fuel molecules, and blending limits, and the types of approved fuels will increase as these are evaluated through this process[2].

Pathway	Feedstocks
Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK) (Annex 1)	**Municipal solid waste, agricultural and forest wastes, energy crops**
Hydroprocessed Esters and Fatty Acids (HEFA) (Annex 2)	**Oil-based feedstocks (e.g., soybean oil, canola oil, jatropha, algae, camelina, and yellow grease)**
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (Annex 3)	**Sugars**
FT-SPK with Aromatics (Annex 4)	**Municipal solid waste, agricultural and forest wastes, energy crops**
Alcohol-to-Jet Synthetic Paraffinic Kerosene (Annex 5)	**Cellulosic biomass, corn ethanol**
Catalytic Hydrothermolysis Synthesized Kerosene (Annex 6)	**Fatty acids or fatty acid esters or lipids from fat oil greases**
Hydrocarbon-Hydroprocessed Esters and Fatty Acids (HEFA) (Annex 7)	**Algal oil**
Fats, Oils, and Greases (FOG) Co-Processing (Annex A1)	**Fats, oils, and greases**
FT Co-Processing (Annex A1)	**FT biocrude**

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[2] A detailed list of the SAF pathways is included in the appendix.

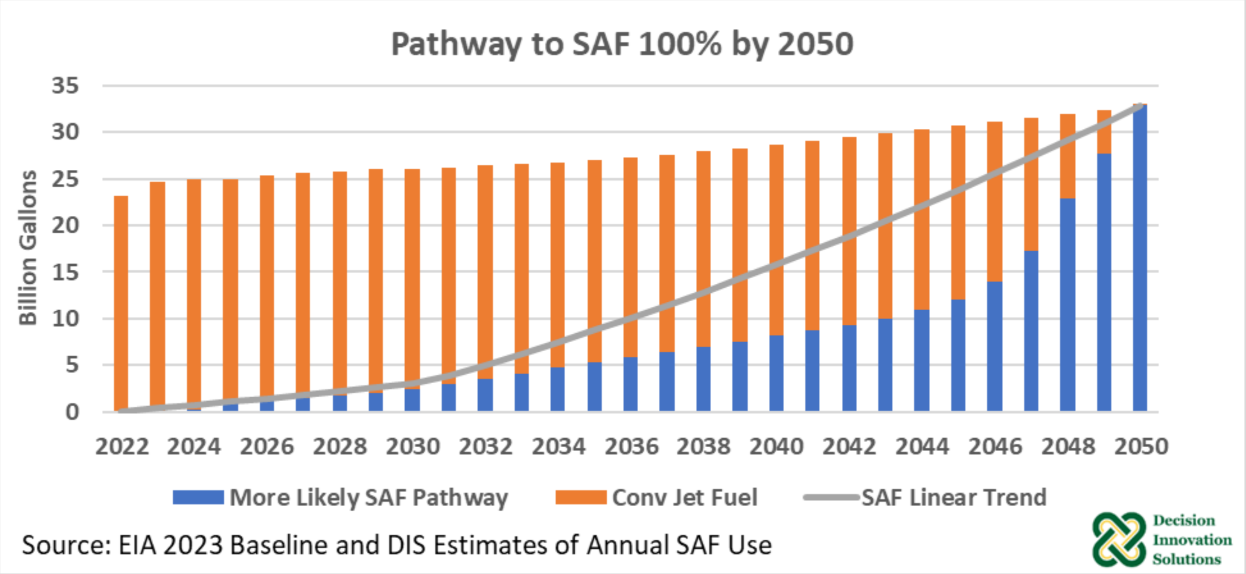
4 U.S. SAF Pathway(s)

The Energy Information Administration (EIA) in their 2023 Outlook forecasts jet fuel use will rise to 32.887 billion gallons[3] by 2050 from 23.111 million gallons of use in 2022. In 2022, it is estimated that 15.8 million gallons of SAF were produced in the U.S., representing less than 0.1% of total jet fuel use.

A goal has been established to use 3 billion gallons of SAF by 2030 in the U.S. and to have production of 35 billion gallons of SAF in the U.S. by 2050. Additionally, there are industry objectives to use 100% SAF in aviation fuels by 2050. For this analysis, the latter goal of 100% SAF by 2050 was used. SAF production in 2050 was set equal to the EIA's 2050 jet fuel production projection 32.887 billion gallons.

Figure 2 presents two potential pathways for the U.S. aviation industry to reach 100% SAF by 2050. One scenario assumes that 3 billion gallons will be available and used annually by 2030 and then assumes a linear trend on replacement of conventional jet fuel with SAF from 2030 to 2050. This scenario is given by the gray line in Figure 2.

A more likely scenario is one where there is a strong push to achieve 3 billion gallons of SAF production in the U.S. by 2030 but the ramp-up to 100% SAF use in the U.S. falls short of a linear trend and has a slower ramp-up throughout the 2030s and into the 2040s and then rapidly accelerates beginning in the mid-2040s with rapid deployment of CO2-based Power-to-Fuels technology advances and becomes much more cost effective. This scenario is shown by the blue bars in Figure 2.



Source: EIA 2023 Baseline and DIS Estimates of Annual SAF Use

Figure 2. Pathway to SAF 100% by 2050

The Environmental Protection Agency (EPA) collects renewable fuel data as part of the Renewable Fuel Standard. Although the data is labeled as production data, it gives an approximate consumption of biofuels such as SAF. According to this data about 5 million gallons of SAF were consumed in 2021 and over 18 million gallons in 2023 (through September) (see Figure 3). Two other commercial producers of SAF are World Energy, which began production in 2016 at their Paramount facility in California, and international producer Neste. World Energy supplies SAF to Los Angeles International Airport and

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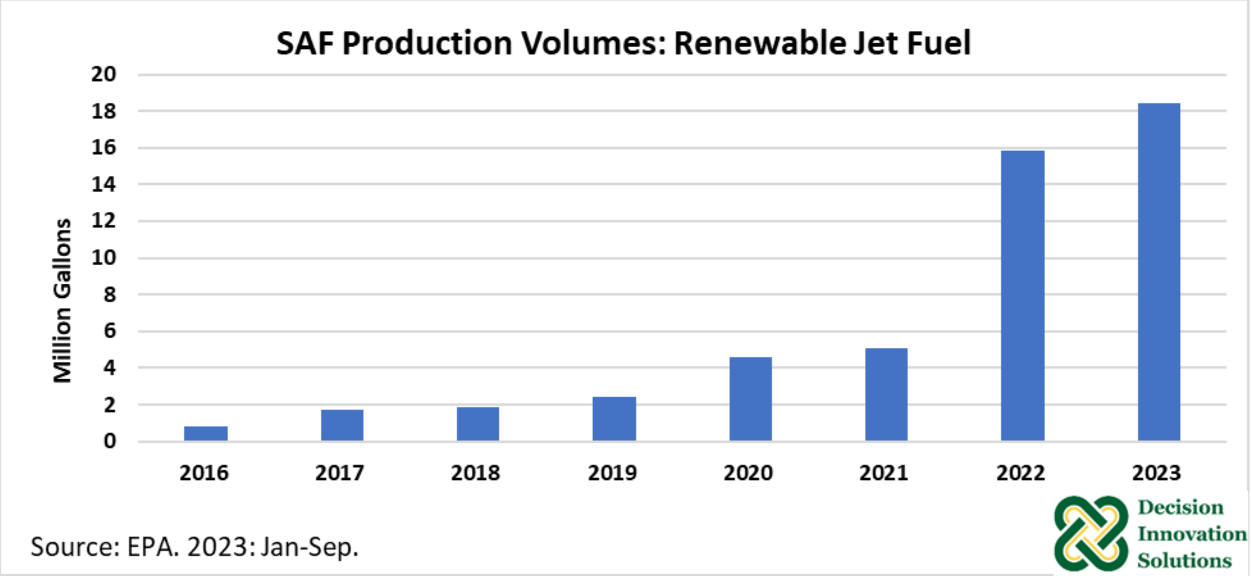
[3] Converting trillion Btus into million gallons by multiplying by the conversion factor of 7.4195 gallons of kerosene type jet fuel per 1 million Btus.

Ontario International Airport. Neste supplied SAF to San Francisco International Airport in 2020, and in 2021 the company introduced SAF at a regional airport (Telluride Regional Airport) and at a county airport (Aspen/Pitkin County Airport) in Colorado. More producers have begun supplying SAF to customers in 2023 and several more facilities are under construction or ramping up production over the coming years. The demand side is also beginning to pull product through the system with many airlines having signed agreements with existing and future SAF producers to utilize hundreds of millions of gallons of these fuels (US DOE, 2023, Sustainable Aviation Fuel).



Source: EPA. 2023: Jan-Sep.

Figure 3. SAF Production Volumes: Renewable Jet Fuel

Figure 4 is an example of the potential pathways by major feedstock type for SAF aiming to reach the stated goals of 3 billion gallons of SAF use in the U.S. by 2030 (although the DIS pathway only reaches 2.4 billion gallons of SAF in 2030) and to reach 100% SAF utilization in the U.S. by 2050 using the DIS "more likely" pathway for SAF adoption in the U.S. This example follows the McCurdy-ICF pathway estimates for Fischer-Tropsch (FT) SAF which grows to approximately 2.7 billion gallons by 2050, and adds to that the DIS estimates for HEFA-based SAF, corn-ethanol-based SAF (ETJ), assumes that other Alcohol to Jet (ATJ) will grow slowly and top out at about 2.4 billion gallons, and Power to Fuel (PTF) options will fill in the residual to meet the overall goals and annual milestones along the way to the ultimate goal of 100% SAF utilization in the U.S. by 2050 (McCurdy, 2023). The pathway estimates assume that once production is ramped up, PTF from CO2 from ethanol plants will make up a significant portion of the initial PTF component of SAF and that other (non-corn CO2 or other feedstocks) PTF fuels will fill in the requirements to meet "Net Zero" by 2050. Key assumptions for these pathways results are summarized below and discussed in more detail in sections 0-9 and sections 13.7-13.9 in the appendix.

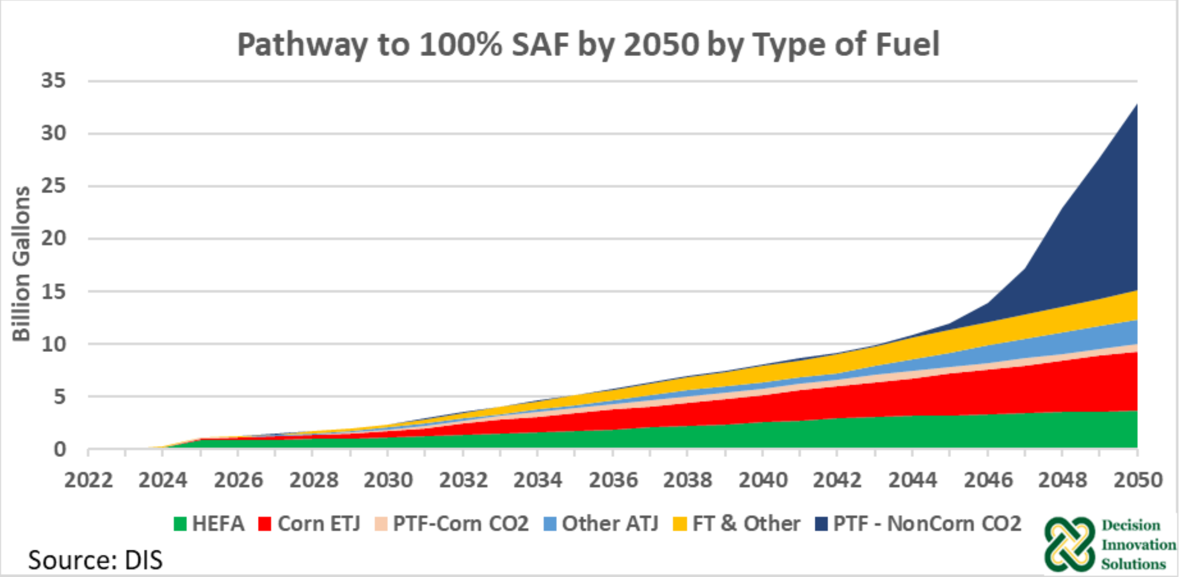


Figure 4. Fulfillment of U.S. SAF Demand by year, 2021 – 2050; DIS Estimates

In this set of pathways[4], HEFA-based SAF is the early leader. It rises from approximately 16 million gallons used in 2022 to 1.1 billion gallons in 2030, and then rises to 3.7 billion gallons in 2050. The DIS HEFA pathway accounts for co-product production of renewable diesel (RD) from other pathways and assumes that HEFA-based renewable energy capacity will be re-directed to SAF as other sources of RD ramp up.

The ETJ pathway begins with 21 million gallons coming online in 2024, ramps up to 623 million gallons in 2030, and rises through the remaining period to 5.59 billion gallons of ETJ-SAF by 2050. This ETJ pathway assumes that U.S. corn production grows at the rate of the 1980-2023 trendline (driven by increasing trends for corn yields while maintaining corn acres in line with recent levels), that non-ethanol use of corn (exports, feed, food) grows at the rate of the 2013-2023 trendline (55 million bushels per year), and that the balance of corn would be available for ethanol production. This production would satisfy both the EIA baseline for light-vehicle use and meet export demand and that the balance would be available for ethanol production that could be used for ETJ-SAF production with ETJ-SAF production ramping up from 5% of the potential newly available ethanol being used for ETJ-SAF in 2024 and reaching 100% of the extra ethanol being available and used for ETJ-SAF production by 2050. This also assumes that the combination of policy incentives, technological advances, and infrastructure development are sufficient to lower the CI score of corn-based ethanol enough so that it can be successfully transformed into SAF.

This pathway assumes that the ethanol produced with carbon capture and sequestration and used for ETJ represents 0.2% of ethanol production in 2024, 8.6% of ethanol in 2030, and 45.9% of ethanol production in 2050. The DIS pathway assumes that plants producing ethanol for ETJ will be a mixture of existing plants that install carbon capture and sequestration and new plants that are built specifically for ethanol production for ETJ and incorporate CCS at construction either by tying into an existing CO2 pipeline or through on-site direct injection of CO2.

The Other Alcohol to Jet (ATJ-SAF) pathway starts out at 20 million gallons of production in 2024 and grows to 140 million gallons by 2030 and then continues to increase to 2.4 billion gallons by 2050.

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[4] Specific pathway details are contained in Section 5.

The FT-SAF pathway begins with an estimated 26 million gallons of FT-SAF in 2023, increases to 300 million gallons by 2030, and rises throughout the remainder of the pathway to 2050, reaching 2.7 billion gallons of FT-SAF use in 2050.

The Power to Fuel (PTF-SAF) pathway has two parts[5]. The first part is PTF-SAF that is made from CO2 captured at ethanol plants that produce ethanol for light-duty vehicles, capture CO2 and then that captured CO2 is converted into SAF either nearby or in plants that receive their CO2 from an existing pipeline, or by rail. This pathway is modeled to grow from 10 million gallons in 2024 to 180 million gallons by 2030 and then continues to increase through 2050, reaching 674 million gallons of SAF in 2050 and utilizes 90% of the CO2 captured from ethanol production that is used in light-duty vehicles. Note that due to current tax policy, it is assumed that for ethanol to be used for ETJ, the CO2 must be captured and sequestered. Thus, the only CO2 from ethanol plants that is available for SAF production is from ethanol which is blended and used in light-duty vehicles. If the EPA approves a scoring model for ethanol for which the CO2 is used as a feedstock in SAF production, then this may change as part of the CI score which currently is assigned to ethanol may be assigned to the CO2 feedstock, but for this analysis, ethanol for which the CO2 is used as a feedstock for SAF, none of the CI score has been assigned to the CO2 and the ethanol does not have a low enough CI score to be used as SAF feedstock.

The second part of the PTF pathway uses feedstocks other than CO2 from corn ethanol production. For this study, we have modeled this CO2 as primarily being of direct air capture (DAC). This pathway is expected to grow from 10 million gallons in 2024 to 40 million gallons by 2030 and then rise to 17.8 billion gallons in 2050. Currently, this pathway is likely the most expensive pathway for SAF production, but it is assumed that technology advances will occur that allow for this pathway to become much more cost effective in the future and will be the largest source of SAF by 2050, ultimately supplying 42% of total SAF used in the U.S. in 2050.

The DIS pathway for SAF production in the U.S. does not reach 3 billion gallons until 2032 (only reaching 2.402 billion gallons in 2030); only reaches 22% market penetration by 2040; does not exceed 50% market penetration until 2047; and ramps up very rapidly in the 2048-2050 period. “Speeding up” the adoption rate of this pathway could be achieved if policy initiatives, tax incentives, market demand and public support align for swifter development of cost reductions in PTF, more complete facilitation of ETJ from existing ethanol plants, and more cost-effective development of the FT pathways.

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[5] The Brandlt *et. al. models* indicate that each ton of captured CO2 can be transformed into 17.0589 gallons of SAF.

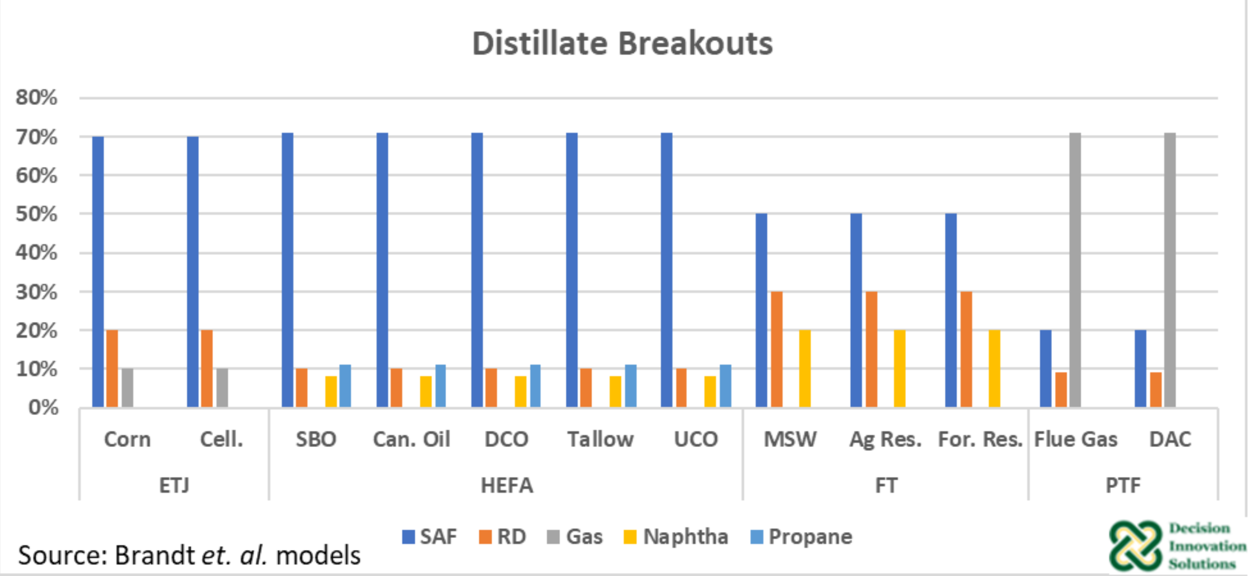
5 Operational Models of HEFA, ETJ, PTF, and FT

Operational models are used to understand the relative competitiveness of each SAF feedstock and pathway under projected incentives and cost structures. Models needed to be specified at the feedstock level as CI scores of finished SAF can vary significantly by feedstock, even for the same general pathway.

Models developed by Brandt *et. al.* (2021a, 2021b, 2021c) were used to create hypothetical operational models. The models developed by Brandt *et al* contained key default parameters including product yields, CAPEX costs, OPEX costs, and historic fuel price relationships among others. Figure 5 and Table 2 outline some of the key defaults taken from these models.

Note: Actual industry experiences may differ from the parameters contained in the models used. And, we expect industry to achieve greater yields, improved efficiencies, and reduced costs over time as the pathways expand commercially. However, given the nascent nature of the SAF industry at this time, and the lack of publicly available data on actual operations, we believe the models used in this report provide results that are directionally correct and reflect the relative performance of the pathways correctly.

Figure 5 shows the distillate breakout from each pathway. It is important to note that not all output product of an SAF plant is SAF. Some mixture of co-products including renewable diesel, aviation gasoline, naphtha, and propane are produced as well. We used the highest possible SAF distillate percentage available in the models developed by Brandt *et. al.* in this analysis and these are included in Figure 5. ETJ and HEFA have the highest percentages of modeled SAF from the distillate stack while PTF pathways have lower percentages of SAF.



Source: Brandt *et. al.* models

Figure 5. Distillate Breakouts

Table 2 provides some key default values including distillate yields and plant level capacity and production. Given the assumptions used in this paper, ETJ and HEFA plants will have much higher production of SAF per plant than FT and PTF pathways.

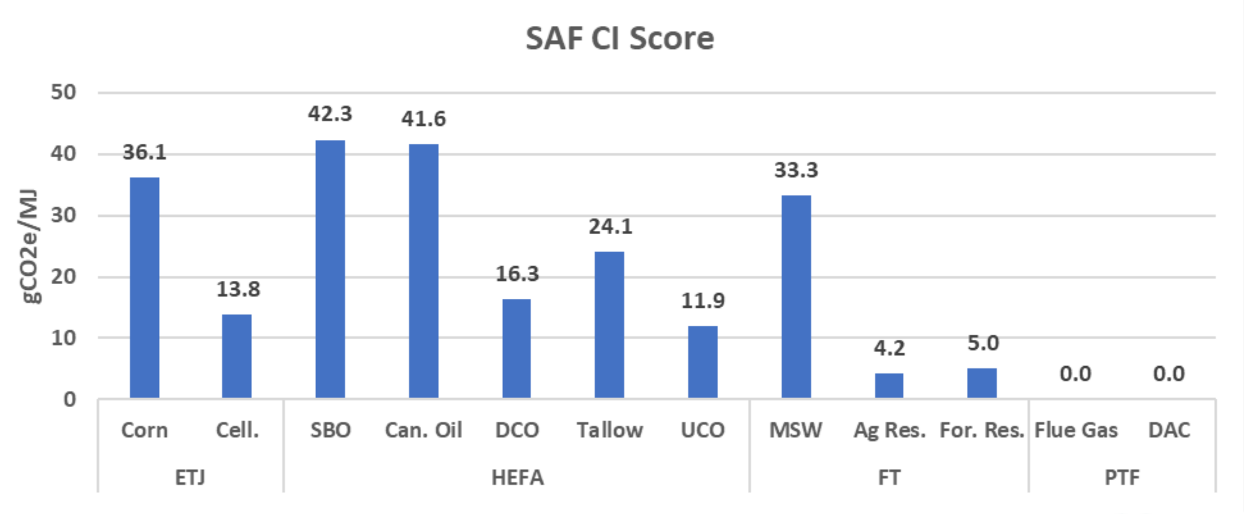
Table 2. SAF Key Factors

Processing Technology	Feedstock	Yield (MT distillate/ MT feedstock)	Plant Feedstock Capacity (1,000 MT feestock/yr)	Plant Distillate Capacity (mil gal distillate/yr)	SAF Production (mil gal/yr)
ATJ	ethanol	0.60	1,260	264	185
HEFA	vegetable oils	0.83	892	264	185
HEFA	FOGs	0.83	892	264	185
FT	MSW	0.31	1,290	132	70
FT	forest residues	0.18	1,290	106	41
FT	agricultural residues	0.14	1,290	79	31
PTF	flue gas	0.24	1,290	264	22
PTF	DAC	0.24	1,290	264	22

Notes: FOGS = fats, oils, and greases; MSW = municipal solid waste; DAC = direct air capture
Source: Adapted from ICAO SAF rules of thumb and supported by Brandt *et. al.* models

Current price levels were collected for all necessary inputs for each feedstock pathway. In general, these did not vary significantly from the model defaults, though some feedstock prices had relatively large differences. For example, soybean oil has increased in price notably since the models were originally developed.

CI score estimates were also collected so 45Z tax credits could be estimated. Most CI score estimates are from the GREET Aviation module (Figure 6). The module did not contain flue gas or direct air capture (DAC). Aggressive assumptions of a zero CI score for the CO2 used to produce these fuels. As noted later in the report, even with aggressively low CI scores, these fuels still are not yet projected to be cost competitive. All CI scores for SAF were adjusted by relative fuel energy content to get CI scores of co-product fuels.



Source: GREET Aviation Module, DIS Assumptions for Flue Gas and DAC

Figure 6. SAF CI Scores

Reporting only costs and revenues of the SAF plant can be misleading because of the differences in the assumed percent of the distillate converted to SAF. For this paper, these assumed distillate levels mean pathways like ETJ and HEFA will be better able to capture SAF benefits, as a higher percentage of their total distillate is SAF. Pathways with lower SAF distillate yields will have a harder time utilizing SAF benefits, because the benefits apply to a lower percentage of their total distillate.

For this reason, values for revenues and expenditures of SAF plants are reported on a per mass of distillate basis instead of only on an SAF basis. This allows for better comparison of the total profitability of the plant. Using assumed prices collected by DIS and models created by Brandt *et. al.* revenues and expenditures of multiple SAF pathways were calculated for a projected year 2050.

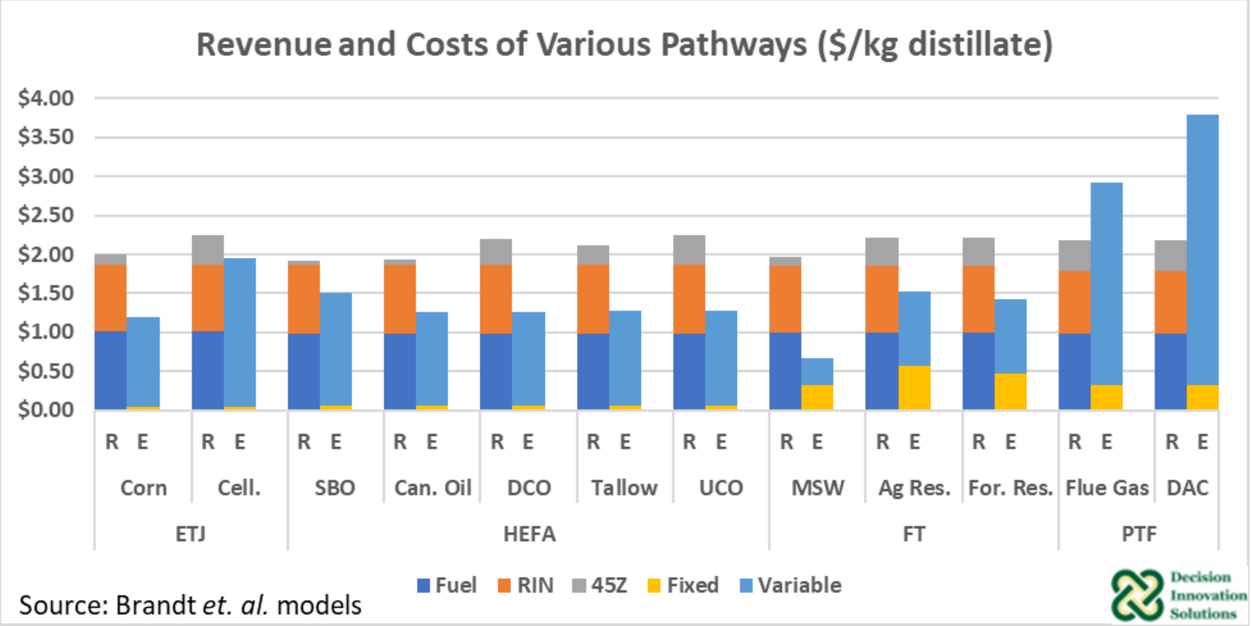
EIA long term projections were used for jet fuel, electricity, and natural gas prices. The historic relationship between jet fuel and other wholesale fuel prices was used to determine the prices of other fuels. In most other cases a large assumption was made that prices would increase at exactly the rate of inflation.

Two additional large assumptions relate to RIN prices and other feedstock prices. First, it is assumed that RIN prices will remain at current levels. RIN prices are essentially policy driven as they are based on EIA's mandated blend rates relative to US production capacity, so they are extremely difficult to forecast. Second, it is assumed feedstock prices will remain unchanged from current levels, except for adjustments to inflation. This is the large assumption and least likely to hold as large increase in demand from SAF production will likely increase prices of all feedstocks.

With these admittedly large assumptions, it is still possible to see the relative profitability of various SAF pathways. Corn ETJ looks very profitable, with cellulosic ETJ also slightly profitable. This even included a higher ethanol price to accommodate cellulosic ethanol production. All HEFA pathways are very profitable, especially distillers corn oil (DCO) and used-cooking oil (UCO), two pathways with relatively low CI scores. The Fischer-Tropsch pathways analyzed here also look profitable, especially for municipal solid waste (MSW). Though this assumes feedstocks can be obtained at relatively low costs. This assumption may not hold, particularly for MSW at relatively high quantities of production.

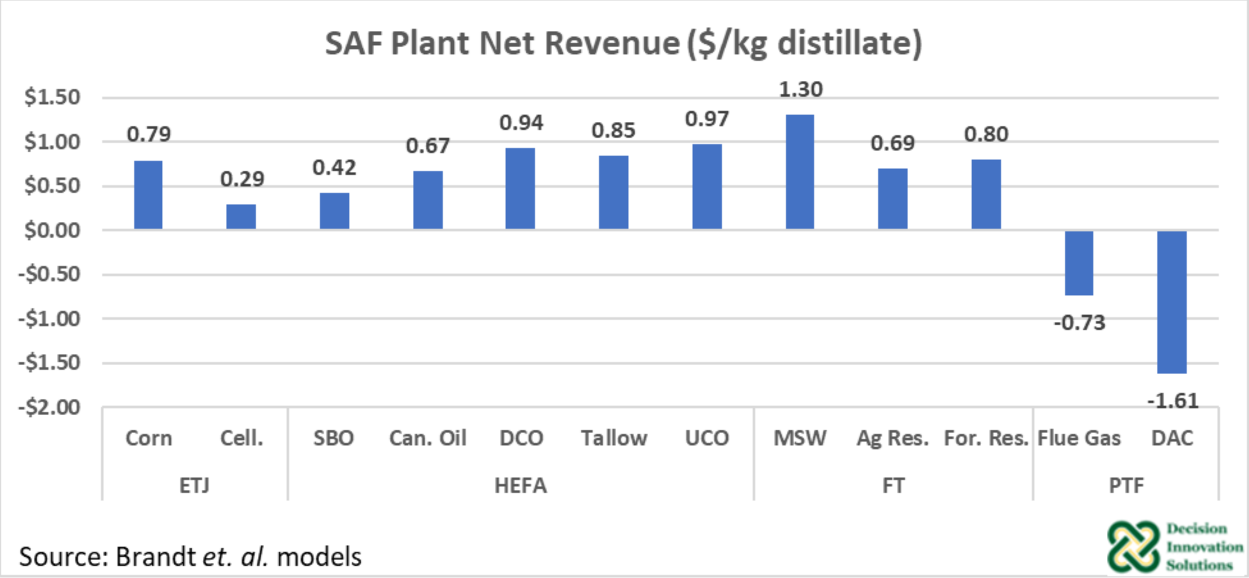
Figure 7 shows the revenue and costs of various feedstocks and pathways assessed in this analysis. Figure 8 shows the net revenue at the SAF plant level reported on a dollar per kg of distillate level. As noted above, the varying distillate breakouts make it misleading to report the net operating returns of an SAF plant based solely on SAF output.

With all previous stated assumptions, MSW has the greatest net revenue per kg of distillate mix at $1.30/kg. PTF pathways show negative returns even with an aggressive assumption of a 0 CI score for these pathways. No assumptions were made about the technological improvements to reduce relative costs. Alternatively, technological advances that would increase the relative percentage of SAF from the distillate in these pathways (or increase the amount of distillate per unit of input) would raise revenue and potentially make these pathways look more attractive in the future.



Source: Brandt *et. al.* models

Figure 7. Revenue and Costs of Various Pathways ($/kg distillate)



Source: Brandt *et. al.* models

Figure 8. SAF Plant Net Revenue ($/kg distillate)

6 HEFA-based Biofuels and HEFA-SAF Forward Production Pathways

Feedstock supplies for HEFA-based fuels primarily come from vegetable oils (soybean oil, distillers corn oil, and canola oil), animal fats (tallow, choice white grease, poultry fat) and recovered fats (yellow grease, brown grease, and used cooking oil). In 2022, it is estimated that 23.282 billion pounds of these feedstocks were used for combined methyl-ester biodiesel, renewable diesel, and SAF fuel production. In 2022, 51.5% of the HEFA feedstocks were soybean oil (SBO), 16.2% was distiller corn oil (DCO), 4.2% was canola oil (CANO), and 28.2% was from animal fats and other fats/oils (Table 3).

Table 3. HEFA-Based Biofuels Feedstock Use by Type of Fuel (2022)

HEFA-Based Biofuels Feedstock Use by Type of Fuel (2022)				
	Million Pounds			
Feedstock	**ME-BD**	**RD**	**HEFA-Fuels Total**	**Share Pct**
Soybean Oil	6,828	5,154	11,982	51.5%
DDG Corn Oil	1,279	2,484	3,763	16.2%
Canola Oil	968	-	968	4.2%
Inedible Tallow	370	863	1,232	5.3%
White Grease	703	-	703	3.0%
Yellow Grease	1,235	2,194	3,429	14.7%
Brown Grease	549	-	549	2.4%
Poultry Fat	274	341	616	2.6%
Other/Residual	40	-	40	0.2%
Total	12,246	11,036	23,282	100.0%
Source: EIA				

Forward projections of soybean production were done by applying the 1980-2023 trend for soybean yields to the current level (10-year average) of soybean acres (Figure 9). The U.S. soybean yield is increasing by 0.549 bushels per acre per year. The 10-year average of soybean harvested acres is 83.7 million acres. Projecting these forward results in 4.332 billion bushels of soybean production in 2024 and increases to 5.526 billion bushels of soybean production in 2050.[6]

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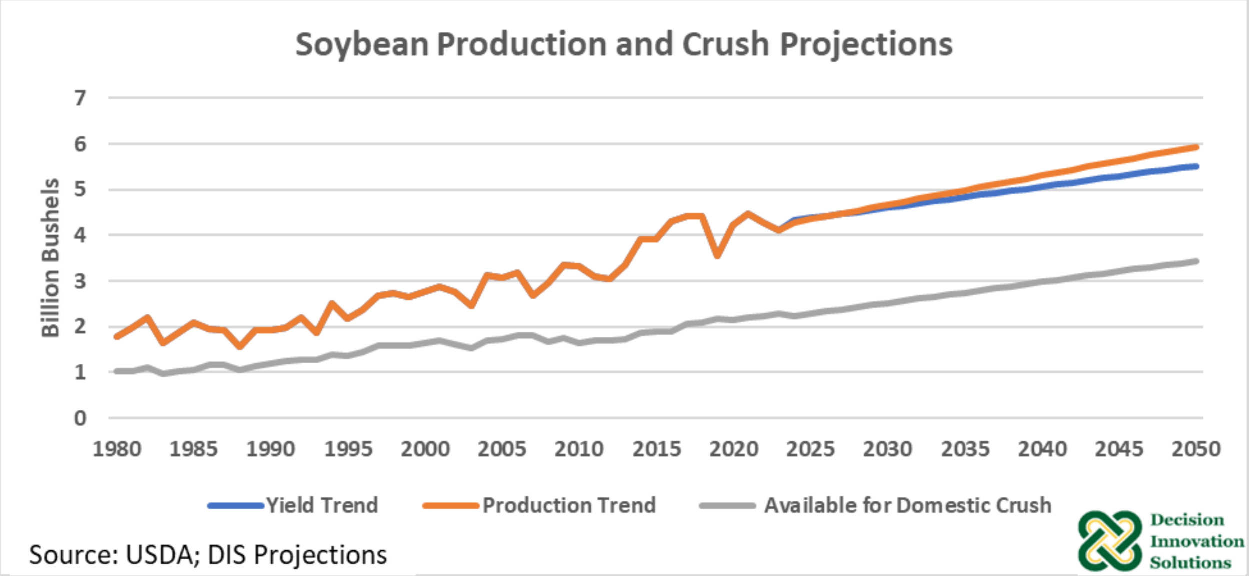
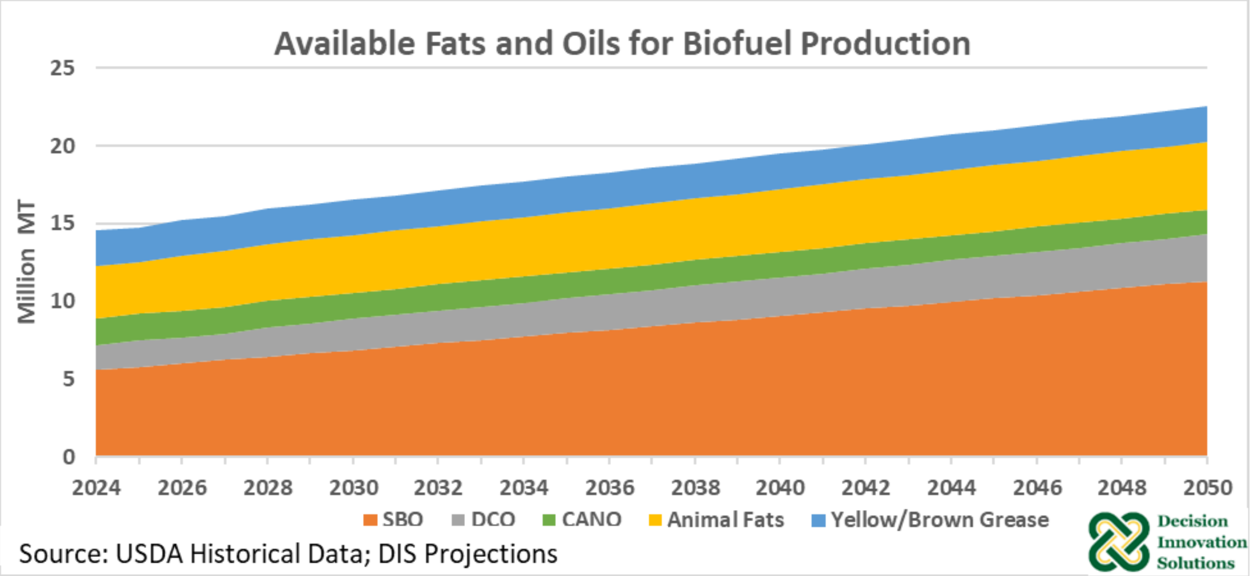
[6] DIS calculated forward soybean production using a simple 1980-2023 production trend. This method resulted in slightly less soybean production in the near term (2024-2026) but resulted in more soybean production for the years 2027 through 2050 with 5.947 billion bushels in 2050. For this analysis DIS selected the more conservative production estimate.



Source: USDA; DIS Projections

Figure 9. Soybean Production and Soybean Crush Projections

Fats and oils available for HEFA-based biofuel production were projected based on soybeans available for domestic crush, a soybean oil yield of 11.88 pounds of oil per bushel (19.8% oil content); DCO yields from ethanol production of 0.7 pounds per bushel processed for ethanol, and trendline projection of total animal fats[7] (Figure 10).



Source: USDA Historical Data; DIS Projections

Figure 10. Available Fats and Oils for Biofuel Production

The forward projections for HEFA-based biofuels used the EIA 2023 baseline projections for biodiesel, and renewable diesel and used the balance of the HEFA feedstocks for HEFA-SAF production (Figure 11).

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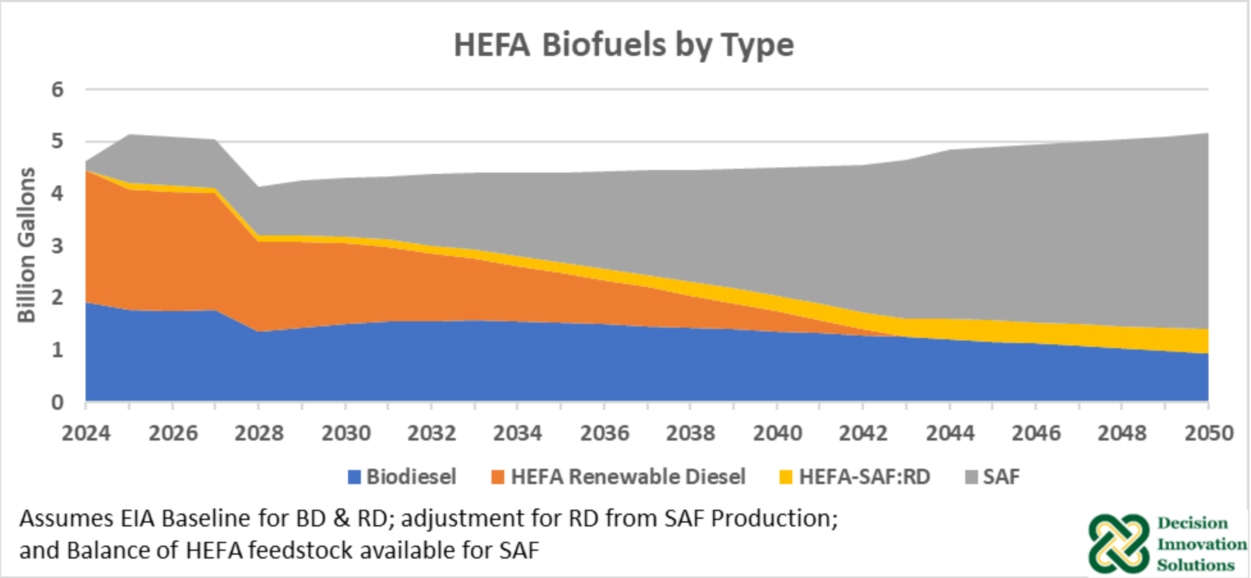
[7] Fat yield coefficients for animal fats used per million pounds of meat production are: lard: 1.3%; choice white grease: 5.03%; poultry fat: 4.70%; beef edible tallow: 7.00%; and beef inedible tallow of 14.00%. Brown grease and yellow grease data was added to historic totals for animal fats from 2005 through 2023.

The production coefficient for HEFA-SAF was 10.62 pounds of HEFA feedstock per gallon of HEFA-SAF. Each 10.62 lbs of feedstock produces a distillate product that could be distilled to 68% SAF, 8% RD, 8% Naphtha, and 16% propane. The initial ramp-up of HEFA-SAF production assumes 187 million gallons of HEFA-SAF in 2024, rising to 1 billion gallons of HEFA-SAF by 2030, then rising from 2031 through 2050 based on HEFA feedstock available for HEFA-SAF. Total projected HEFA-based biofuels rise from 4.015 billion gallons in 2024 to 6.522 billion gallons in 2050. Methyl-ester biodiesel production is projected to peak in 2026 at 1.857 billion gallons and then decline to 1.001 billion gallons in 2050. Renewable diesel production is estimated to be 2.119 billion gallons in 2024, declining to 2.073 billion gallons in 2031 and then increasing to 3.025 billion gallons in 2050.



Assumes EIA Baseline for BD & RD; adjustment for RD from SAF Production; and Balance of HEFA feedstock available for SAF

Figure 11. HEFA Biofuels by Type

6.1 HEFA Availability Maps

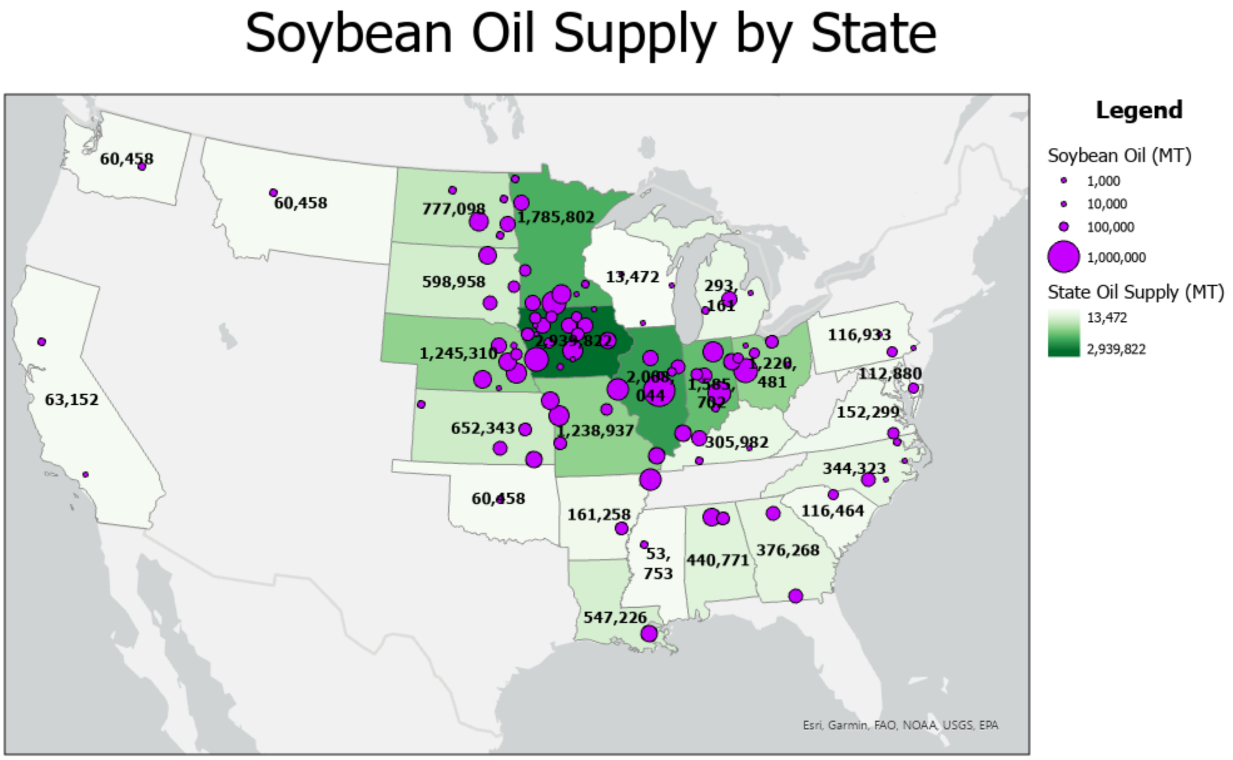
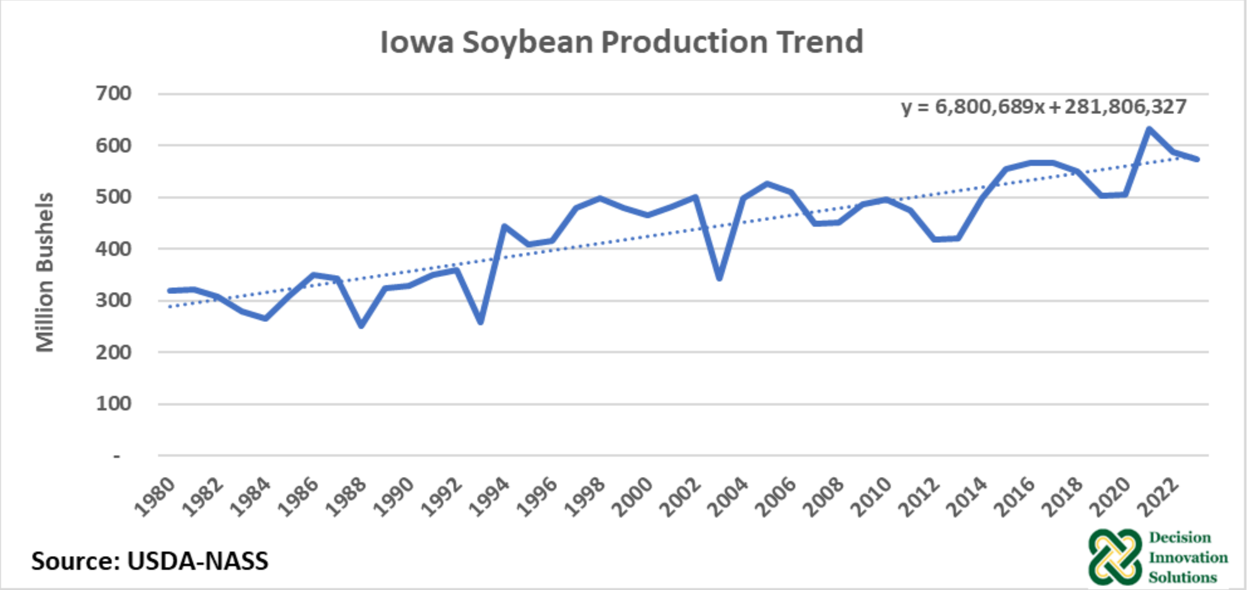


Figure 12. State Soybean Oil Supply and Soy Processing Plants

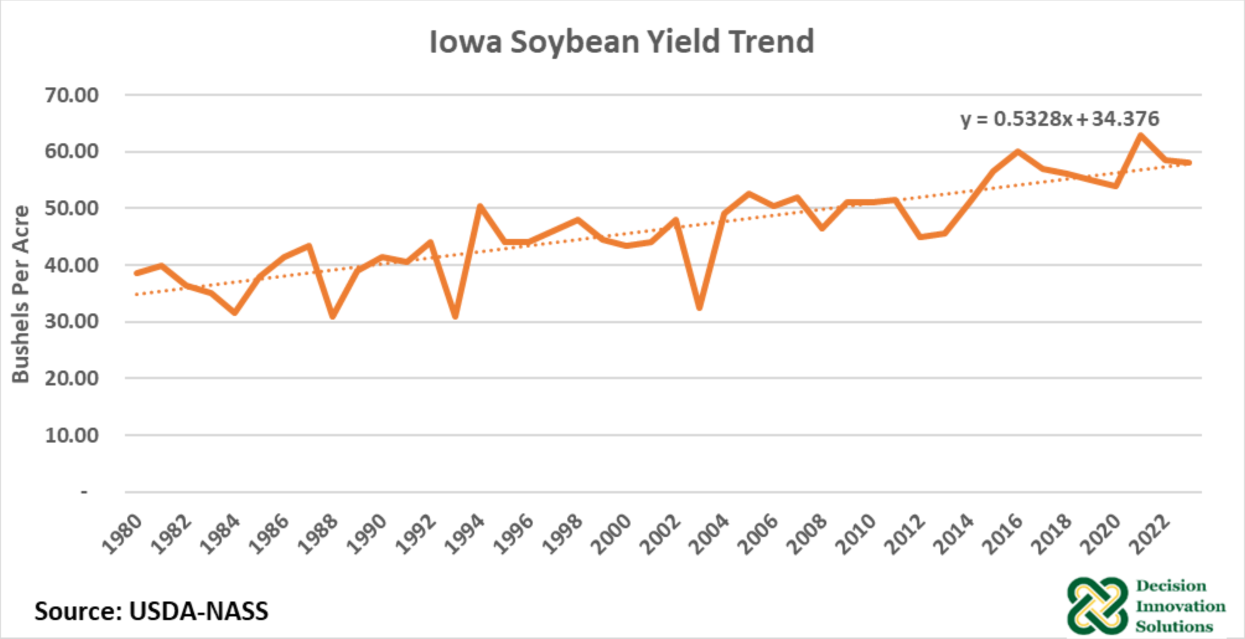
Iowa has 14 large, commodity soybean crush facilities that can process about 580 million bushels of soybeans per year and produce 2.94 million metric tons of soybean oil per year. Iowa produces 662.7 million pounds of animal fats (300,615 MT) each year. Iowa currently has 10 biodiesel production facilities and no renewable diesel or SAF plants.



Source: USDA-NASS

Figure 13. Iowa Soybean Production Trend

Iowa soybean production is increasing by 6.8 million bushels per year (Figure 13). The yield trend in Iowa is an increase of 0.53 bushels per acre per year (Figure 14). If soybean production is projected forward to 2050 for Iowa there would be an additional 183 million bushels of soybean production in Iowa



Source: USDA-NASS

Figure 14. Iowa Soybean Yield Trend

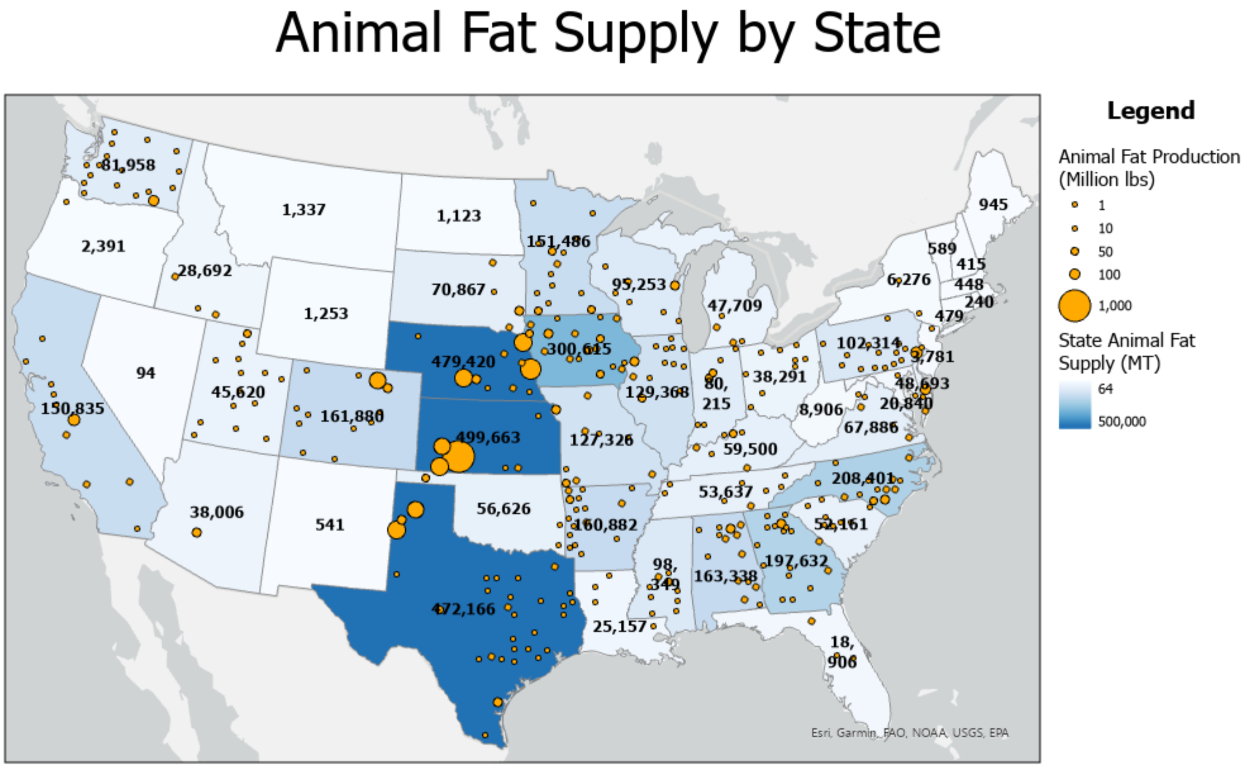


Figure 15. State Animal Fat Supply and Major Counties

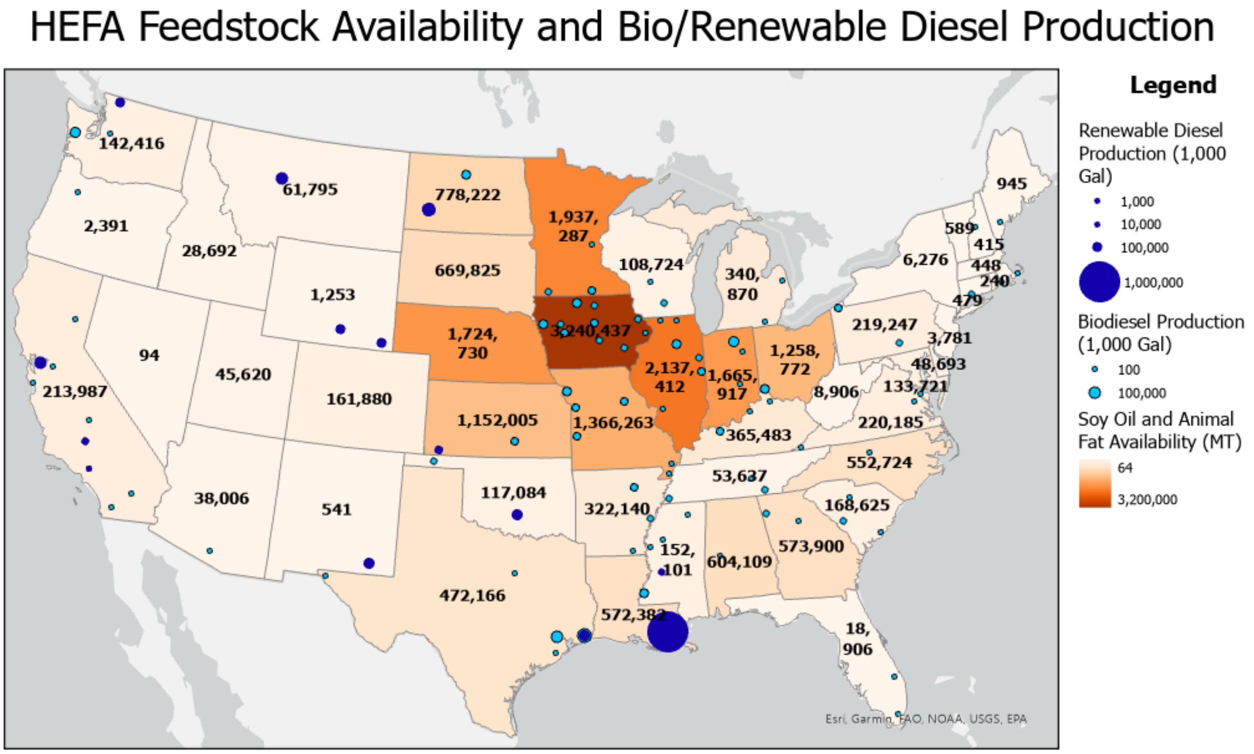

HEFA Feedstock Availability and Bio/Renewable Diesel Production

Figure 16. State HEFA Feedstock Availability and Bio/Renewable Diesel Production Facilities

6.2 HEFA-SAF Distribution of New Production

Biodiesel production developed as a very distributed system with 87 plants located in 38 states and with only one plant with greater than 100 million gallons per year of capacity. Of the 87 plants, 77 have less than 50 million gallons of annual capacity and half of the plants are 12 million gallons or less in capacity (Figure 17).

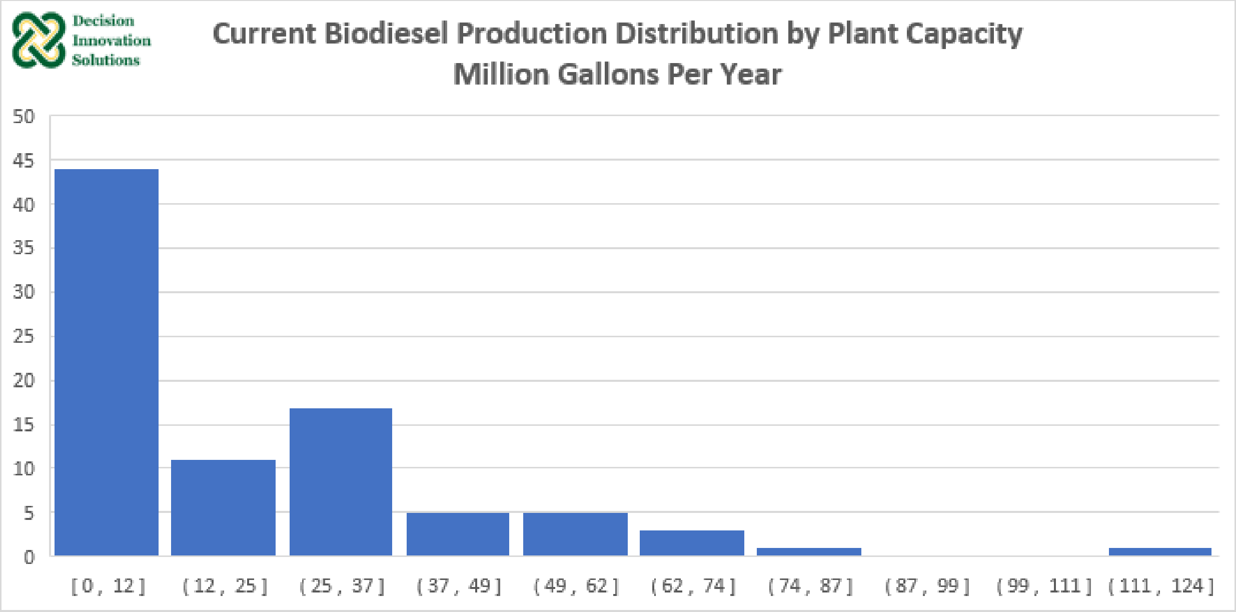


Figure 17. Current Biodiesel Production Distribution by Plant Capacity

In contrast, renewable diesel production capacity is developing differently. To date, there are 17 plants operating in 11 states with only 7 of the plants having less than 100-million gallons of capacity and the largest one with nearly 1 billion gallons of capacity (Figure 18). Eight of the plants have between 100-200 million gallons of capacity. The largest renewable diesel production facilities are located so that they can distribute their production through pipelines.

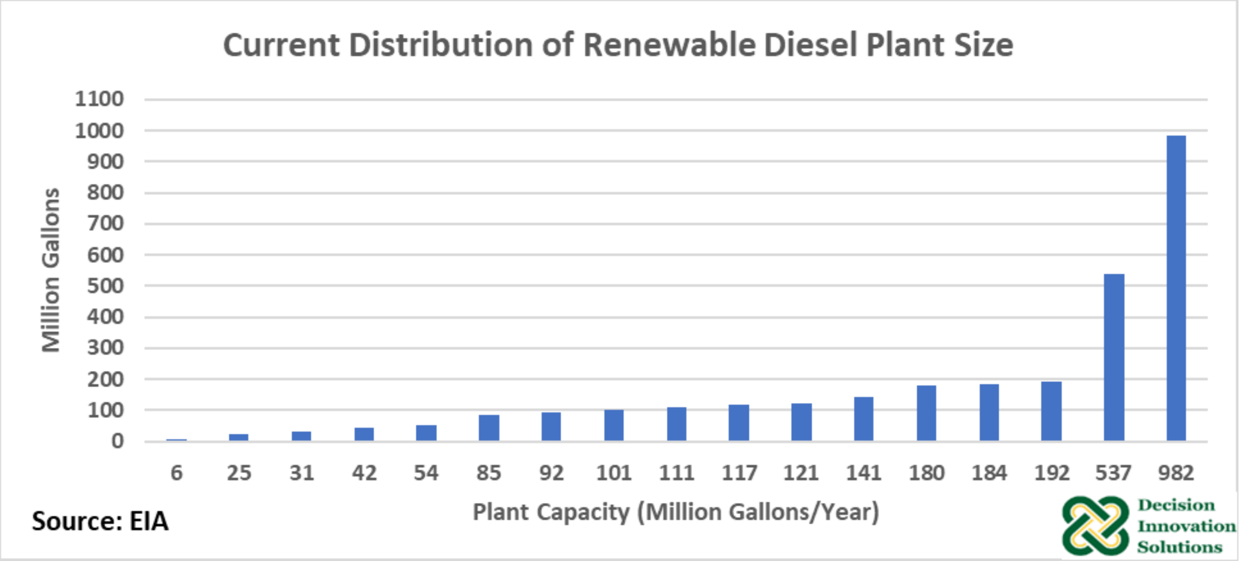


Figure 18. Current Distribution of Renewable Diesel Plant Size

SAF production so far has developed at a relatively small scale (which is normal at the onset of a new industry). However, several conversions of existing refineries for renewable diesel and SAF are at larger scale and the recently announced SAF facility in southeastern Kansas (co-located with a new soybean processing plant) is reported to be a 135-million-gallon facility. The Brandt *et. al.* SAF models sized HEFA plants at 185 million gallons per year of SAF which would have them processing about 250 million gallons of distillate. Currently there are seven announced or operating HEFA-based RD/SAF plants that will, at capacity, produce more than 2.6 billion gallons of HEFA-based RD/SAF fuels (Figure 19). In 2050, DIS projects that a total of 3.7 billion gallons of HEFA-based RD/SAF will be produced. When all current renewable diesel and planned/announced expansions of capacity at existing and new plants are completed (projected to mostly be done by 2025 or 2026), there could be as much as 4.9 billion gallons of HEFA-based RD/SAF capacity. If that is the case, then there is no need for more expansion of HEFA-based biofuels capacity unless some of the current biodiesel production ceases and those feedstocks are re-directed to HEFA-based RD/SAF.

What could develop is the upgrading of existing RD plants to RD/SAF capacity as more RD is produced as the co-product of ATJ and FT pathways. If enhanced DCO recovery technologies are widely adapted, then there will be room for about 1.1 billion gallons of HEFA-based RE/SAF capacity that needs to be built.

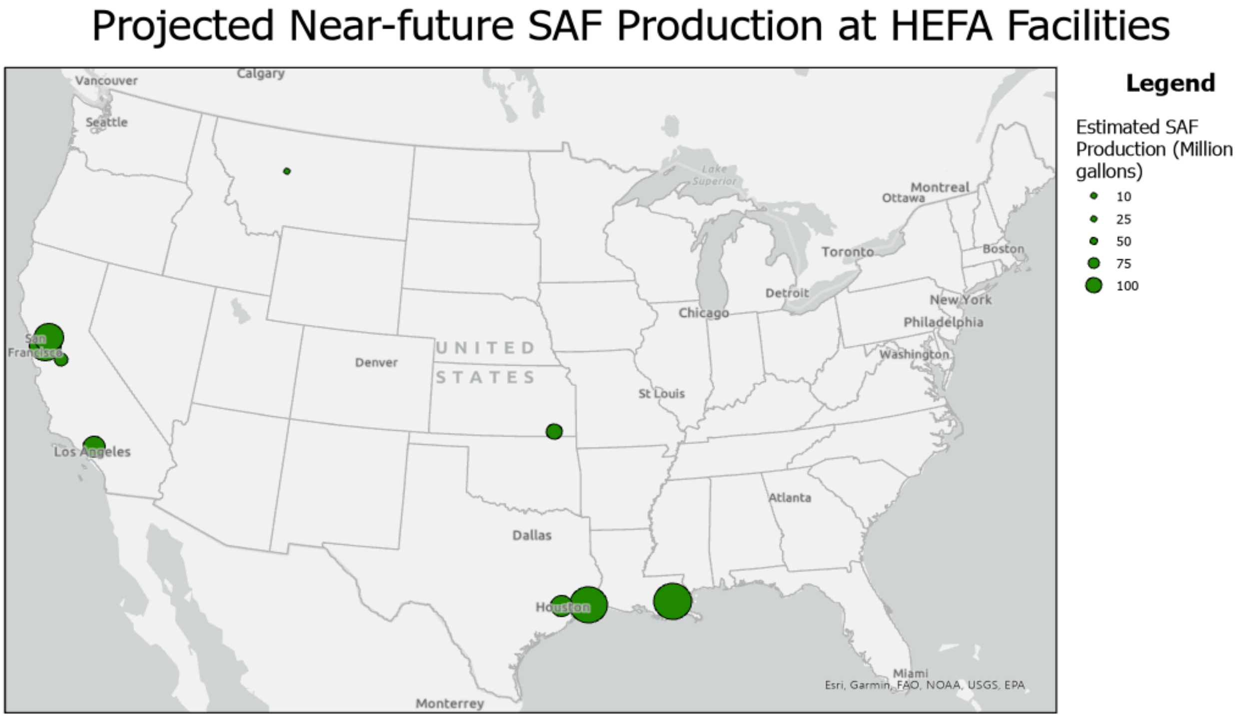


Figure 19. Projected Near-Future SAF Production at HEFA Facilities

With an average modeled HEFA-based SAF plant size being about 250 million gallons of distillate, total HEFA-SAF could be satisfied with one more large scale HEFA plant built in the U.S. Gulf Coast area, but it could also mean 4 to 6 modeled-sized HEFA-based plants being built where new soybean oil production is locating. That would likely be in the Midwestern states. For the purposes of this study, one new HEFA-based plant will be modeled for each of Illinois, Nebraska and South Dakota and 3 new HEFA-SAF plants for Iowa since these are the states most likely to see new soybean crush capacity developed and/or have more DCO available due to enhanced DCO recovery (Figure 20).

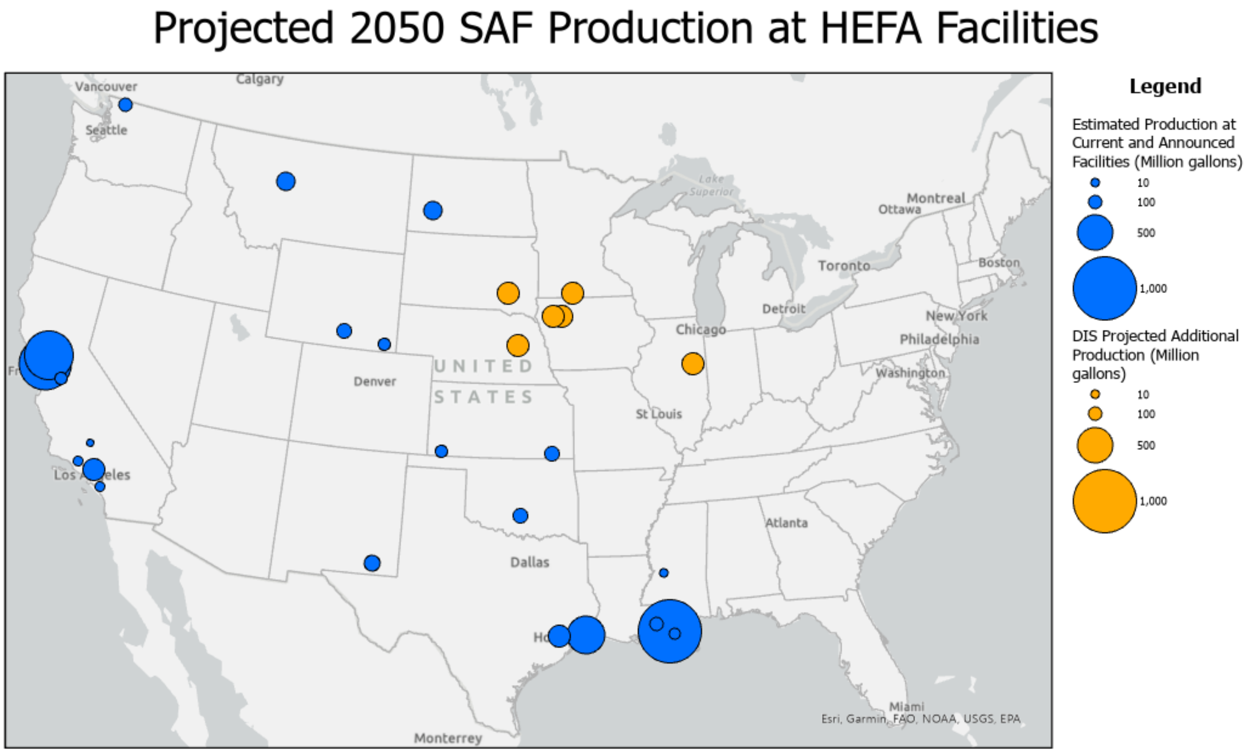
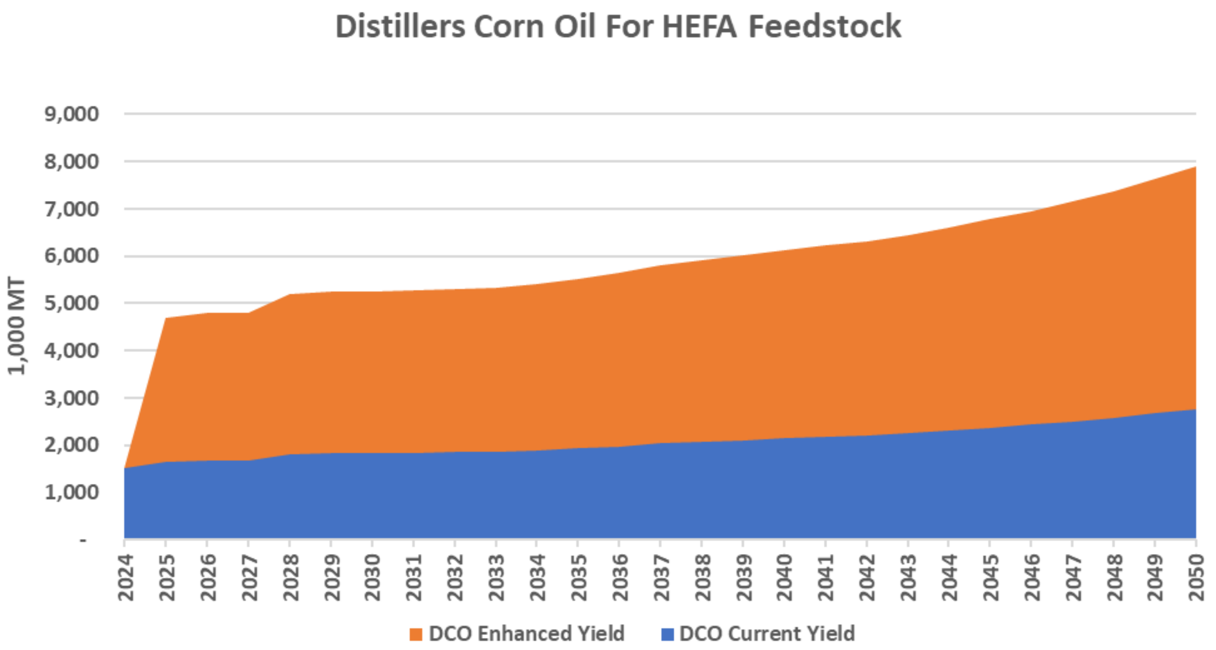


Figure 20. Projected 2050 SAF Production at HEFA Facilities

6.3 Distillers Corn Oil to Renewable Diesel and/or SAF

At one time, the maximum DCO extraction yield was around 0.4-0.5 lbs/bu. Today, the average DCO yield is closer to 0.7 lbs/bu. The total potential DCO yield is close to 2.0 lbs/bu. Today's DCO recovery is still only around 30% efficiency, and the actual yield range is a whopping 0.5-1.2 lbs/bu (Trucent, 2019).

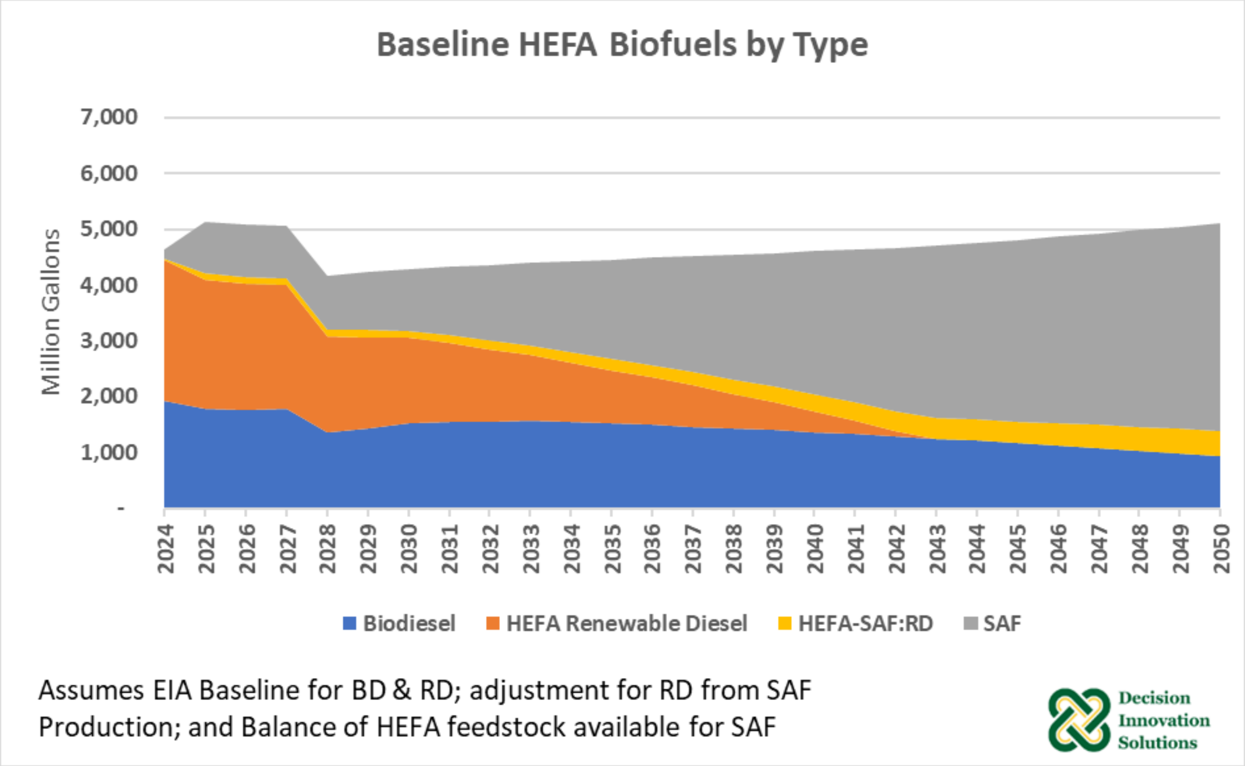
Figure 21 shows the projected amount of DCO that would be available in the future from corn processed for ethanol if the current average yield of DCO of 0.7 lbs/bu is applied to projected corn processed for ethanol with significant amounts of ethanol being used for ETJ and how much DCO would be generated for feedstock for HEFA-based SAF if the DCO yield was nearer the "theoretical ideal" level of 2.0 lbs/bu. If this higher DCO yield is reached, the amount of DCO for HEFA feedstock would increase from 1.6 mmt in 2025 to 4.7 mmt in 2025 and by 2050 instead of 2.8 mmt of DCO there would be 7.9 mmt of DCO available for HEFA feedstock.



Source: DIS Projections
Note: Current DCCO Yield at 0.7 lbs/bu; Enhanced DCO yield at 2.0 lbs/bu

Figure 21. Distillers Corn Oil for HEFA Feedstock

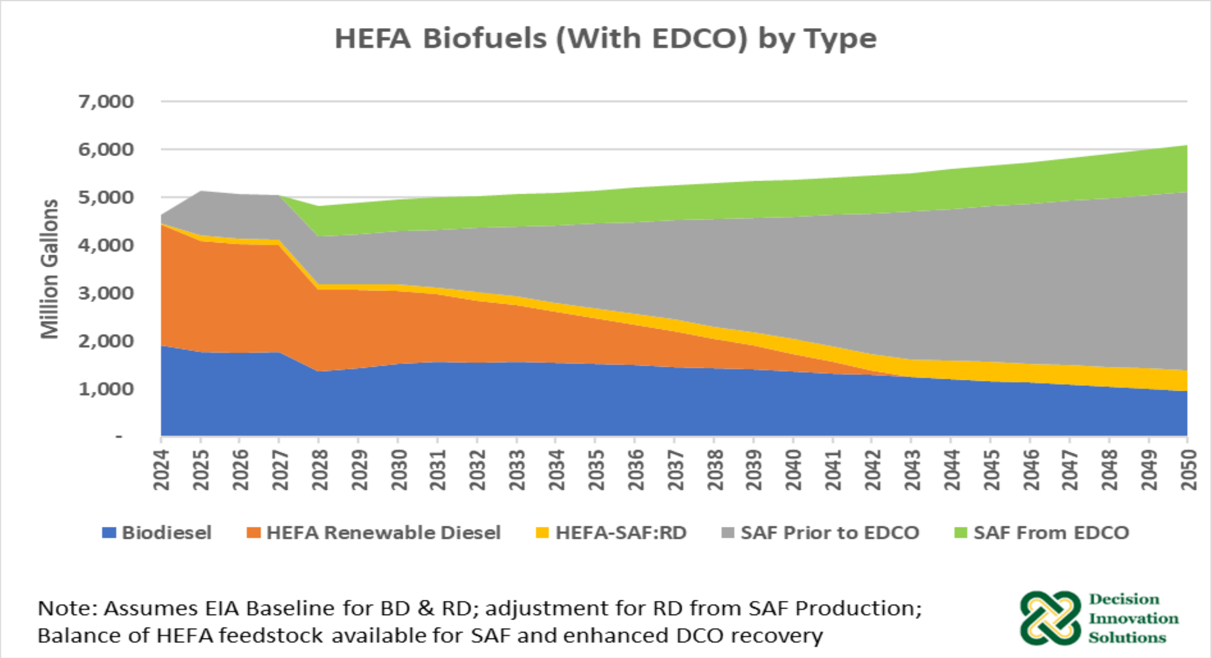
In Figure 22 the baseline of HEFA biofuels by type of fuel is shown. Biodiesel from HEFA follows the EIA baseline scenario. HEFA renewable diesel begins as the primary source of renewable diesel but diminishes over time because SAF pathways produce some level of renewable diesel as a co-product. Therefore, over time the amount of SAF produced from HEFA steadily increases as supplies of HEFA feedstocks increase and less HEFA feedstock is needed for production of renewable diesel from HEFA as the primary product.



Assumes EIA Baseline for BD & RD; adjustment for RD from SAF Production; and Balance of HEFA feedstock available for SAF

Figure 22. Baseline HEFA Biofuels by Type

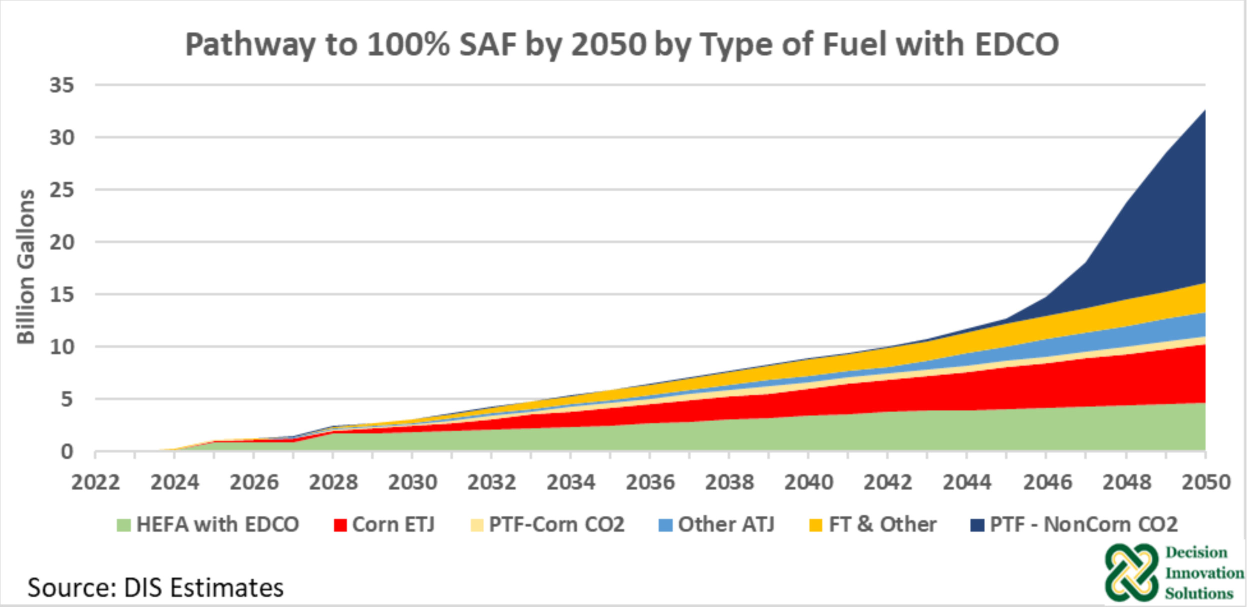
In the scenario in which DCO production is enhanced, there is a significant amount of "new" HEFA feedstock (labeled as EDCO) available for SAF production as shown in Figure 23. Given time for installation of enhanced DCO recovery equipment, the modeled increase in SAF due to enhanced DCO recovery begins in 2028 with 655 million gallons and expands to 995 million gallons of SAF in 2050.



Note: Assumes EIA Baseline for BD & RD; adjustment for RD from SAF Production; Balance of HEFA feedstock available for SAF and enhanced DCO recovery

Figure 23. HEFA Biofuels (with EDCO) by Type

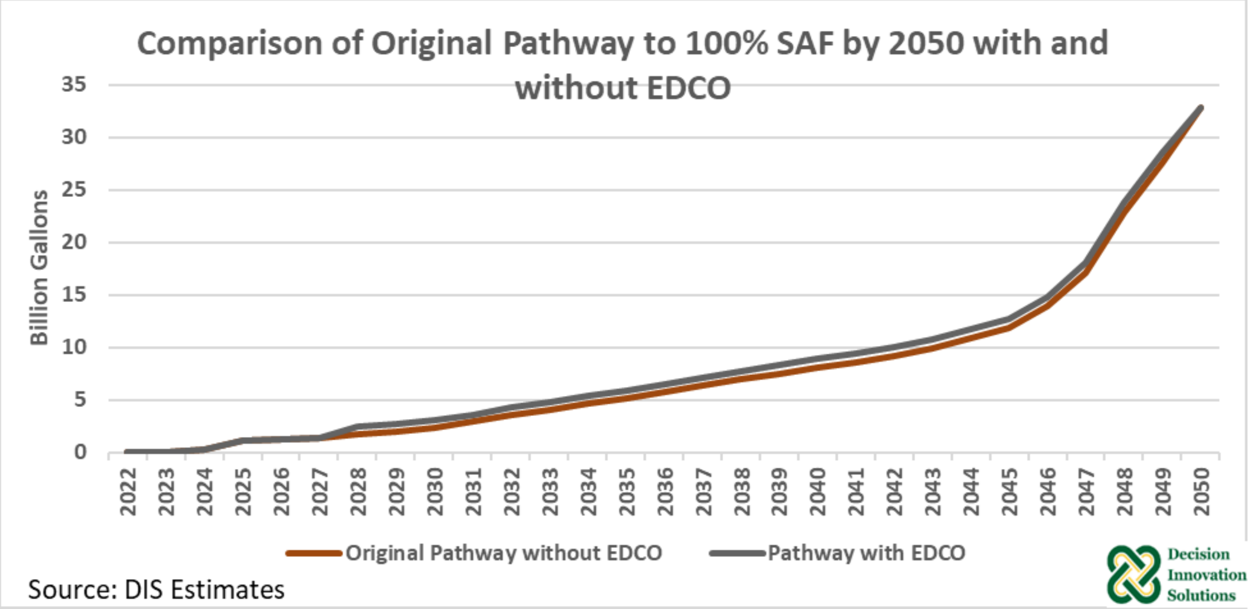
Figure 24 shows the overall pathways for SAF to 2050 with the additional HEFA-based SAF that would come from enhanced DCO recovery. In this set of pathways, total HEFA-based SAF in 2050 is 4.7 billion gallons; FT-SAF is 2.7 billion gallons; corn ETJ-SAF is 5.6 billion gallons; other ATJ is 2.4 billion gallons; Ethanol CO2-ETJ is 674 million gallons; and PTF-SAF is 16.7 billion gallons.



Source: DIS Estimates

Figure 24. Pathway to 100% SAF by 2050 by Type of Fuel with EDCO

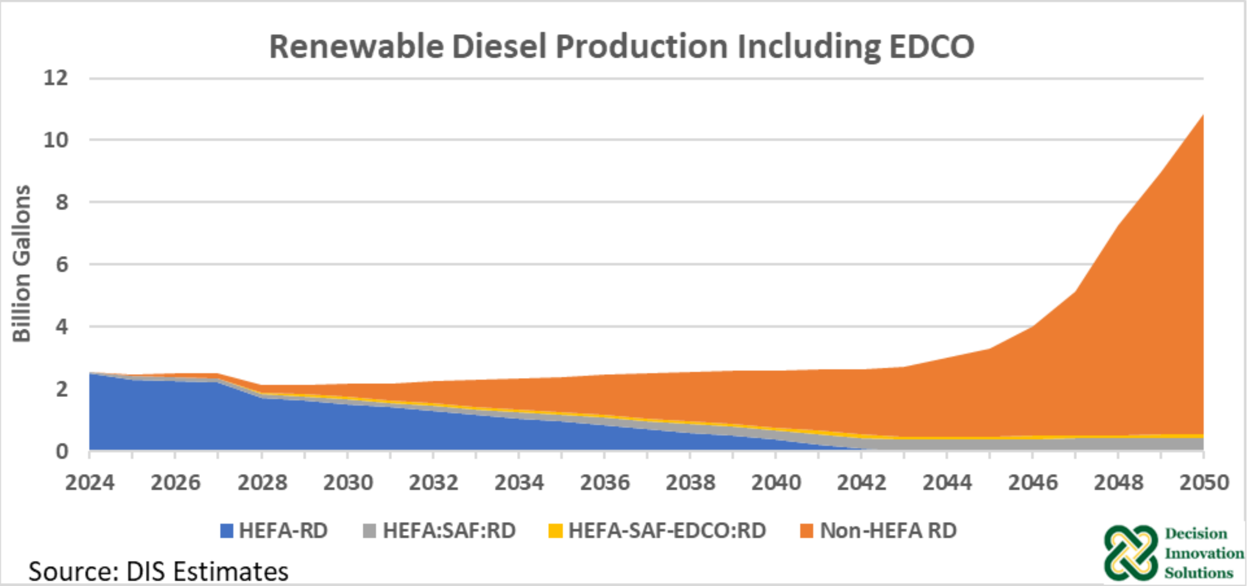
Producing SAF with enhanced DCO recovery marginally increases the amount of SAF that is available at intermediate points along the timeline. Figure 25 shows a comparison of the pathways to 100% SAF by 2050 with and without enhanced DCO recovery. EDCO does make more SAF available throughout the 2030s and early 2040, and ultimately reduces some of the PTF-SAF that is needed in 2050.



Source: DIS Estimates

Figure 25. Comparison of Original Pathway to 100% SAF by 2050 with and without EDCO

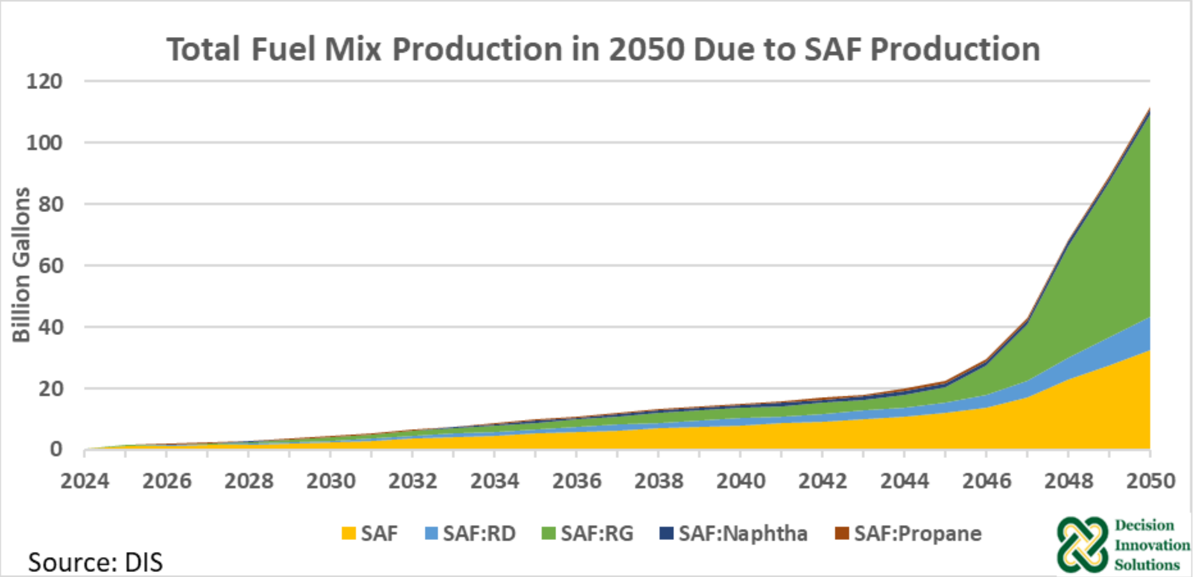
Because the distillate production in the HEFA pathway produces a mixture of SAF and renewable diesel, adding more EDCO to the HEFA stocks also increases the amount of RD that is produced as a byproduct of SAF production. By 2050, it is estimated that an additional 119 million gallons of RD from the production of SAF from EDCO will also be produced and total RD production as a byproduct of all SAF production could reach 10.8 billion gallons in 2050 with nearly 10.3 billion gallons of the RD resulting from PTF-SAF byproduct production (Figure 26).



Source: DIS Estimates

Figure 26. Renewable Diesel Production Including EDCO

Every pathway to SAF production also produces other byproduct fuels. If the U.S. achieves enough SAF production for 100% replacement of petroleum-based jet fuel by 2050, there will be substantial amounts of other fuels also produced. In 2050, it is estimated that along with 32.7 billion gallons of SAF, there will be 10.8 billion gallons of RD, 65.7 billion gallons of renewable gasoline, 1.5 billion gallons of naphtha, and 855 million gallons of propane produced (Figure 27).



Source: DIS

Figure 27. Total Fuel Mix Production in 2050 Sue to SAF Production

While there is likely to be substantial demand for the SAF, RD, naphtha, and propane, it is not clear that there will be demand for 65.7 billion gallons of renewable gasoline alongside the regular gasoline that will still be produced as part of the petroleum distillation process that is making diesel, asphalt, tar, and other products. If the distillation of PTF-SAF can be modified so that less RG is produced and more RD is produced, that would likely result in less market distortions as PTF-SAF production is ramped up in the 2040s.

7 Potential Gains Enabled by Ethanol-to-Jet (ETJ) in the Midwest

For the past three years, the 12 Midwestern states (IA, IL, IN, KS, MI, MN, MO, ND, NE, OH, SD & WI) produced 93.6% of the ethanol in the U.S. These Midwestern states also produced 86.7% of the corn in the U.S. over the past three years. Furthermore, corn production in the U.S. has historically trended upward primarily due to gains in yields. If the current trend in corn production continues, the U.S. will produce nearly 20.7 billion bushels of corn by 2050. However, demand for corn is not expected to grow as quickly, especially ethanol demand. The EIA forward projection has ethanol consumption through blending for light-vehicle use declining slightly. ETJ through corn ethanol is a pathway that can utilize the additional corn that comes from higher trending yields and forestall a significant decline in corn acreage and subsequent negative impacts on the economies of the Midwestern states.

7.1 ETJ Fuel Opportunity Scenarios

If Midwest ethanol plants can lower the CI score of their ethanol through CCS, the potential of using ethanol as an intermediary feedstock for sustainable aviation fuel (SAF) increases. With CCS, ETJ can account for a significant portion of that market and provides pathways for expansion of capacity at existing ethanol plants and the potential for new ethanol plants.

To model where new ethanol plants might developed are if the corn ethanol to jet pathway developed two different scenarios are analyzed to estimate Midwest ethanol growth due to ETJ.

- **Scenario 1:** Each of the Midwestern states maintains their current shares of national ethanol production
- **Scenario 2:** Ethanol production in each Midwestern state expands according to the estimated “excess corn” that will be available in 2050 based on trendline production and trendline use of corn for “other than ethanol” uses.

7.2 Ethanol Industry Opportunities in the Midwest with CCS

Iowa State University’s ethanol model was used to estimate the ethanol margin under (1) normal conditions and (2) under conditions where the ethanol plant claimed either the 45Z or (3) the 45Q tax credit. Key assumptions regarding the size of the plant and fixed costs were taken from the Iowa State Ethanol model (Hofstrand, 2023). Key assumptions made to run the model are outlined in Table 4.

Notably, corn price was assumed to be constant in all scenarios and was set to the long run average price from 2007-2023. Natural gas (NG) prices were calculated the same way. The ethanol complex prices were calculated by regressing corn prices against the price of each product.

Table 4. Key Assumptions for All Scenarios

Prices			Yield Factors		
Corn	$/bu	$ 4.67	Ethanol Yield	gal/bu	2.88
Ethanol	$/gal	$ 1.86	NG use	mmbtus/gal	30
DDGS	$/ton	$ 162.95	DDGS yield	lb/bu	16
Corn Oil	$/lb	$ 0.41	DCO	lb/bu	0.7
NG	$/1000 ft^3	$ 6.20	Other Variable Costs	$/gal	$0.22
			Fixed Costs	$/gal	$0.20

Source: Iowa State Ethanol Model and DIS Estimates

Next the key assumptions and results of the three scenarios outlined above are outlined in Table 5. A baseline margin before additional incentives is outlined below. 45Z and 45Q amounts (credit per gallon of ethanol) are added for their respective scenarios. CCS and CCU costs are assumed to be equal to the value of the 45Q tax credit for both CCS and CCU respectively. The sale of CO2 is set such that margins are equal for ethanol plants. If the price were not this high, ethanol plants would likely opt for CCS and the 45Z tax credit in lieu of CCU and the 45Q tax credit. Therefore, margins are equal under both alternative scenarios. These margins are expected to be about 3.5 times higher under the alternative pathways. However, if CCS costs at the ethanol plant level are higher or lower than forecasted, this will change the margin. For example, if an ethanol plant can capture CO2 and have it sequestered via pipeline for less than $0.49/gallon of ethanol (About $81/ton of CO2 for CCS or $57/ton for CCU) then there would be additional net revenue for the ethanol plants. For a 100-million-gallon ethanol plant, the increased margin ($0.25/gallon) would translate into $25 million per year of increased net revenue. For the 14.4 billion gallons of ethanol currently being produced in the Midwestern states, an additional 25 cents per gallon of net margin would mean $3.6 billion per year in increased revenues flowing through these plants if all gallons were enabled to collect CO2 and either utilize it for PTF-CO2 or sequester it so that the ethanol could be used for ETJ.

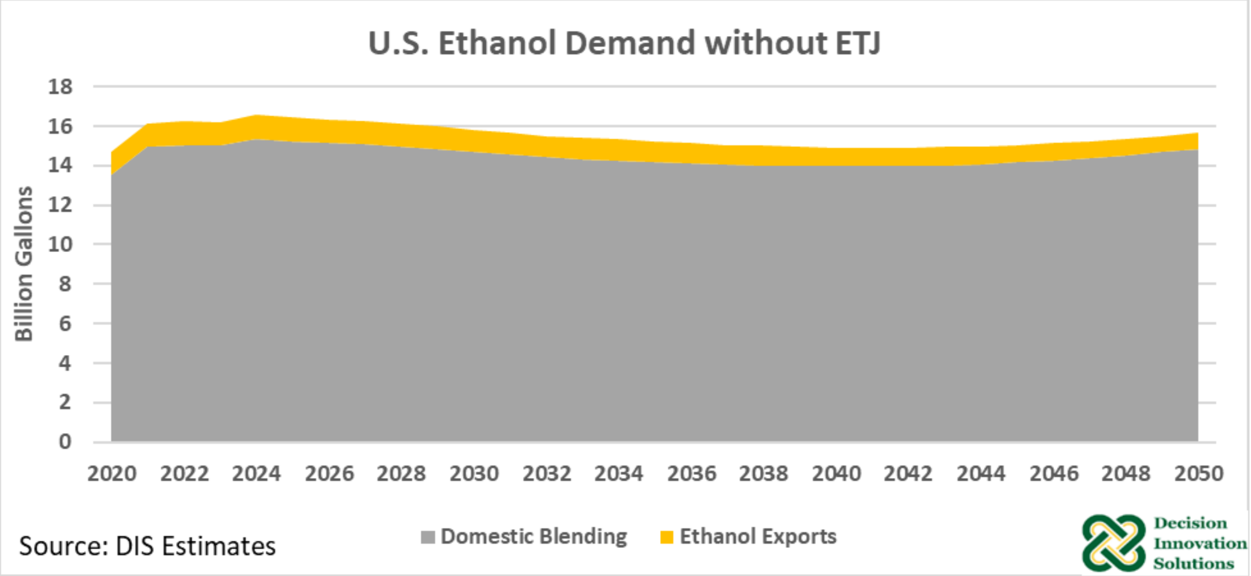
Table 5. Ethanol Scenario Analysis

Variable	Baseline	45Z	45Q	Unit
Baseline Margin	$ 0.10	$ 0.10	$ 0.10	$/gal
45Z Tax Credit	$ -	$ 0.49	$ -	$/gal
45Q Tax Credit	$ -	$ -	$ 0.17	$/gal
Sale of CO2 for PTF	$ -	$ -	$ 0.25	$/gal
CCS Cost	$ -	$ 0.24	$ -	
CCS or CCU Cost	$ -	$ -	$ 0.17	$/gal
Final Margin	$ 0.10	$ 0.35	$ 0.35	$/gal

Source: Iowa State Ethanol Model and DIS Estimates

7.2.1 Available Corn with Trendline Production

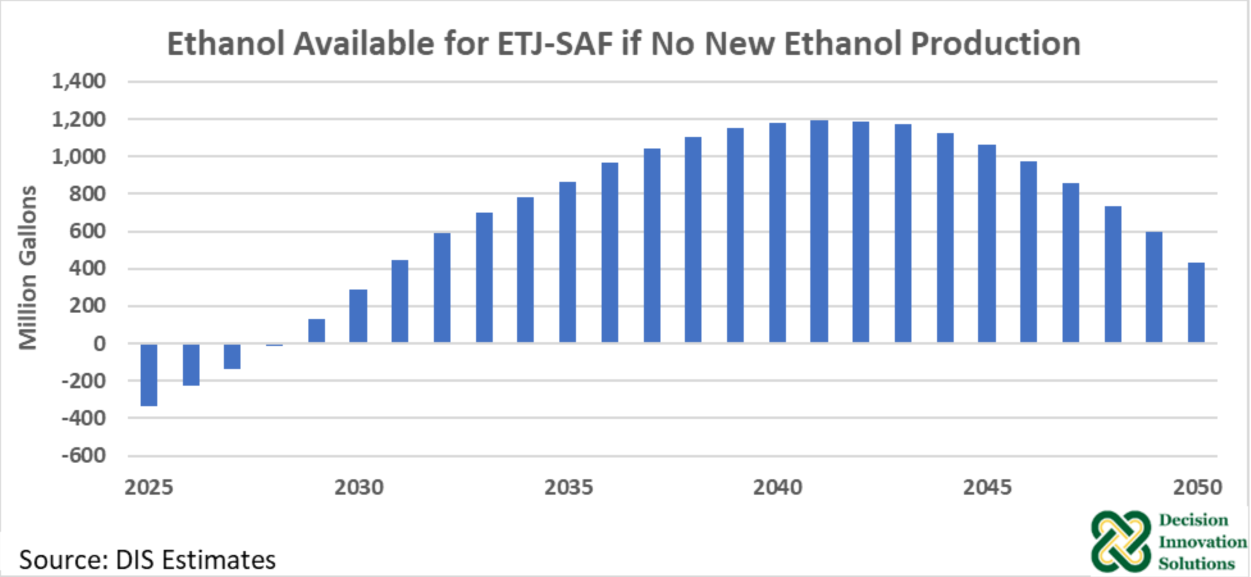
Without demand for ethanol for ETJ, the baseline demand profile for U.S. ethanol peaks outs in 2023-2024 and declines into the late 2030s before turning upward a bit according to the current EIA baseline (Figure 43). The U.S. currently produces approximately 16.1 billion gallons of ethanol on an annual basis.



Source: DIS Estimates

Figure 28. US Ethanol Demand without ETJ

Some of the current ethanol production already captures and sequesters CO2[8] and would be eligible for use as a feedstock for ETJ, however, this does not represent the majority of production. Without ETJ for broad-based ethanol demand, there will still be some ethanol available from current production that if it has carbon capture and sequestration at the plant (such as ADM in Decatur, IL, and Marquis Energy in Hennepin, IL) then by 2036 there could be 1.2 billion gallons of current ethanol production that is in excess of what the EIA baseline indicates will be needed for light vehicle use and exports (Figure 29). This amount of surplus ethanol production would put downward pressure on the ethanol market if a new market like SAF from ETJ is not developed.



Source: DIS Estimates

Figure 29. Ethanol Available for ETJ-SAF if No New Ethanol Production

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[8] Approximately 10.8% of ethanol-based CO2 currently is captured and sequestered either through on-site sequestration or sent via pipeline for sequestration as a part of enhanced oil recovery.

In 2050, without an expansion of new uses for corn, there could be significant "surpluses" of corn in many Midwestern states assuming that the 1980 trend for corn production continues and that trendline consumption of corn for purposes other than ethanol (growth of 55 million bushels per year) continue to develop. Figure 30 shows the "surplus" bushels of corn that would exist if trendline production is maintained without expanded uses like ETJ. For Iowa, the surplus corn without expanded use is 1.498 billion bushels in 2050.

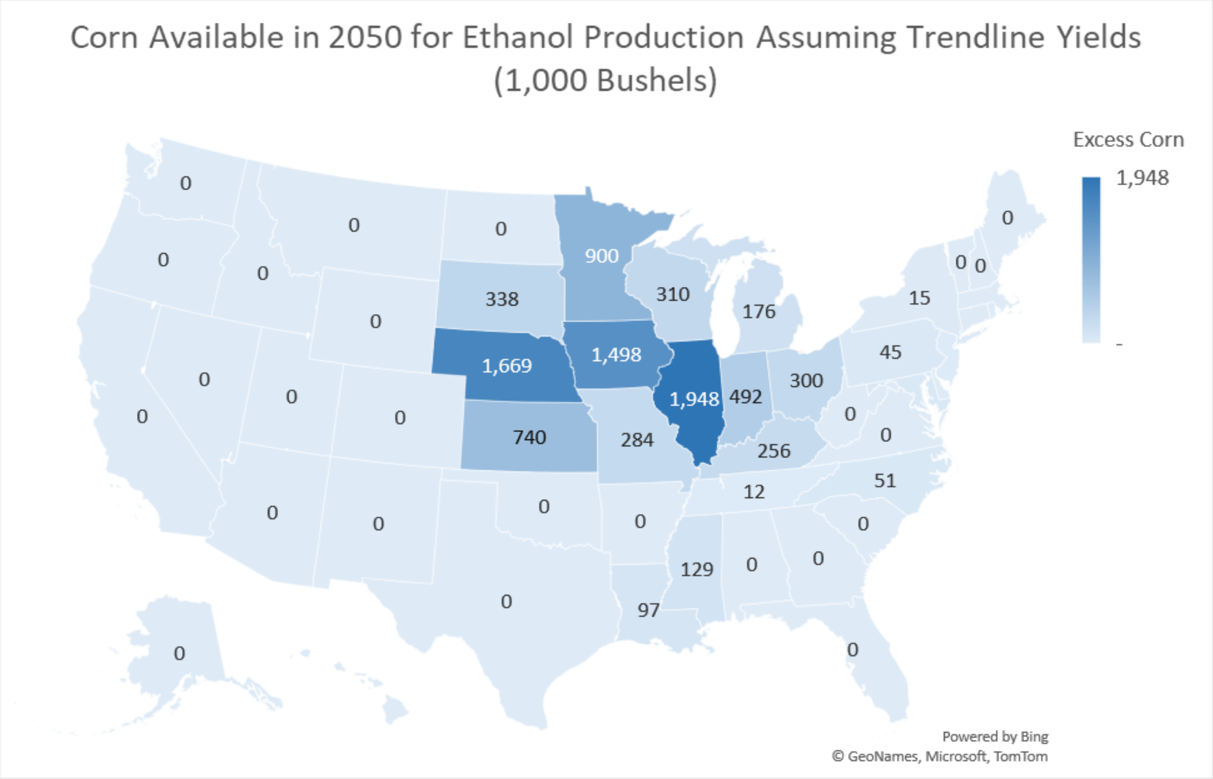


Figure 30. Corn Available in 2050 for Ethanol Production Assuming Trendline Yields

The two scenarios for use of this "surplus" corn are shown in Figure 31 through Figure 34. Figure 31 shows where new ethanol production would likely be built to use the "surplus corn" in 2050 if the plants were built based on the current distribution of ethanol production (by state). In this case, there would be 12.4 billion gallons of new ethanol production built in the Midwest. This is modeled as 63 new 200-million gallon-per-year corn ethanol plants spread across the 12 Midwestern states with 18 of those new ethanol plants built in Iowa.

If ETJ-SAF plants are built nearby the new ethanol plants to minimize the transportation cost of the ethanol feedstock, the build-out pattern, if based on the distribution of current ethanol processing capacity, the result would be the map in Figure 32 assuming the SAF plants are designed to use 426 million gallons of ethanol and to produce 178.9 million gallons of SAF as well as 30% of their distillate which would fractionate to RD and other fuels. If allocated based on current distribution of ethanol production facilities, Iowa would build 8 new ETJ-SAF plants.

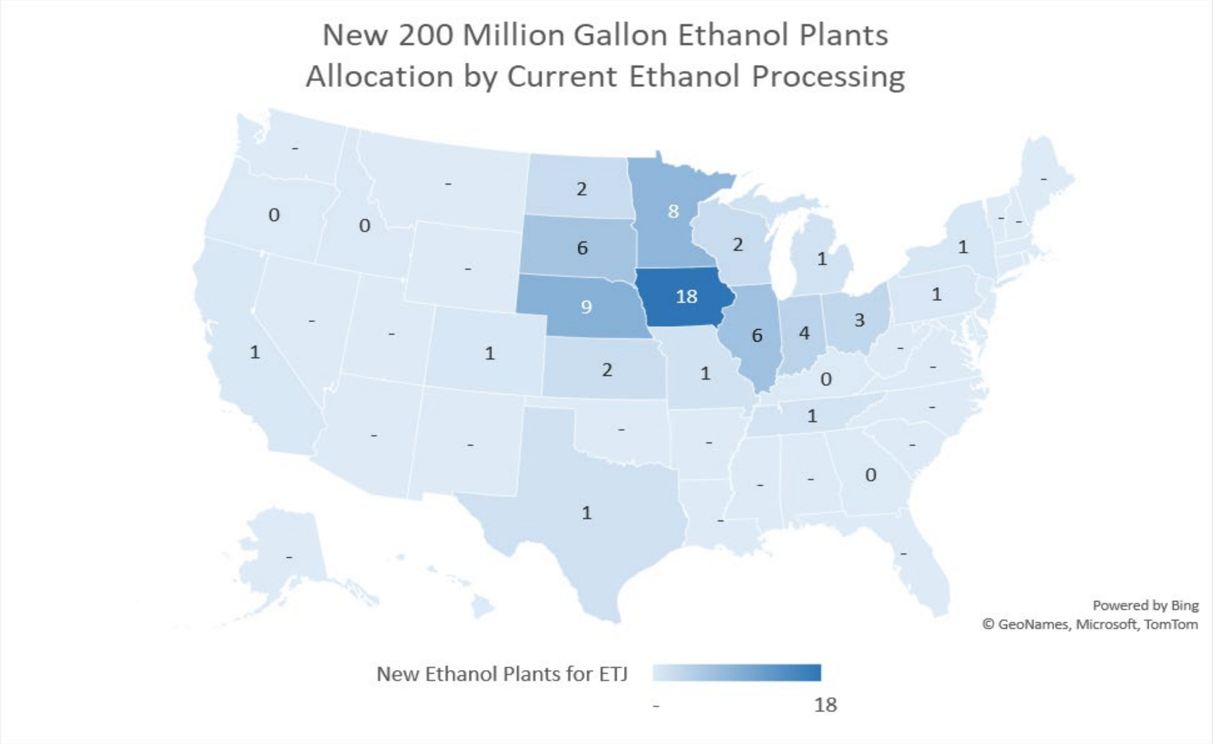


Figure 31. New 200-Million Gallon Ethanol Plants -- Allocation by Current Ethanol Processing

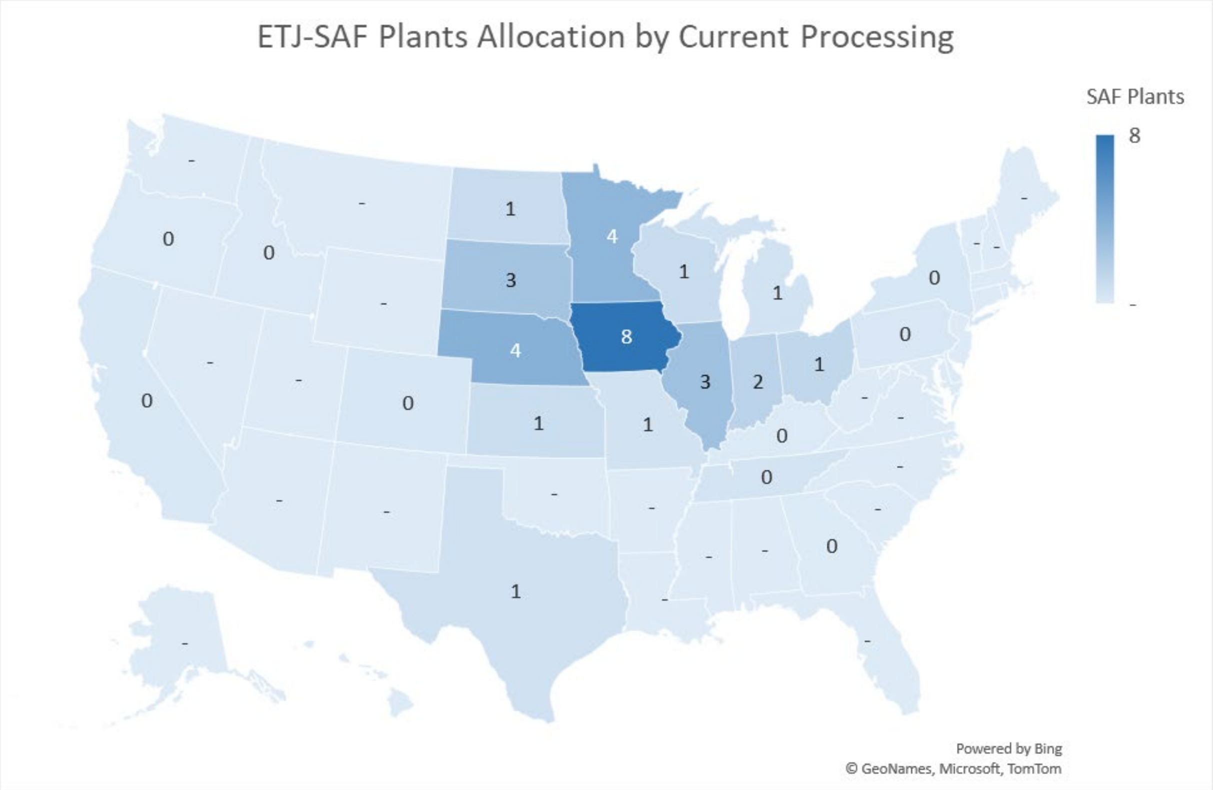


Figure 32. ETJ-SAF Plants Allocation by Current Ethanol Processing

In Figure 33 and Figure 34 the distribution of the new ethanol plants and associated SAF plants is based on the distribution of the calculated surplus corn rather than current distribution of ethanol production.

In this case, less plants are built in Iowa (7 less), South Dakota (4 less), and North Dakota (2 less), Ohio (1 less), and more plants would be built in Illinois (8 more), Nebraska (3 more), Kansas (3 more), Minnesota (1 more), Missouri (1 more). There is no difference between the scenarios for ethanol plants in Indiana, Michigan, and Wisconsin. What could sway siting decisions for ethanol plants away from Iowa, Nebraska, Minnesota, and South Dakota in favor of Indiana, Michigan, and Ohio is the potential for onsite, direct injection of CO2 for sequestration which is geologically feasible in those states versus the need for carbon capture and sequestration via pipeline in the states where the most surplus corn is likely to be.

For ETJ-SAF plants, if new ethanol plants are built based on surplus corn projections in 2050 rather than on the current distribution of ethanol production, then states with less ETJ-SAF plants would be Iowa (3 less), South Dakota (2 less), Minnesota (1 less), and North Dakota (1 less). States with more ETJ-SAF plants would be IL (4 more), Nebraska (2 more), Kansas (2 more), and five states (IN, MI, MO, OH, and WI) would have the same number of ETJ-SAF plants built under either scenario.

Note: While two of the three current ETJ plants are not in the Midwest, there are a number of reasons why early development of production facilities may be located away from the feedstock supply. In one case it may be to facilitate importation of low-carbon sugarcane-based ethanol since carbon sequestration policy in the Midwest is still unsettled. In another case, relatively easy access to the end-use market may have played a role in the siting of the facility.

There are pro and con arguments regarding the siting of ETJ production facilities close of feedstock supplies versus siting production facilities near jet fuel use locations or near access to pipelines that distribute jet fuel to major airports. DIS believes that if an abundance of low-carbon ethanol feedstock is available in the Midwest, then the advantages of minimizing feedstock transportation costs will play a major role in the siting of future, large-scale ETJ plants, but there is uncertainty about where future large-scale plants will be located.

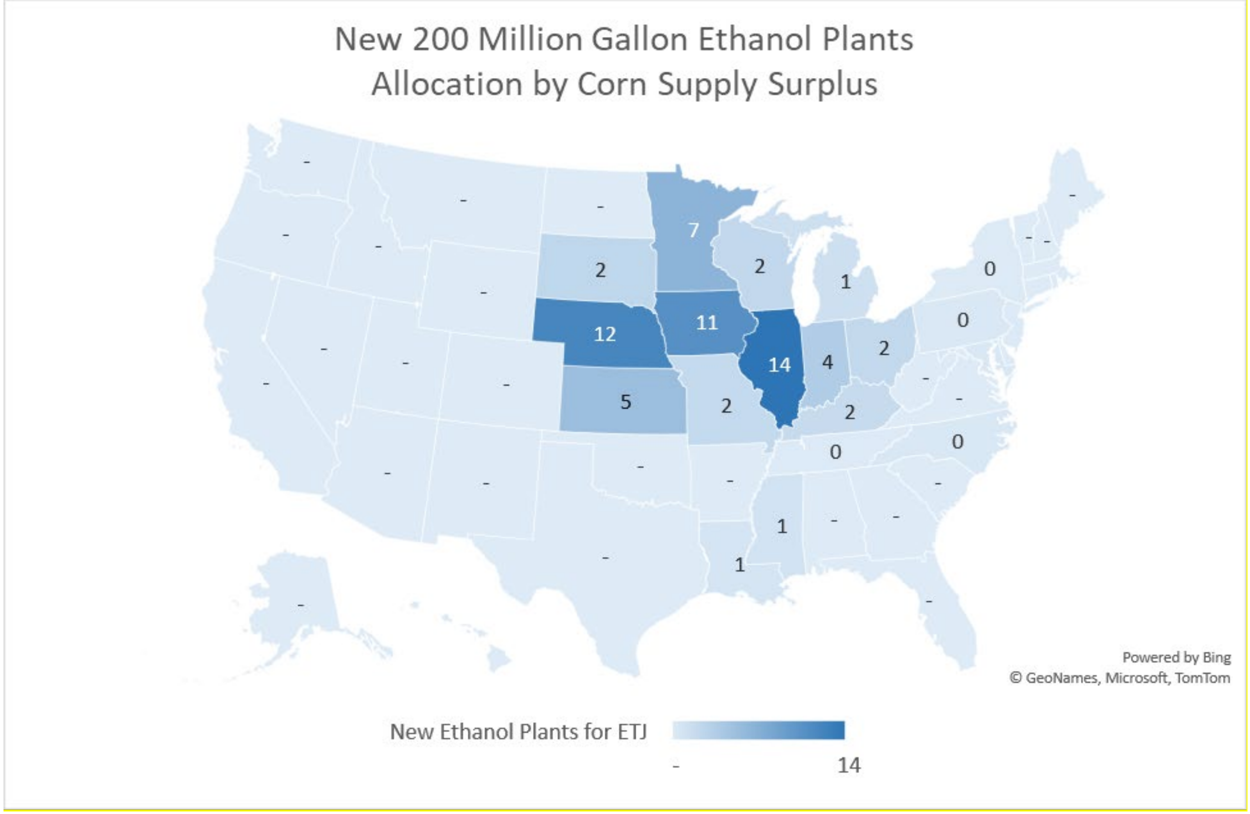


Figure 33. New 200-Million Gallon Ethanol Plants -- Allocation by Corn Supply Surplus in 2050

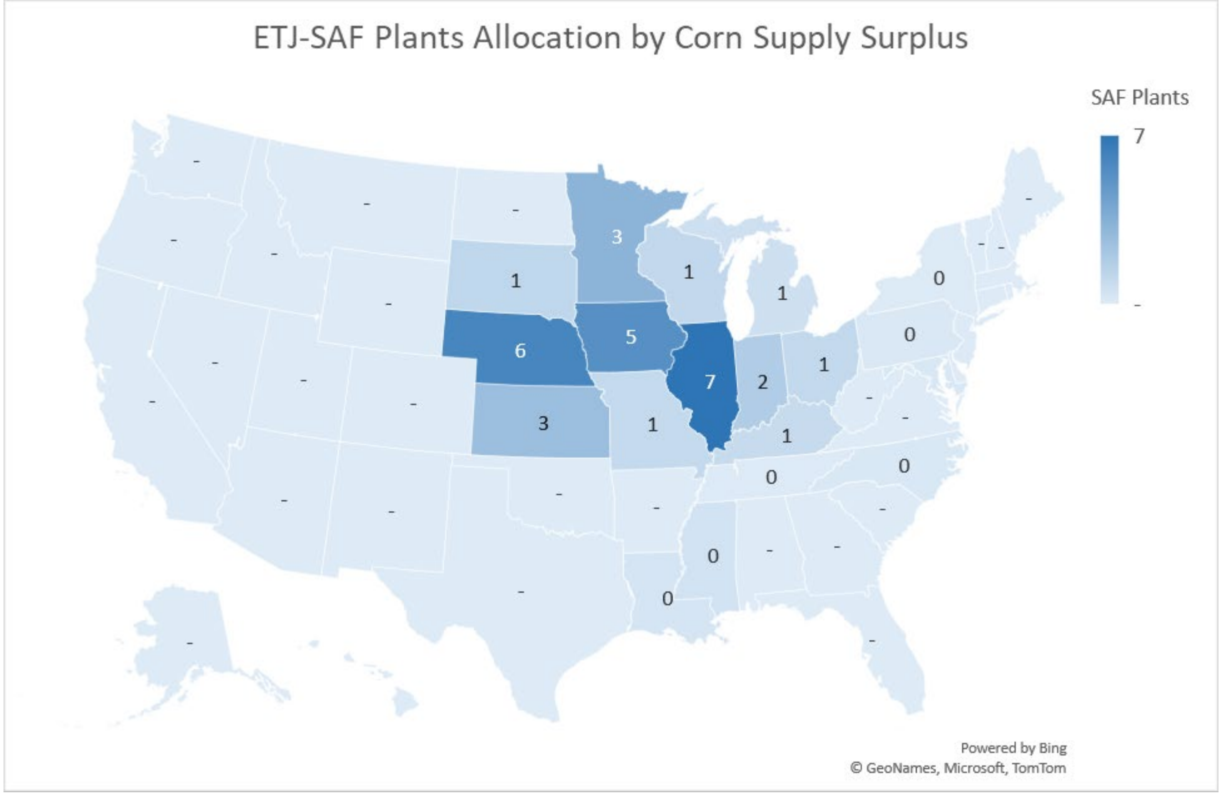
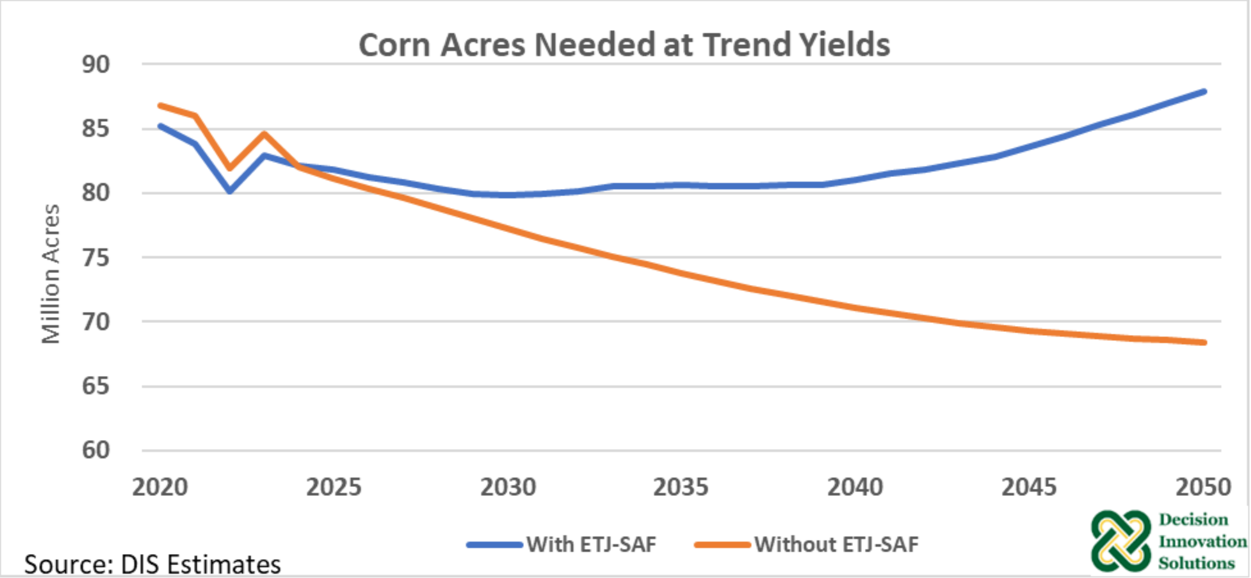


Figure 34. ETJ-SAF Allocation by Corn Supply Surplus (2050)

7.3 Corn Market Outlook with and Without ETJ

Without new demand for corn through ETJ, assuming trendline yields, U.S. corn acreage will begin to slip in 2024 and decline throughout the study period falling to 68.4 million acres harvested for grain by 2050 (Figure 35). With ETJ, corn acres harvested for grain stabilize at roughly 80 million acres and then after 2024 rise to about 87 million acres. This includes allowance for growth of non-ethanol uses of corn at approximately 55 million bushels per year.

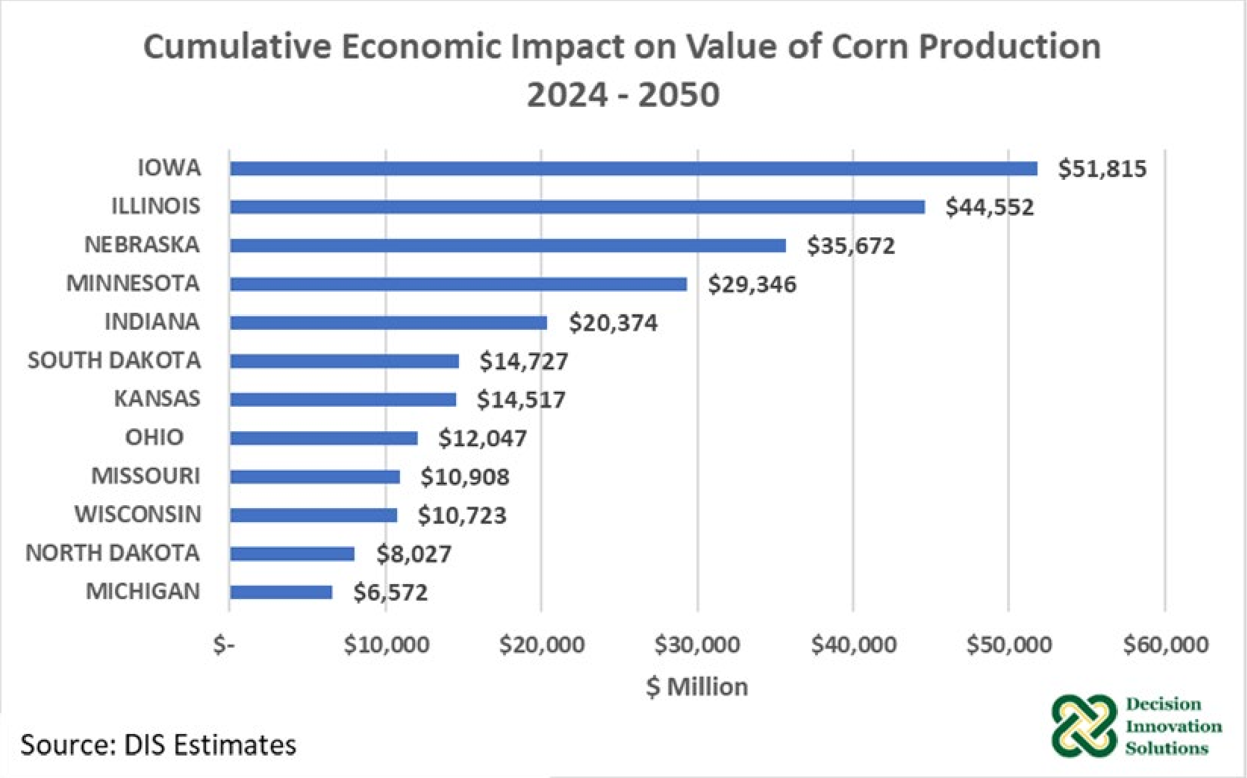


Source: DIS Estimates

Figure 35. Corn Acres Needed at Trend Yields

One measure of the economic impact of facilitating corn use for ETJ is the difference in the value of corn production with ETJ demand and without ETJ demand. Using a “stable price” of $4.67/bu the lost value of corn production was calculated in today’s dollars. Figure 36 shows the state-by-state cumulative impacts across the Midwest between having a robust ETJ industry develop and not having that new demand for corn. For the Midwestern states in total, the difference in value of production of the corn crop with ETJ-SAF versus the scenario of no significant new corn demand is $259.3 billion across the 2024-2050 period. **This is nearly $10 billion per year, on average.**

If that $10 billion per year impact is spread across the current 83 million acres of corn, then it would amount to $120 per acre of corn and for a 1,000-acre farm with 50/50 corn-soybeans, it would amount to $60,240 per year less revenue, on average over the next 25 years. Clearly, the annual impacts would be greater further out in the future than they would be near-term, but strong upward trends in production need to be accompanied with strong upward trends in utilization or as has been experienced in the past, sharp, painful adjustments to both price and acreage will develop. Just how the corn market would adjust is uncertain (both in magnitude of price and acreage adjustments), and where those adjustments would be made geographically is uncertain, but policy decisions now could have lasting effects on how these adjustments would develop over the next few decades. As shown in Figure 36, farmers in Iowa, as the leading corn production state, have the most at stake (nearly $52 billion) from this new opportunity (or a decline of $52 billion from the failure to take advantage of the new opportunity).

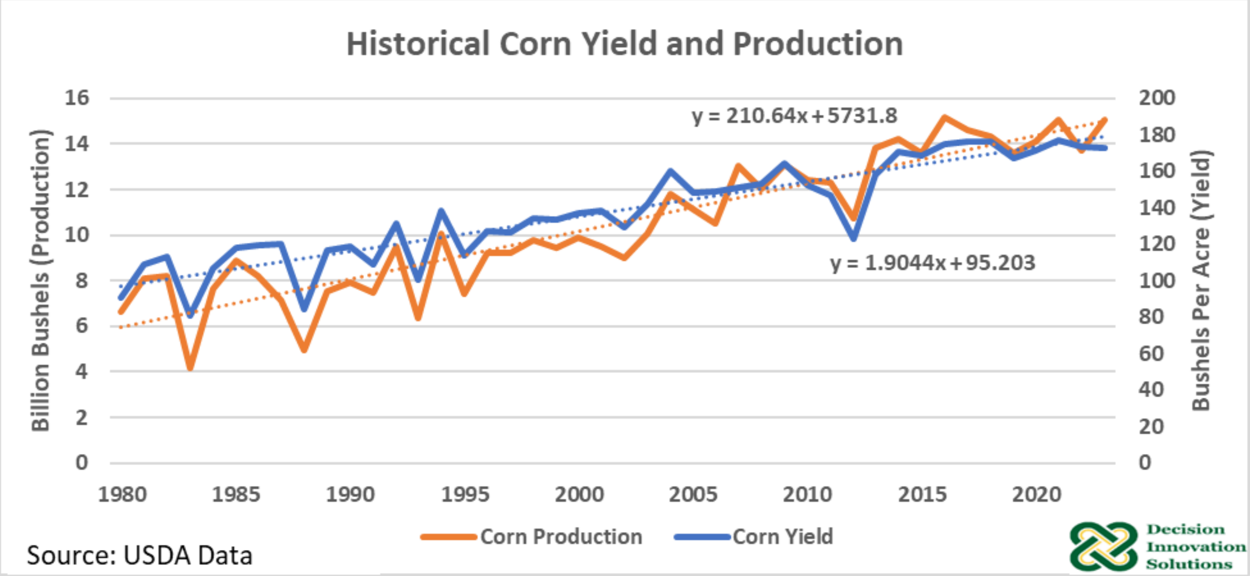


Source: DIS Estimates

Figure 36. Cumulative Economic Impact on Value of Corn Production 2024-2050

7.4 Corn Production, Ethanol Production and ETJ-SAF Production Forward Pathways

Corn production is a product of the harvested corn acreage and annual yields. While acreage and yields vary year-to-year, yields exhibit a strong uptrend over the past 40+ years. Over the period of 1980 through 2023, corn yields are increasing at the rate of 1.90 bushels per acre per year. Corn production shows a slightly steeper slope (See Figure 37) and is increasing by 210.64 million bushels per year.

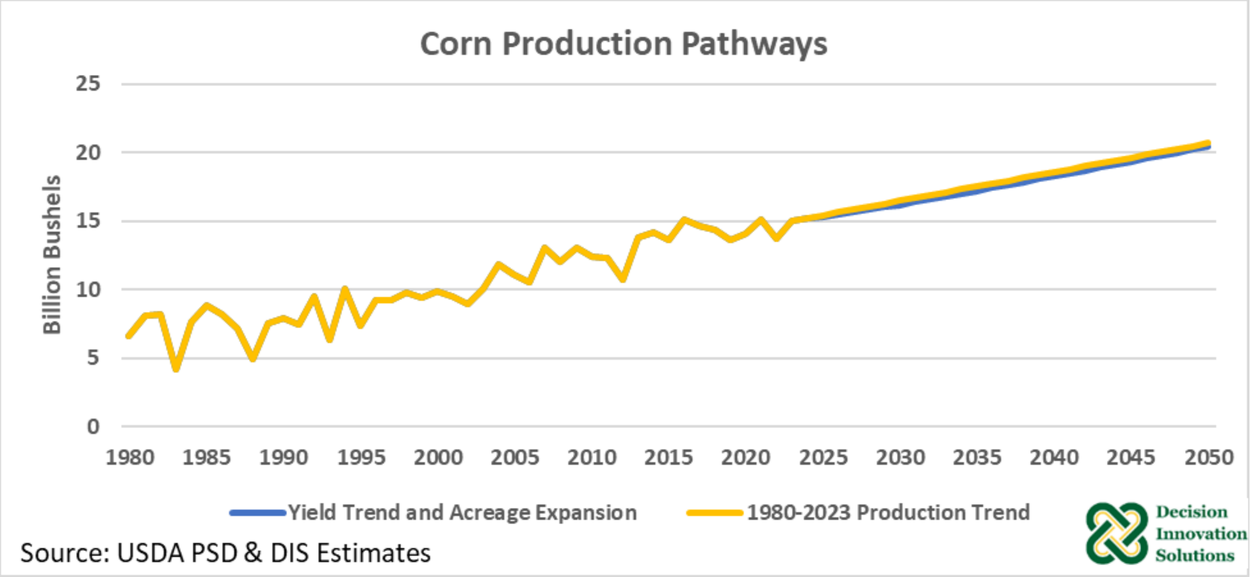


Source: USDA Data

Figure 37. Historical Corn Yield and Production

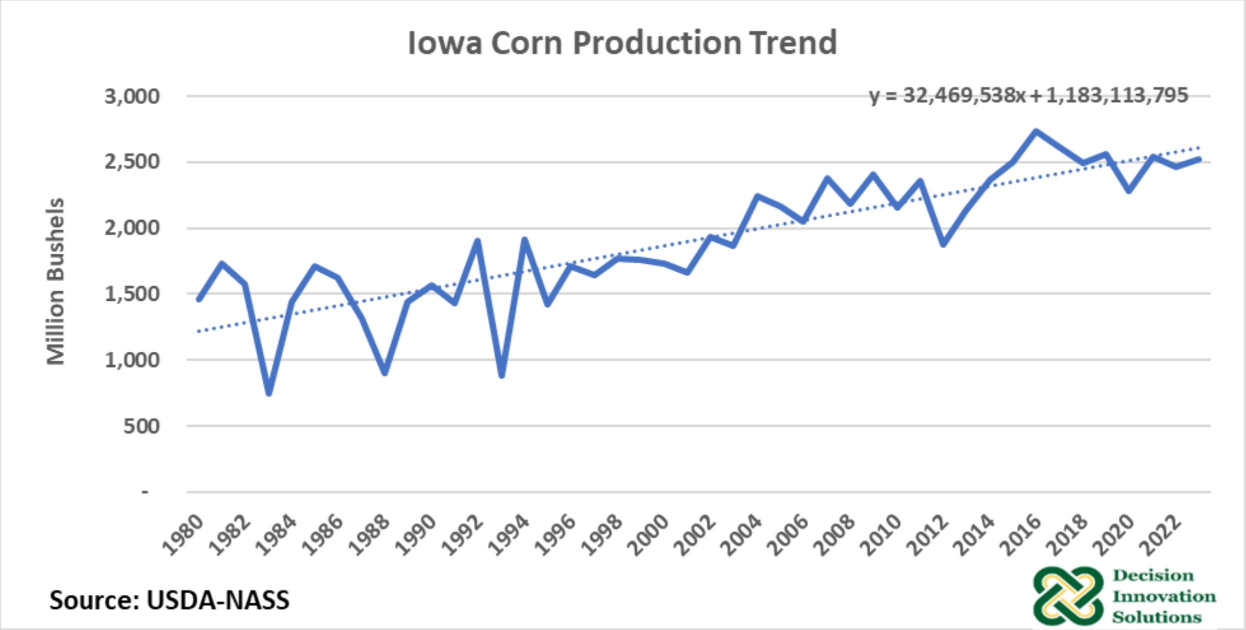
To project forward corn production, we examined two approaches. The first was to simply use the production trend from 1980-2023 to project forward corn production for 2024 through 2050. This projects growth in corn production of 210 million bushels per year and results in 20.467 billion bushels of corn production in 2050.

The second approach was to apply the trend yield on a forward basis and to gradually increase corn acreage after 2030 from current acreage levels (83 million acres harvested) to 87 million acres harvested for grain by 2050. A maximum of 87 million acres was chosen as it is a recent high in harvested corn acres. That pathway is also shown in Figure 38 and is represented by the blue line on the graph. That pathway resulted in 20.687 billion bushels of corn production in 2050. For the analysis in this report, we used the simple trendline forecast of corn production as the corn supply.



Source: USDA PSD & DIS Estimates

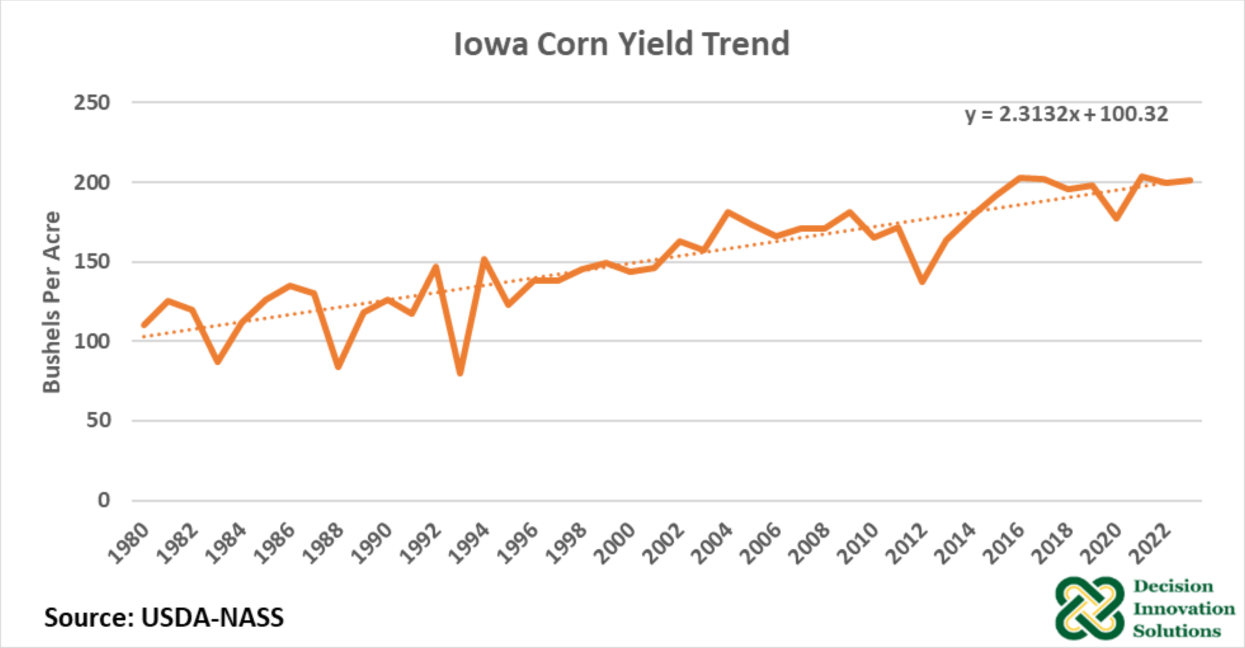
Figure 38. Corn Production Pathways



Source: USDA-NASS

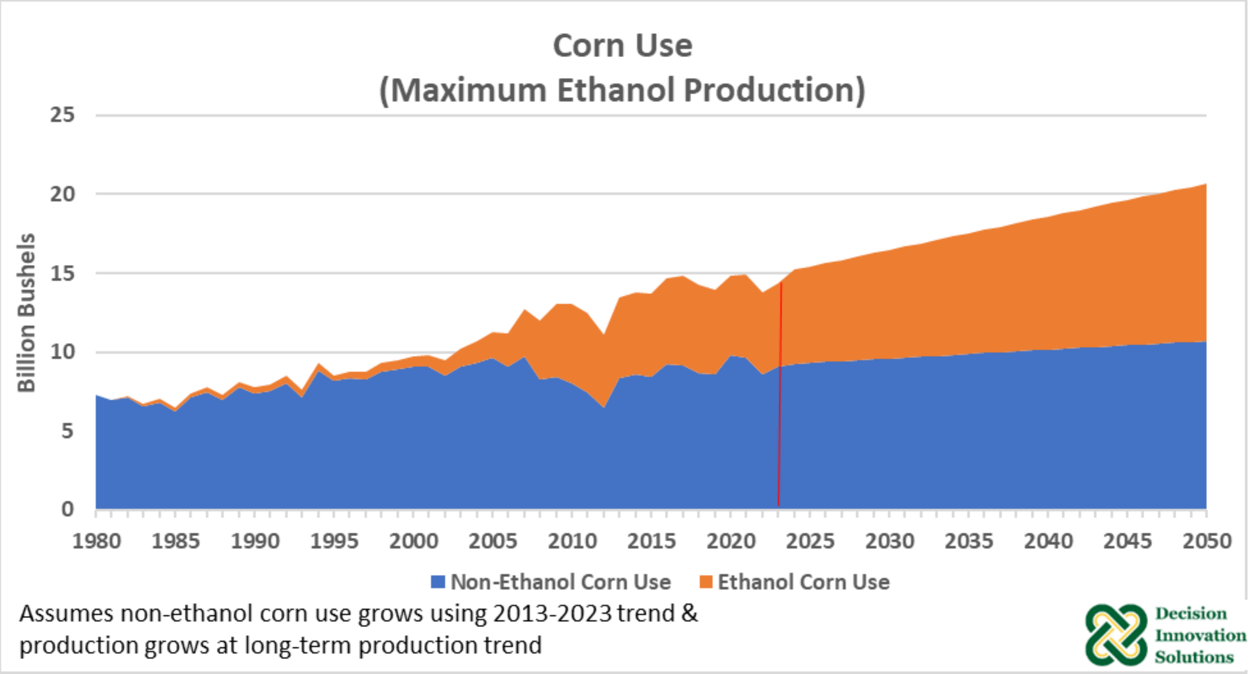
Figure 39. Iowa Corn Production trend

Iowa’s corn production is rising by 32.5 million bushels per year (Figure 39). Iowa’s corn yield is increasing at the rate of 2.31 bushels per acre per year (Figure 40), faster than the national corn yield which is rising at 1.9 bushels per acre per year.



Source: USDA-NASS

Figure 40. Iowa Corn Yield Trend

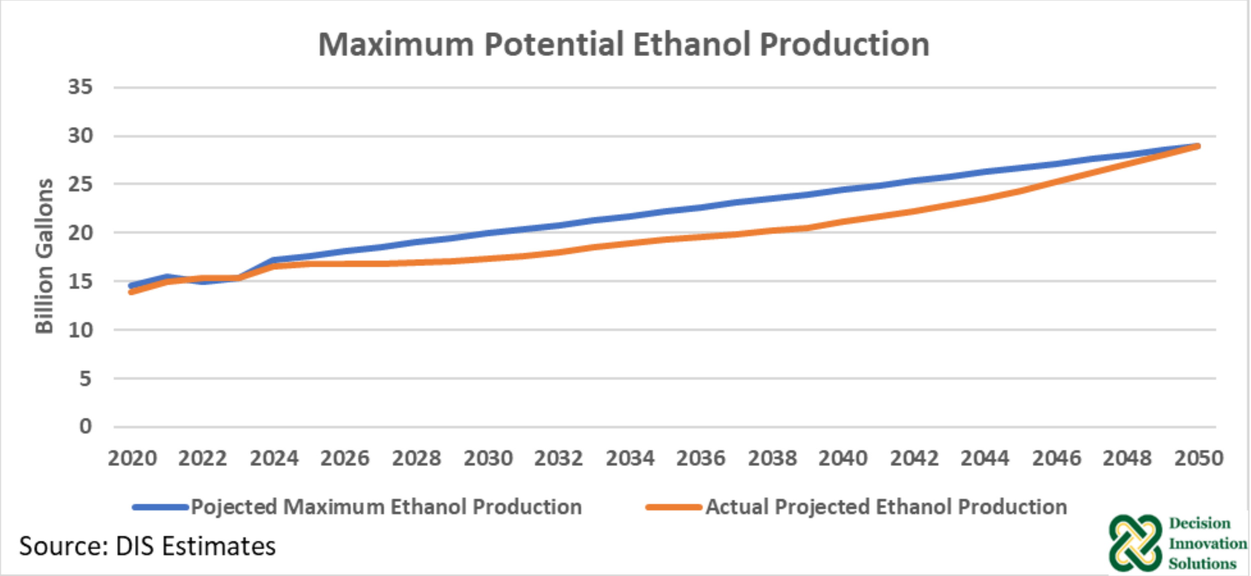


Assumes non-ethanol corn use grows using 2013-2023 trend & production grows at long-term production trend

Figure 41. Corn Use (Maximum Ethanol Production)

To determine the quantity of corn that could be available for ethanol production, historical corn usage for all non-ethanol uses (feed, food, exports) was determined and a 2013-2023 trend was applied to project non-ethanol corn use for the 2024 through 2050 period (Figure 41). A shorter trend was used here as this is the period after major ethanol expansion had taken place. The 2013-2023 trend increases non-ethanol corn use by 55 million bushels per year. The non-ethanol corn use was subtracted from projected corn production to project corn available for ethanol production if the demand were to develop due to use of ethanol as a feedstock in ethanol to jet (ETJ-SAF) fuels.

An estimate of the maximum amount of corn-based ethanol production (Figure 42) was estimated from the forward projection of corn available for ethanol production. Based on the projected available corn supply, corn-based ethanol production could increase from the current 15.3 billion gallons of production (2023 estimate) to 28.97 billion gallons in 2050 (assumes 2.9 gallons of ethanol from a bushel of corn).



Source: DIS Estimates

Figure 42. Maximum Potential Ethanol Production

The maximum amount of ethanol available for ETJ-SAF production (Figure 43) is calculated by taking the projected maximum amount of ethanol production and subtracting ethanol being blended with gasoline for light vehicle use and a forward projection of ethanol exports.[9] Using this approach, in 2024 there could be 687 million gallons of ethanol available for ETJ-SAF production. By 2050, there could be 13.305 billion gallons of ethanol available for ETJ-SAF production (Figure 43). These projections assume that policy and technology will be in place that can allow corn-based ethanol to be used as a feedstock for ETJ-SAF through carbon capture and storage (CCS).

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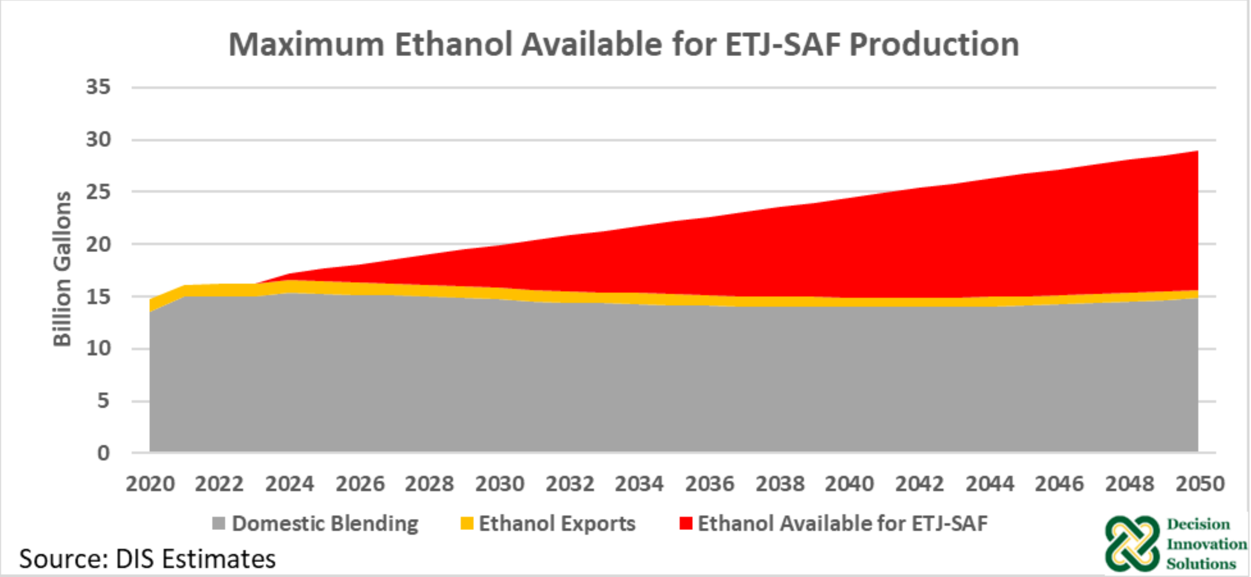
[9] Projected ethanol exports from the U.S. were based on the 2016-2022 trend for ethanol exports.

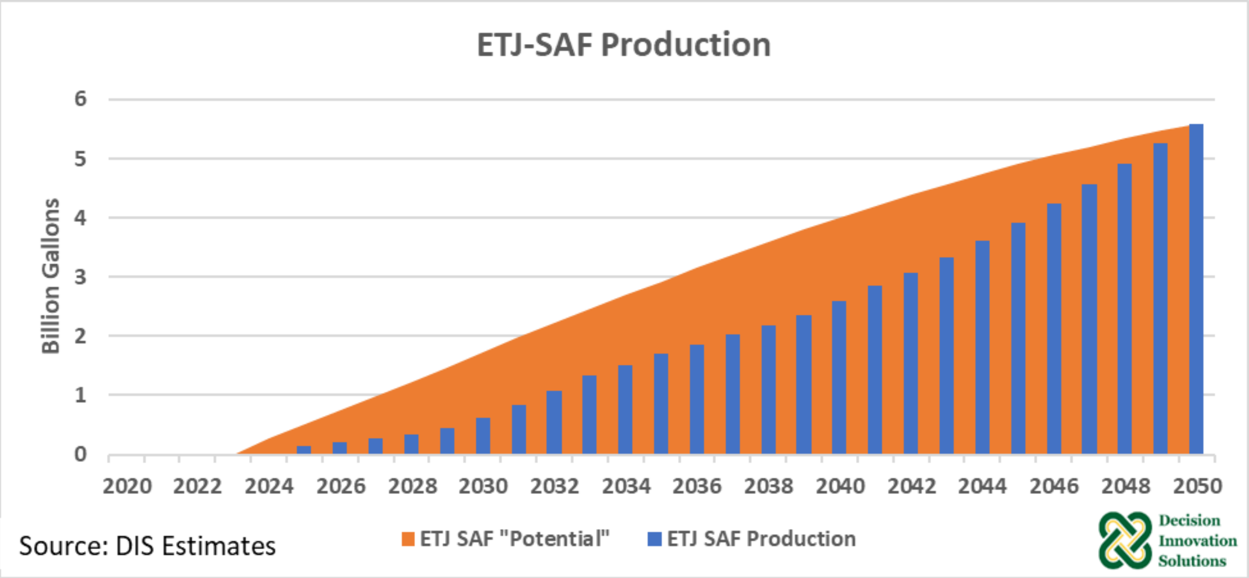


Maximum Ethanol Available for ETJ-SAF Production

Source: DIS Estimates

Figure 43. Maximum Ethanol Available for ETJ-SAF Production

Two projections were made of ETJ-SAF production. The first is the maximum potential ETJ-SAF which is a function of the maximum amount of ethanol which is available for ETJ-SAF production (Figure 44). It assumes that it will take 1.6667 gallons of ethanol for each gallon of distillate and that 70% of the distillate is ETJ-SAF. Accordingly, 415 million gallons “could” be produced in 2024 and production of ETJ-SAF could increase to 5.59 billion gallons by 2050.



ETJ-SAF Production

Source: DIS Estimates

Figure 44. ETJ-SAF Production

The actual production of ETJ-SAF is projected as an increasing percentage of potential production and assumes that policy and technology will enable the CI score of ethanol to be low enough to be used as a feedstock for ETJ-SAF and that there will be sufficient policy and incentives as well as technology to support the demand side of SAF within the aviation industry. Actual production of ETJ-SAF is modeled as starting with 21 million gallons in 2024, increasing to 988 million gallons by 2030 as part of the effort to reach 3 billion gallons of SAF by 2030, and then increases to full utilization of the potential ETJ-SAF by 2050.

7.4.1 Corn Distribution Maps

Figure 45 shows estimated corn supply net of feed demand by state. As shown, Iowa has the largest net positive supply of more than 1.9 billion bushels. Texas has the largest net negative supply of more than 200 million bushels. Existing corn ethanol plants are shown with yellow dots, and existing non-ethanol corn processing plants are shown with pink dots. Corn processing is heavily concentrated in the Midwest, where all states have a positive net corn supply.

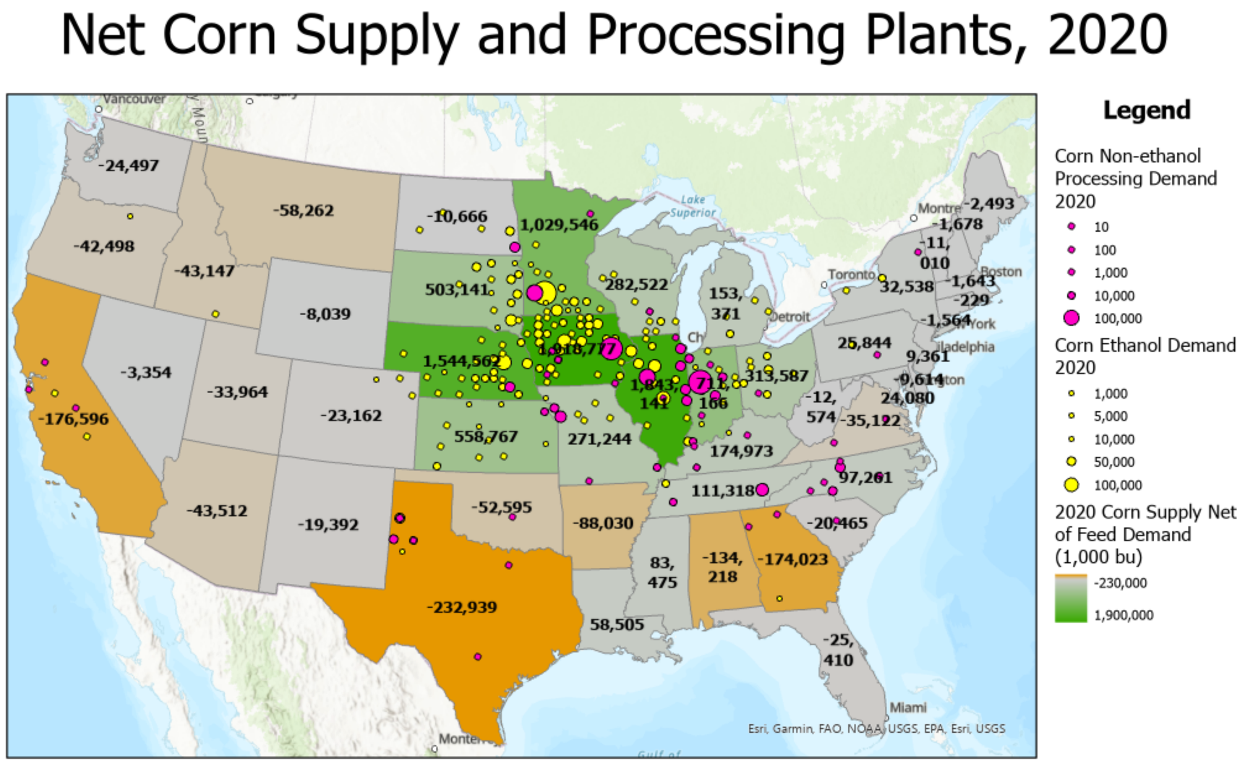


Figure 45. Map of Net Corn Supply and Processing Plants, 2020; Source: USDA, DIS

Figure 46 is similar to Figure 45, but corn supply, feed demand, and non-ethanol processing demand are estimated based off the projected 2050 values. Supply, net of feed demand, is expected to increase in most Midwestern states, as corn production is projected to increase at a faster rate than corn feed demand.

Net Corn Supply and Processing Plants, 2050

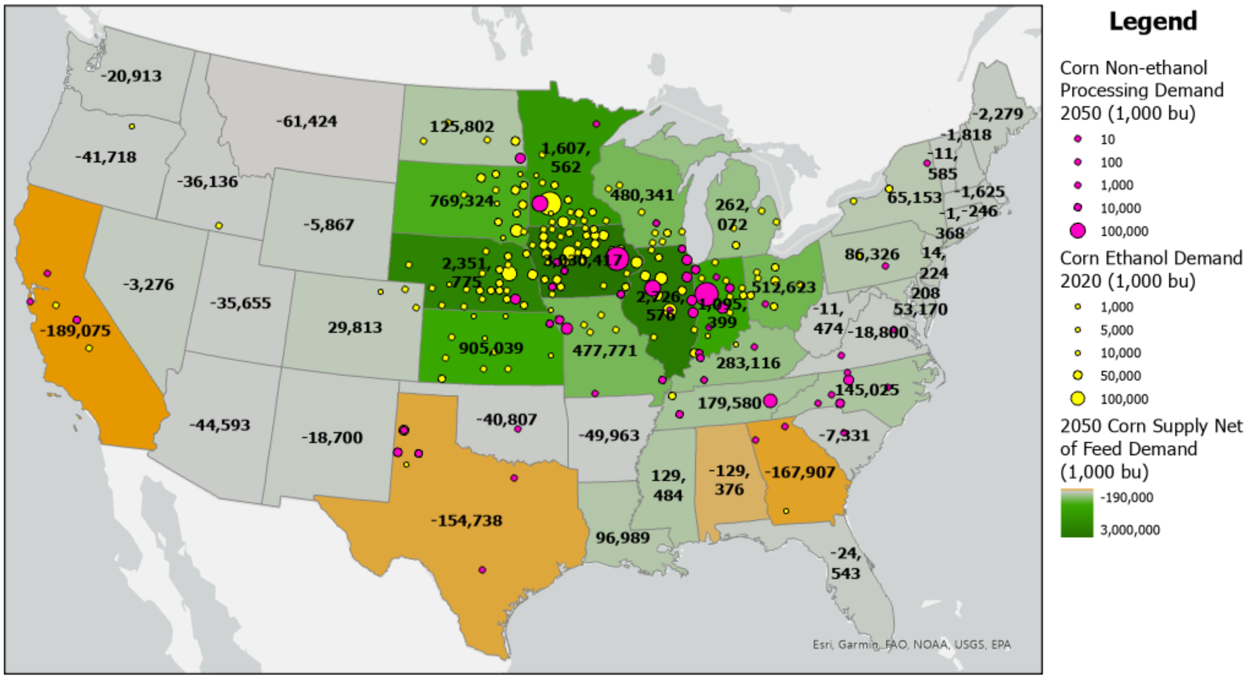


Figure 46. Map of Net Corn Supply and Processing Plants, 2050

Figure 47 shows the projected corn available for new ethanol by state, calculated as projected corn supply net of projected feed demand, projected non-ethanol processing demand, and current ethanol processing demand. Note that this estimate does not include corn exports. Iowa, Nebraska, and Illinois are expected to each have more than 1 billion bushels available for additional ethanol production. All of the Midwest, with the exception of North Dakota, is projected to have corn available for additional ethanol production.

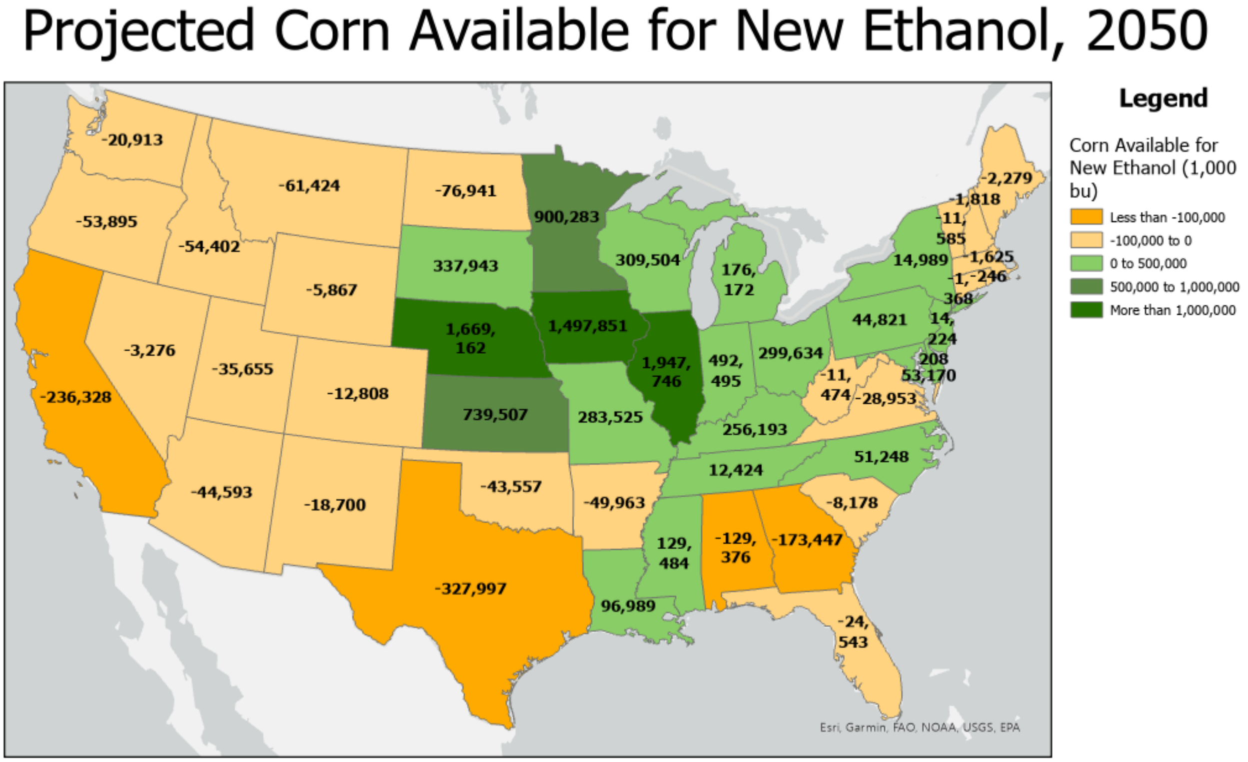


Figure 47. Map of Projected Corn Available for New Ethanol, 2050

7.5 Corn Basis Impacts

In this analysis, a long-term "stable price" for corn was used to model SAF supplies from a variety of feedstocks with the relative pricing between the various feedstocks remaining stationary. In the absence of new ETJ, and assuming trendline corn yields, excess corn production will accrue across the Midwest and prices will fall to stimulate acreage reductions in subsequent years. A 2023 study of the economic impact of CO2 pipelines in South Dakota by the Dakota Institute reported that average basis premiums at reporting ethanol plants were 13 cents per bushel higher than elevators in South Dakota, 12 cents per bushel higher than elevators in Iowa, 14 cents per bushel higher than elevators in Minnesota, 16 cents per bushel higher than elevators in North Dakota, and 28 cents per bushel higher than elevators in Nebraska. A prior study[10] by DIS found that corn basis in Iowa has increased more than 20 cents per bushel since 2001 with most of the increase seen in areas that have significant ethanol production. That same study reported that in February 2023, Iowa corn basis at ethanol plants was 7 cents per bushel higher than other elevators or feedmills, basis in Minnesota at ethanol plants was 14 cents per bushel higher, South Dakota ethanol plants 16 cents per bushel higher, and Nebraska ethanol plants 18 cents per bushel higher. It is expected that at least these amounts of advantages would carry forward to new ethanol capacity that is built to supply ethanol for ETJ.

As shown in Figure 33, to fully utilize the corn production from trendline yields, there could be 63 more 200-million-gallon ethanol plants built in the Midwest between now and 2050 with 14 of those in Illinois, 12 in Nebraska, 11 in Iowa, 7 in Minnesota, 5 in Kansas, 4 in Indiana, 2 each in South Dakota, Wisconsin, Missouri, and Ohio, and one in Michigan. The impact on corn basis locally will depend on the

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[10] Comparative Economics of Carbon Sequestration for Iowa Ethanol Plants, Decision Innovation Solutions, February 2023

specific location in the state in which these ethanol plants would be built, and for each 200-million-gallon ethanol plant there is demand for approximately 70 million bushels of corn.

Across Iowa, the new ethanol plants, each using approximately 70 million bushels of corn annually with an estimated average basis premium of 10 cents per bushel, would add $77 million of additional income to farmers who merchandise corn to these ethanol plants. And this is beyond the economic impact of standard returns for producing those 770 million bushels of additional corn beyond what is being produced in 2023. For a 1,000-acre farm with 50/50 corn and soybeans and trendline national yields, this would mean $11,760 more income in 2050. Since Iowa yields are typically 11% higher than national yields, the impacts for a 1,000-acre Iowa farm with 500 acres of corn would likely be more than $13,000 per year.

Across the Midwest, 63 new ethanol plants each using 70 million bushels of corn annually with an average basis premium of 10 cents per bushel would add $441 million of additional income to farmers who merchandise corn to these ethanol plants. And this is beyond the economic impacts of standard returns for producing those 4.41 billion bushels of additional corn beyond what is being produced in 2023. For a 1,000-acre farm with 50/50 corn and soybeans and trendline national yields, this would mean $11,760 more income in 2050.

8 CO2 Pipeline Industries Opportunities

As of the writing of this report, there are three CO2 pipelines still under active development in the Midwest. Wolf Carbon Solutions is still working on their pipeline through eastern Iowa and Illinois. Summit Carbon Solutions is still working on a CO2 pipeline that would cross parts of five Midwestern states (IA, MN, NE, SD, and ND). The exact number of facilities that will capture CO2 is unknown, although a prior-released analysis was conducted that included 31 collection facilities. If regulatory approval for the main trunk line, pumping stations and the sequestration site facilities is eventually approved, it is likely that other facilities that were considering carbon sequestration via pipeline could be added to the Summit Carbon pipeline.

TallGrass Energy's Trailblazer Pipeline Company received regulatory approval to convert their existing 400-mile-long natural gas pipeline into a carbon dioxide transportation network in October 2023. Trailblazer now intends to repurpose this pipeline for the transportation of CO2 from emissions sources in Nebraska and Colorado to geologic formations in Wyoming, where it will be permanently stored through the Trailblazer Conversion Project.

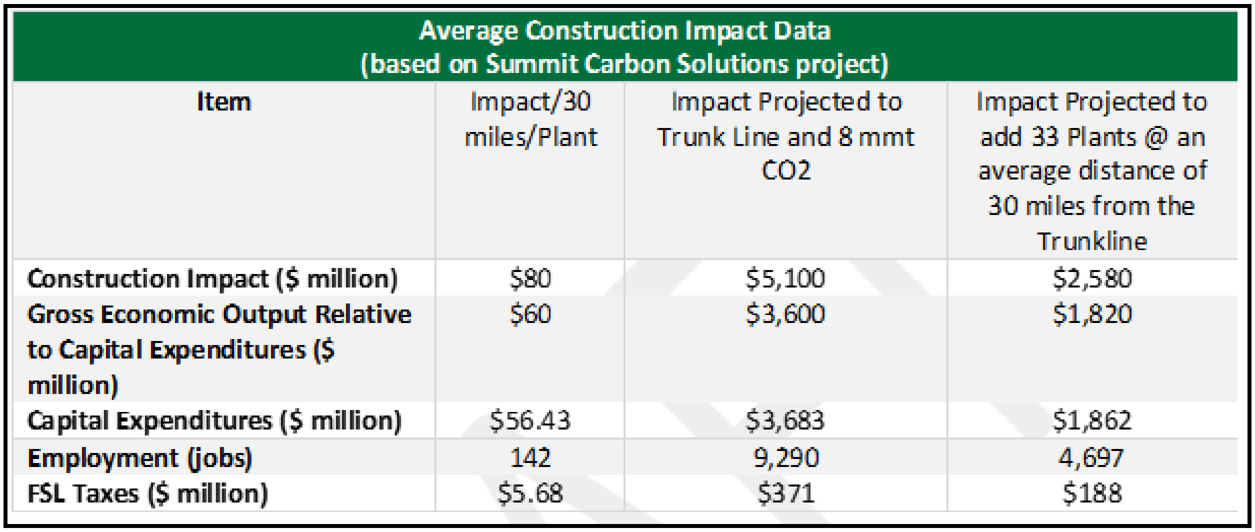
Active ethanol plants across the U.S. currently produce approximately 37.3 million metric tons of CO2 annually. Approximately 7.5 mmt of CO2 (15.3%) are currently being captured for utilization. Approximately 5.25 mmt of CO2 (10.8%) are being captured (or will shortly be captured) on site for storage either on-site or very nearby. If completed with its original potential participating ethanol plants, the Summit Carbon pipeline would capture and sequester approximately 7.96 mmt (18.2%) of CO2. The TallGrass pipeline is expected to capture and sequester approximately 1.15 mmt (2.4%) of CO2. The Wolf and Navigator CO2 pipelines were originally slated to capture and move 11.02 mmt (22.6%) of CO2 from ethanol plants.

Based on locations of ethanol plants relative to geological formations that may be conducive to on-site carbon capture and sequestration, there is approximately 5.2 billion gallons of ethanol in the Midwestern states that could be produced by current plants that could potentially sequester carbon dioxide on-site. These ethanol plants would sequester approximately 14.5 mmt of CO2 annually. By 2050, that still leaves 8.1 billion gallons of ethanol for SAF (with the need to sequester 22.7 mmt of CO2 annually) that will need to have carbon sequestered either via CO2 pipeline or through new ethanol plant construction that is done in areas with on-site sequestration capability. The TallGrass pipeline will enable carbon capture and sequestration on 413 million gallons of ethanol (sequestering 1.2 mmt of CO2 annually. The original Summit Carbon pipeline encompassed 2.8 billion gallons of ethanol, and Navigator and Wolf pipelines were anticipated to sequester carbon from 3.96 billion gallons of ethanol. Combined, the plants on these three proposed CO2 pipelines would have sequestered 19 mmt of CO2 annually.

By 2050, ethanol plants producing ethanol that will be used as a feedstock for SAF will generate approximately 37.3 mmt of CO2 that will need to be captured and sequestered. With the development of on-site CO2 capture and sequestration by several ethanol producers roughly 14% of the ethanol needed for SAF will have carbon capture and sequestration in place in the near-term. If all current ethanol plants that have the potential to do on-site sequestration build out that capacity, that would account for 42% of the ethanol needed for SAF by 2050. There would still be a need for 21.5 mmt of CO2 annually to be captured and sequestered if that ethanol is to have a CI score sufficiently low enough to allow it to be used as SAF feedstock. If the Midwest produces 93% of the ethanol for SAF, then that would require an additional 20 mmt of CO2 be captured and sequestered in the Midwest.

Based on the data from the economic impact assessment conducted on the Summit Carbon Solutions project in 2022 (EY), some inferences can be drawn regarding the scale of impacts per million metric tons of CO2 captured and sequestered. In Table 6 and Table 7, the costs of the Summit Carbon Solutions project were adjusted to a cost per mile basis and then applied to other ethanol plants at an average estimate of 30 miles per plant from the trunkline. For this analysis, the 33 plants are proposed as estimates of plants that have expressed interest in sequestering CO2 via pipeline in the Midwest.

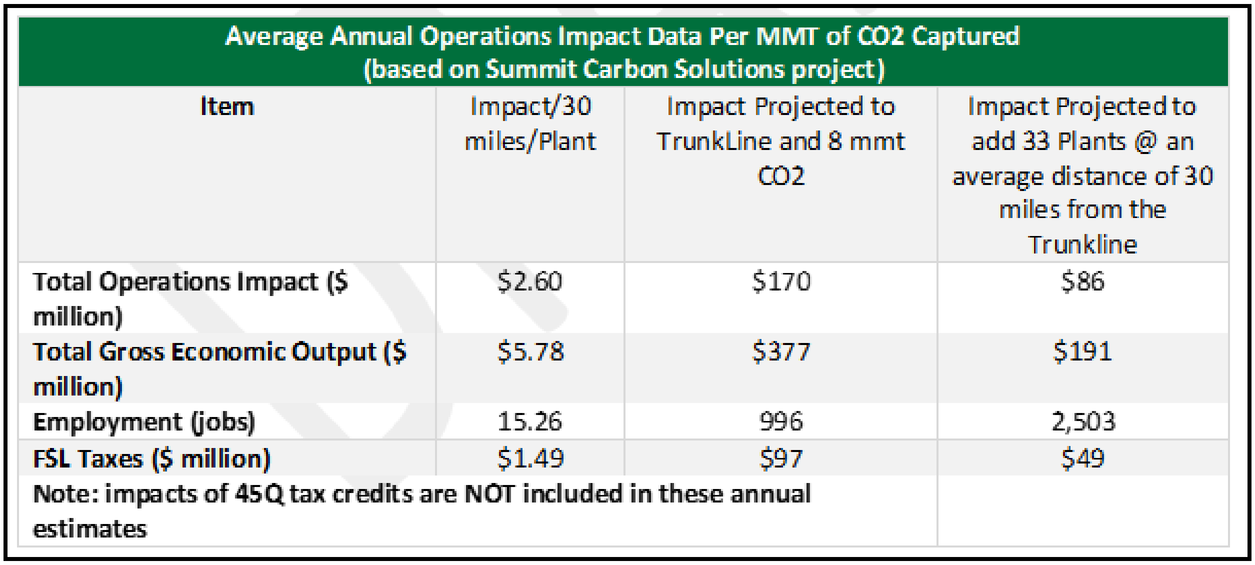
Table 6. Average Construction Impact Data for CO2 Pipeline(s)



Average Construction Impact Data (based on Summit Carbon Solutions project)

Item	Impact/30 miles/Plant	Impact Projected to Trunk Line and 8 mmt CO2	Impact Projected to add 33 Plants @ an average distance of 30 miles from the Trunkline
Construction Impact ($ million)	$80	$5,100	$2,580
Gross Economic Output Relative to Capital Expenditures ($ million)	$60	$3,600	$1,820
Capital Expenditures ($ million)	$56.43	$3,683	$1,862
Employment (jobs)	142	9,290	4,697
FSL Taxes ($ million)	$5.68	$371	$188

Table 7. Average Annual Operations Impact Data Per MMT of CO2 Captured



Average Annual Operations Impact Data Per MMT of CO2 Captured (based on Summit Carbon Solutions project)

Item	Impact/30 miles/Plant	Impact Projected to TrunkLine and 8 mmt CO2	Impact Projected to add 33 Plants @ an average distance of 30 miles from the Trunkline
Total Operations Impact ($ million)	$2.60	$170	$86
Total Gross Economic Output ($ million)	$5.78	$377	$191
Employment (jobs)	15.26	996	2,503
FSL Taxes ($ million)	$1.49	$97	$49
Note: impacts of 45Q tax credits are NOT included in these annual estimates			

Building out CO2 capture and sequestration via pipeline could have substantial positive impacts across the Midwest (Table 8). While the trunkline and 31 connected plants are estimated to generate $5.1 billion in construction impacts, the eventual addition of 33 more plants to that trunkline are estimated to add another $2.58 billion in construction impact. Gross economic impact of capital output relative to capital expenditures is estimated to be $3.6 billion for the trunkline set of CO2 sequestration construction and capital outlay with $1.8 billion of output related to adding the additional 33 plants.

Table 8. Midwest CO2 Pipeline Construction Impact Summary

Midwest CO2 Pipeline Construction Impact Summary				
Event	Employment	Value Added ($M)	Output ($M)	FSL Taxes ($M)
Trunk Line & 31 Plants	9,290	$ 5,100	$ 3,600	$ 371
33 Additional Plants	4,697	$ 2,580	$ 1,820	$ 188

Construction employment is estimated to be 9,290 jobs for the trunkline and another 4,697 jobs for the 33 additional plants. Total federal, state and local taxes from construction activities and capital outlays are estimated to be $371 million from construction of the trunkline and $188 million from construction of the 33 other plants.

Annual operations of the combined carbon collection and sequestration activities are estimated to be $170 million for the trunkline and another $86 million for the 33 additional plants (Table 9). Gross economic output is estimated to be $377 million for the trunkline and $191 million for the additional 33 plants. Operational employment is estimated to 996 jobs at the trunkline and 2,503 jobs for the additional plants. Federal, state and local taxes are estimated to be $97 million from the trunkline and $49 million from the additional plants.

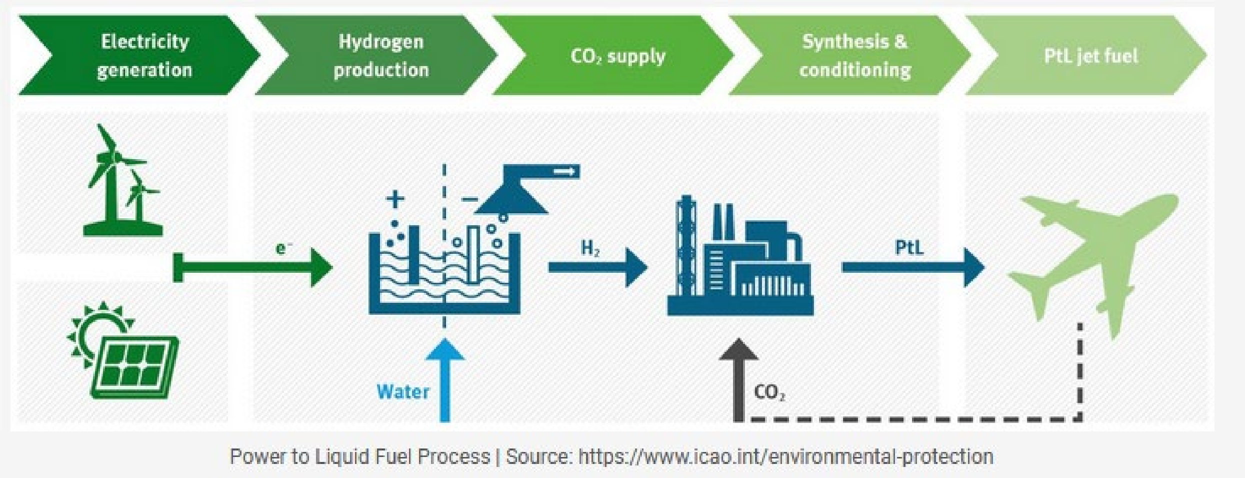
Table 9. Midwest CO2 Pipeline Operations Impact Summary

Midwest CO2 Pipeline Operations Impact Summary				
Event	Employment	Value Added ($M)	Output ($M)	FSL Taxes ($M)
Trunk Line & 31 Plants	996	$ 170	$ 377	$ 97
33 Additional Plants	2,503	$ 86	$ 191	$ 49

Beyond the CO2 that needs to be captured and sequestered so that the ethanol can be used as feedstock for SAF, there is another 41-45 mmt of CO2 available to be captured from ethanol that is blended for light vehicle fuels and could be used as the feedstock for SAF using a PTF-SAF pathway. It is not yet clear whether it would make more economic sense to capture and accumulate this CO2 in pipelines and then build larger scale CO2-based PTF-SAF plants that would extract CO2 from the pipeline or whether it makes sense to simply move the CO2 to a nearby, or on-site, smaller PTF-SAF facility that could use the CO2 as feedstock for PTF-SAF.

9 Power-to-Fuel (PTF-SAF) from Captured Corn Ethanol CO2

Power-to-liquid fuel is a type of Sustainable Aviation Fuel (SAF) that only contains renewables instead of using waste or biological materials like plants. To make it, a facility takes the hydrogen out of water, carbon dioxide captured from the production of ethanol and electricity from renewable energy are all used to make jet fuel (Figure 48).



Power to Liquid Fuel Process | Source: https://www.icao.int/environmental-protection

Figure 48. Power to Fuel Process

According to Sanchez *et. al.* (2018), capture of biogenic CO_2 from fermentation is unique because, unlike many other technologies, it does not require a costly separation of CO_2 and can be applied at existing biorefineries. Practiced commercially for several decades, fermentation of sugars and starch currently produces over 26 billion gallons/y of ethanol worldwide. Moreover, fermentation produces a high-purity (99%) gaseous CO_2 stream consisting only of CO_2, H_2O, and small amounts of organic and sulfur compounds. Thus, purification, dehydration, and compression of fermentation CO_2 streams can be accomplished at relatively low cost via existing technologies, including reciprocating or centrifugal compressors, pumps, and glycol dehydration. Cost estimates for CO_2 capture and compression from fermentation are typically \$30/tCO_2, among the lowest of all CO_2 point sources (Greenberg (2016), Herron (2014) and Psarras (2017)).

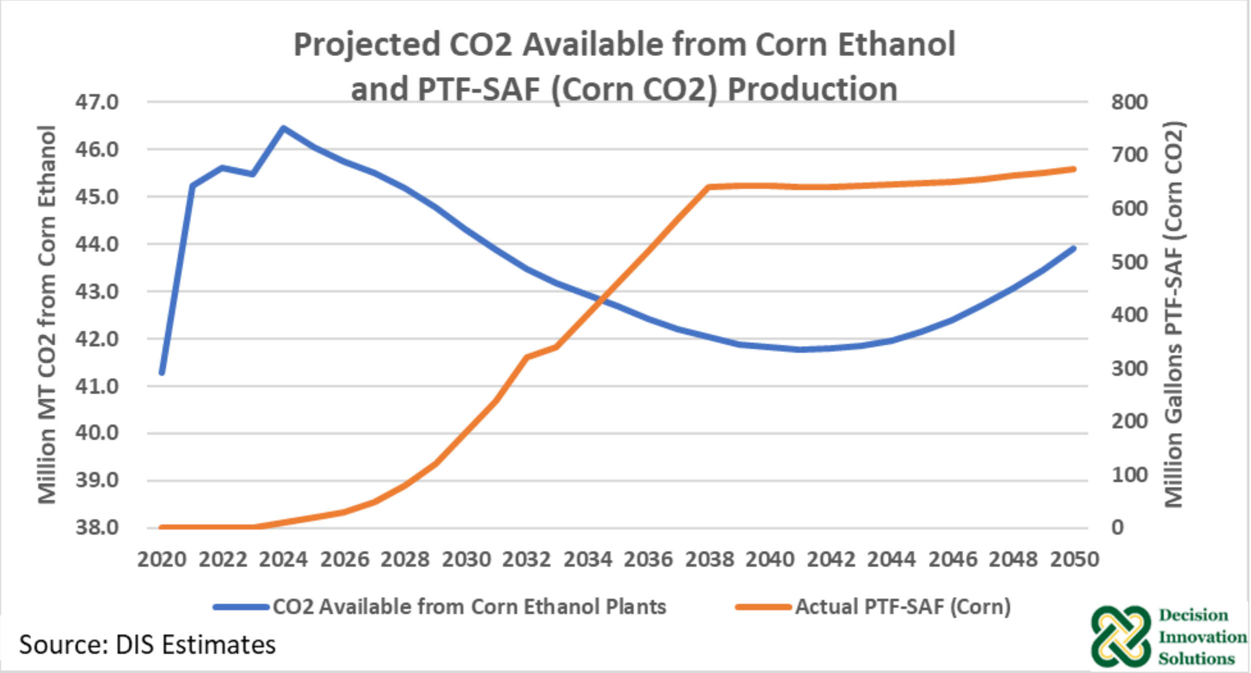
For this pathway, the CO2 is captured from both existing ethanol production and from the new ethanol plants that will come on-line to produce ETJ-SAF. It is assumed that there will be a ramping up of CO2 capture and utilization for PTF-SAF that starts in 2025, slowly expands to about 6% of all corn-ethanol CO2 being captured by 2030 and then ramps up through 2042 when 90% of CO2 from corn ethanol plants will be captured and converted to PTF-SAF. The DIS pathway for PTF-SAF from CO2 from corn ethanol plants then remains at 90% capture and utilization rate through 2050. This pathway assumes that the captured CO2 at the corn ethanol plants is equal to 32% of the weight of the corn processed for ethanol. It also assumes that the CO2 from each million gallons of ethanol can be converted into 0.36 million gallons of distillate that is then distilled into 20% PTF-SAF, 9% RD, and 71% Renewable Gasoline.

Twelve is a company that began producing jet fuel in a lab in 2021 using electricity, water and CO2. Twelve refers to their product as “E-Jet”. The company has broken ground on a commercial-scale facility in Moses Lake, WA and plans to begin operations in 2024. According to media reports, Twelve aims to produce 40 million gallons per year of E-Jet before scaling up production by 10X within the first 5 years of operations. The Twelve operation plans to get CO2 from an ethanol plant in Oregon. Twelve is using a method to transform CO2 into jet fuel in a process called “industrial photosynthesis”. The Twelve process uses an electrochemical reactor that takes water and CO2 and changes them into new chemicals, materials, or fuels using renewable energy. It splits CO2 molecules into carbon monoxide while in a separate electrolyzer, water molecules are broken down into hydrogen and oxygen and then combined into a syngas that is then turned into E-Jet via the Fisher-Tropsch process.

Honeywell has also announced a new technology to produce SAF from green hydrogen and CO2 captured from industrial sources such as an ethanol plant. Honeywell has said that energy producer HF Global has signed on as the first company to use its new technology. HF Global plans to deploy the technology at a facility that will recycle about 2 million tons of captured CO2 per year by 2030 (Kelly, 2023).

DIS projects that with the proper combinations of policy and technology adoption, CO2 can be captured from the majority of ethanol plants over the next 20+ years. The CO2 that could be available from capture at ethanol plants is depicted in Figure 49. Currently, there are approximately 45 million metric tons of CO2 being produced from corn ethanol production. Only a fraction of that is being captured currently. With expansion of ethanol production to produce ETJ-SAF, there could be as much as 80 million metric tons of CO2 captured from U.S. ethanol plants in 2050.

Also shown in Figure 49 is a projection of a potential pathway for expansion of PTF-SAF from corn ethanol CO2. As noted above, Twelve has broken ground on a production facility that should produce PTF-SAF in 2024, and plans to expand that production by 2030. In the DIS pathway for PTF-SAF from ethanol CO2, we project 6% of corn-ethanol CO2 will be captured and turned into 373 million gallons of PTF-SAF from ethanol CO2 by 2030. DIS projects that this pathway will ramp up substantially between 2030 and 2042 and then stabilize at an 90% utilization rate of ethanol CO2 for PTF-SAF from 2042 through 2050.



Source: DIS Estimates

Figure 49. Projected CO2 Available from Corn Ethanol and PTF-SAF (Corn CO2) Production

9.1 Renewable Energy Availability Maps

U.S. Wind energy net generation from all sectors was about 434,297 thousand megawatt hours (MWh), which increased 14.8% from the net generation the previous year. Wind energy accounted for 10% of total electricity net generation from all sectors in 2022.

Texas was the number one state in terms of wind energy net generation in 2022 with 114,786 thousand MWh (26.4%), followed by Iowa (45,762 thousand MWh, 10.5%), and Oklahoma (37,552 thousand MWh, 8.6%) (Figure 50). Iowa is well-positioned to install more wind energy production capacity and to dedicate that new capacity to direct air capture of CO2 and to utilize wind energy for renewable hydrogen production, both of which will be needed for PTF-SAF production.

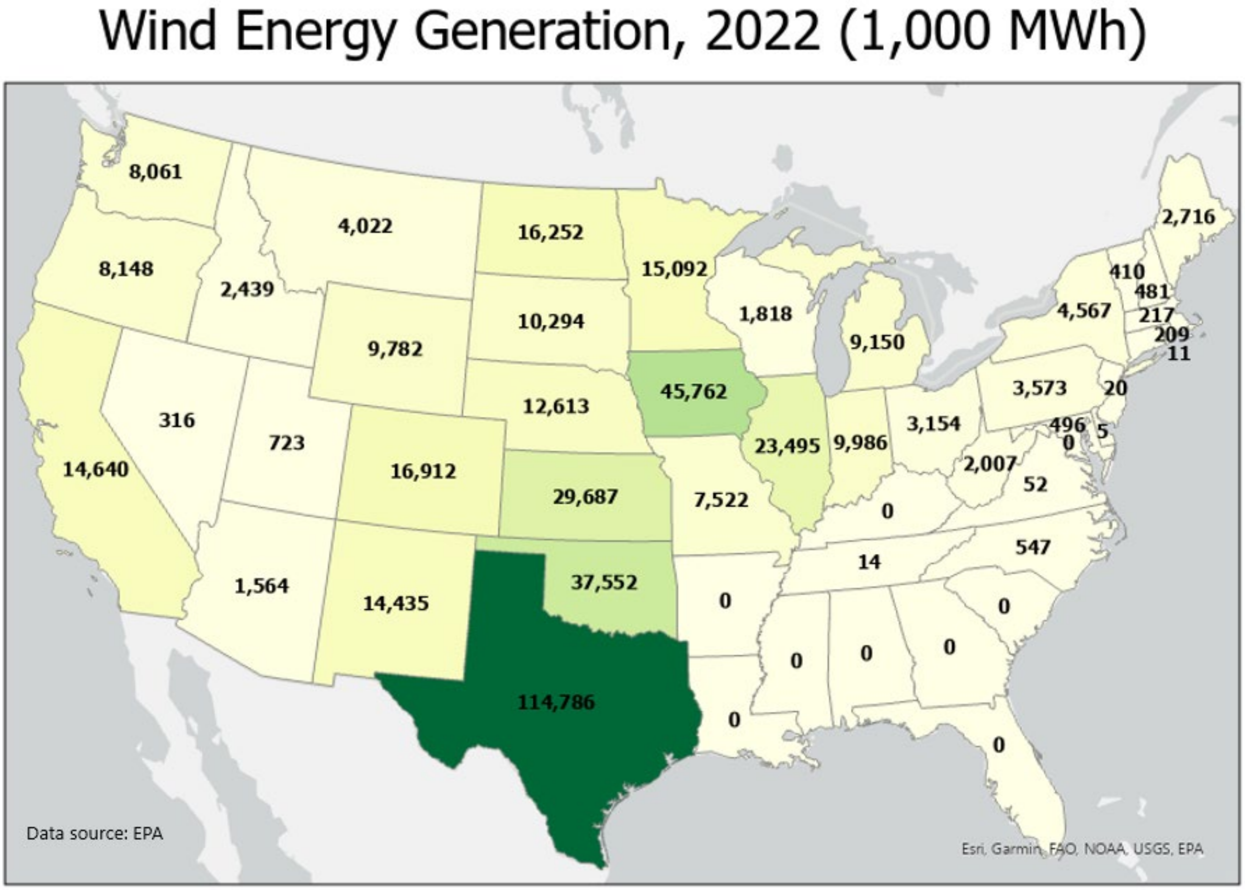
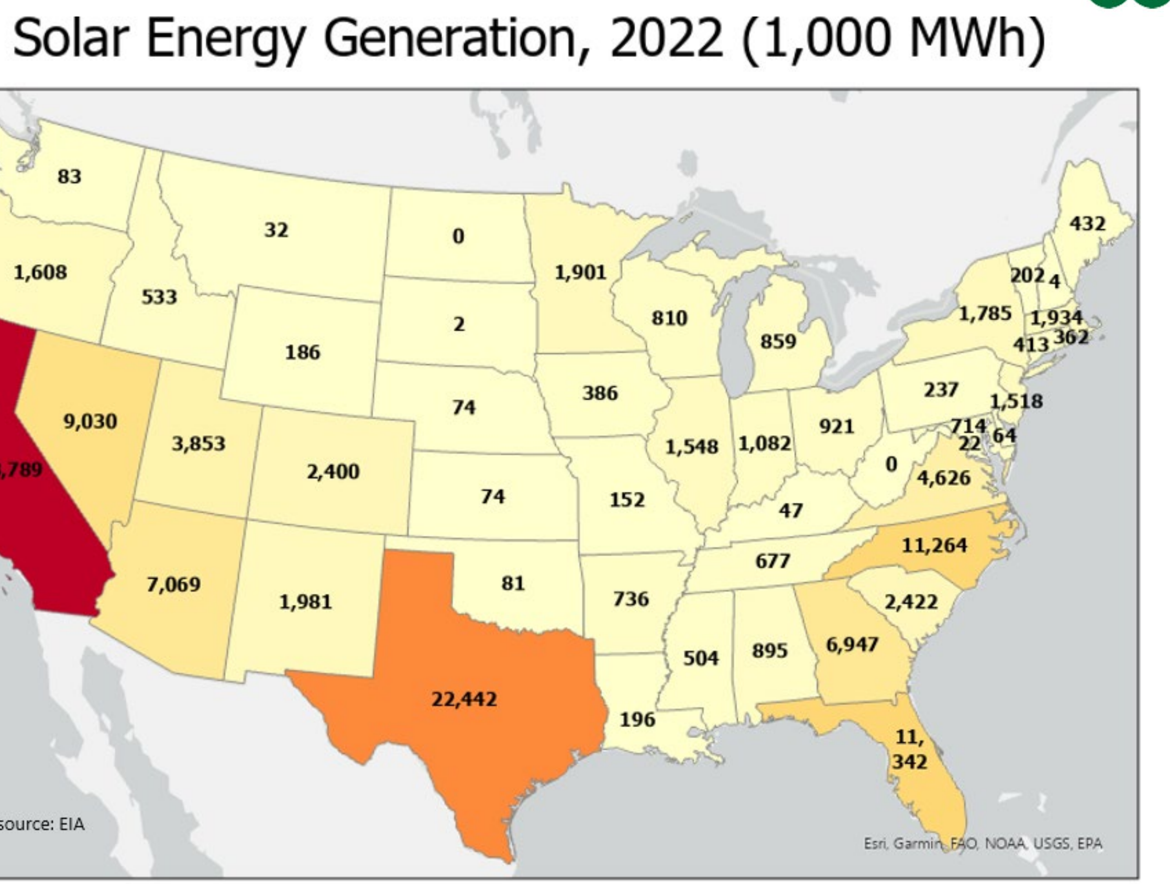

Wind Energy Generation, 2022 (1,000 MWh)

Figure 50. Wind Energy Generation, 2022 (1,000 MWh)

U.S. Solar energy net generation at utility scale facilities, all sectors, totaled 143,797 thousand MWh in 2022, up 24.8% from the previous year. Overall, wind energy generation at utility scale facilities, all sectors, made up 3% of total electricity generation in 2022.

The top three states in terms of solar energy net generation in 2022 were California (37,789 thousand MWh, 27%), Texas (22,442 thousand MWh, 16%), and North Carolina (11,264 thousand MWh, 8%) (see Figure 51).



Solar Energy Generation, 2022 (1,000 MWh)

Data source: EIA

Figure 51. Solar Energy Generation, 2022 (1,000 MWh)

Figure 52 shows the combined total energy generation from wind and solar sources in 2022.

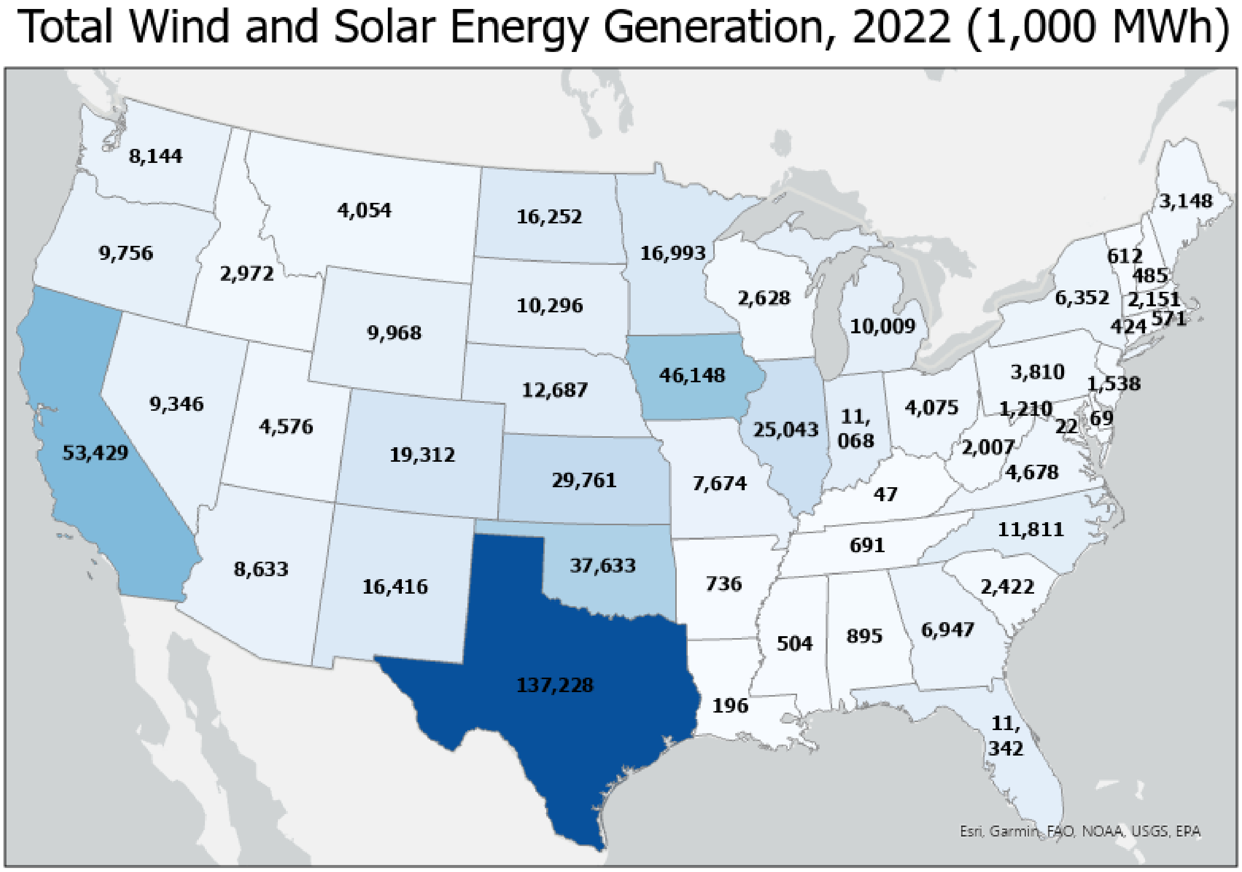


Figure 52. Total Wind and Solar Energy Generation, 2022 (1,000 MWh)

10 Economic Impact Assessment of Future Pathways, Including HEFA, ETJ and PTF[11]

The following economic contribution study was conducted using a combination of IMPLAN, Microsoft Excel, and other sources. IMPLAN is an input-output model used to understand industry relationships and conduct economic assessments for specified local economies. IMPLAN datasets are constructed annually and are derived from many different sources, including the U.S. Bureau of Labor Statistics (BLS), the U.S. Bureau of Economic Analysis (BEA), the U.S. Bureau of Economic Analysis Benchmark Input-Output Account of the U.S., the BEA output estimates, the U.S. Census Bureau's economic censuses and surveys, the U.S. Department of Agriculture's census, and more.

Within IMPLAN, the effects of an economic impact or contribution event are expressed in terms of direct, indirect, and induced effects. These different effect types are defined as follows:

- **Direct Effects** – The economic activity directly attributable to the industry under analysis; in this study, the production of ethanol and SAF from a variety of feedstocks.
- **Indirect Effects** – The effects of local inter-industry spending throughout the supply chain, for example, the seed, equipment, fertilizer, and other inputs used by a farmer to produce corn for an ethanol plant or soybeans for soybean oil processing and feedstock for HEFA-SAF
- **Induced Effects** – The results of employees of the directly and indirectly affected industries spending their income throughout the local economy
- **Total Effect** – The sum of direct, indirect, and induced effects

All results shown throughout the report are in current (2023) dollars. The results of this economic contribution study are reported using the following economic measures:

- **Output:** The broadest measure of economic activity – also commonly referred to as "sales." Output refers to the total value of all sales of an industry within a study area without any deductions for the cost or origination of inputs that were used in the production process.
- **Value Added:** A component of output, this measure includes the total sales minus the costs of inputs. Alternatively, value added is calculated as the sum of labor income (further defined below), taxes on production and imports, and other property-type income. An industry's value added is equivalent to its contribution to GDP.
- **Labor Income:** A subset of value added, includes the sum of employee compensation (i.e., wages and benefits) and proprietor income (i.e., income of self-employed workers). Labor income is the largest portion of household income (which includes non-labor incomes such as interest, dividends, and transfer payments).
- **Employment (Jobs):** A measure of part- and full-time job positions, including contract workers, without regard to their full-time equivalence. Since it is not representative solely of full-time

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[11] While FT technologies will be part of the overall pathway for SAF through 2050, development of geographic dispersion of new FT-SAF facilities is beyond the scope of this study. Thus, it will not be included in the economic impact assessment.

positions or full-time equivalents, care must be made when drawing comparisons to other measures of employment.

10.1 Economic Impact Assessment for Iowa

Table 10 shows the estimated total (annual) operations impact from SAF and associated ethanol production on Iowa. Once the facilities for SAF production from ETJ and HEFA are fully operational, the SAF production industry has the potential to support more than 22,000 jobs and provide nearly $1 billion in labor income, more than $2.7 billion in total value added, and nearly $11.9 billion in total output (sales).

Table 10. Iowa Combined Operations Impact Summary

Iowa Operations Impact Summary				
Event	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
New Ethanol Production	18,018	$ 709.1	$ 1,738.7	$ 7,897.9
SAF from ETJ	2,574	$ 128.9	$ 4.3	$ 492.7
SAF from HEFA	1,577	$ 115.5	$ 977.9	$ 3,508.7
Total	**22,169**	**$ 953.6**	**$ 2,721.0**	**$ 11,899.3**

Table 11 shows the estimated total (one-time) impact from the construction of all new ethanol and SAF production facilities within Iowa. Around $2.3 billion in labor income, $3.1 billion in value added, and $5.8 billion in output is projected to be generated as these facilities are constructed. If the build-out of SAF (and ethanol) production facilities takes place over 25 years, this results in an average impact of $90 million in labor income, $123 million in value added, and $235 million in output each year over that period.

Table 11. Iowa Combined Construction Impact Summary

Iowa Construction Impact Summary				
Event	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
New Ethanol Production	20,432	$ 1,286.6	$ 1,744.4	$ 3,333.1
SAF from ETJ	9,175	$ 587.9	$ 806.1	$ 1,532.5
SAF from HEFA	6,069	$ 389.6	$ 535.3	$ 1,016.8
Total	**35,676**	**$ 2,264.1**	**$ 3,085.9**	**$ 5,882.4**

10.1.1 ETJ-SAF

Five ETJ-SAF facilities (each with an average distillate production of 264 million gallons) are projected to be built across Iowa. Once these facilities are fully operational, they are estimated to directly employ more than 900 workers and provide more than $62 million in labor income annually. Once indirect and induced effects are added, the estimated total impact of SAF production from the ETJ pathway in Iowa is 2,574 jobs and $1.3 million in net value added (Table 12). The direct value added for this event is negative due to the federal subsidies associated with SAF production. While it shows up as a negative in the analysis, in reality, the capturing of the federal subsidies for SAF production would be a net transfer to Iowa of the federal fuel production tax credits. Note that this impact does not include the production of ethanol for these facilities; that impact is estimated separately below.

Table 12. ETJ Operations Impact Summary, Iowa

Impact Summary - Iowa SAF Production Using Ethanol				
Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	945	$ 62.6	$ (143.3)	$ 195.0
Indirect	953	$ 46.1	$ 108.4	$ 228.5
Induced	676	$ 20.2	$ 39.2	$ 69.2
Total	**2,574**	**$ 128.9**	**$ 4.3**	**$ 492.7**

The industries most affected in terms of value added by ETJ production of SAF are largely a part of the energy and transportation sectors (Table 13). Note that the shown industries are those most impacted according to relationships that exist in 2022. It is likely that these relationships will change by 2050, especially if the processes involved in manufacturing ETJ-SAF become more efficient as the industry scales up production.

Table 13. ETJ-SAF Operations Top Industries Impacted, Iowa

Top Industries Impacted - Iowa SAF Production Using Ethanol	
Industry	Total Value Added ($M)
Electric power transmission and distribution	$ 24.1
Electric power generation	$ 12.6
Wholesale - Other nondurable goods merchant wholesalers	$ 10.5
Natural gas distribution	$ 8.5
Monetary authorities and depository credit intermediation	$ 7.9
Owner-occupied dwellings	$ 6.8
Truck transportation	$ 5.8
Rail transportation	$ 3.5
Retail - Nonstore retailers	$ 3.2
Management of companies and enterprises	$ 3.0

Table 14 shows the impact from the construction of the ETJ facilities in Iowa. While operations impacts occur annually, construction impacts are a one-time impact (although for this report, the construction activities are cumulative over the period of 2024-2050). The construction of five ETJ-SAF facilities in Iowa supports an estimated total 9,175 jobs and provides a total of $806 million in total value added to the economy.

Table 14. ETJ-SAF Construction Impact Summary, Iowa

Impact Summary - Iowa ETJ Facility Construction				
Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	5,962	$ 395.9	$ 449.4	$ 870.6
Indirect	1,258	$ 94.5	$ 167.5	$ 330.7
Induced	1,956	$ 97.5	$ 189.2	$ 331.2
Total	**9,175**	**$ 587.9**	**$ 806.1**	**$ 1,532.5**

The industries most impacted by the construction of ETJ facilities include equipment providers, financial services, and truck transportation (Table 15).

Table 15. ETJ Construction Top Industries Impacted, Iowa

Top Industries Impacted - Iowa ETJ Facility Construction

Industry	Total Value Added ($M)
Construction of new manufacturing structures	$ 449.4
Wholesale - Machinery, equipment, and supplies	$ 59.8
Owner-occupied dwellings	$ 34.6
Monetary authorities and depository credit intermediation	$ 12.5
Truck transportation	$ 9.1
Hospitals	$ 8.7
Other real estate	$ 7.2
Management of companies and enterprises	$ 7.2
Insurance carriers, except direct life	$ 7.2
Offices of physicians	$ 7.2

A total of 11 new ethanol plants (each with an average production capacity of 200 million gallons) are projected to be built across Iowa. Once fully operational, these facilities are estimated to directly employ more than 900 workers and provide a labor income of $45 million. Ethanol production has a large indirect effect due to the large quantities of inputs required. Once indirect and induced effects are considered, the estimated total impact of new ethanol production in Iowa is more than 18,000 jobs supported and more than $1.7 billion in value added to the economy (Table 16).

Table 16. Ethanol Operations Impact Summary, Iowa

Impact Summary - New Iowa Ethanol Production

Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	924	$ 44.9	$ 367.9	$ 4,014.1
Indirect	13,391	$ 553.5	$ 1,156.2	$ 3,505.5
Induced	3,704	$ 110.7	$ 214.7	$ 378.4
Total	**18,018**	**$ 709.1**	**$ 1,738.7**	**$ 7,897.9**

The industry most impacted by new ethanol production is grain farming, with an estimated value-added impact of $509 million. Other affected industries include agricultural support activities, agricultural chemical manufacturing, and banking (Table 17).

Table 17. Ethanol Operations Top Industries Impacted, Iowa

Top Industries Impacted - New Iowa Ethanol Production	
Industry	**Total Value Added ($M)**
Grain farming	$ 509.7
Other basic organic chemical manufacturing	$ 369.2
Wholesale - Other nondurable goods merchant wholesalers	$ 92.8
Other real estate	$ 66.3
Monetary authorities and depository credit intermediation	$ 60.3
Support activities for agriculture and forestry	$ 48.0
Pesticide and other agricultural chemical manufacturing	$ 39.9
Electric power transmission and distribution	$ 38.8
Owner-occupied dwellings	$ 37.4
Natural gas distribution	$ 26.3

Table 18 shows the impact from the construction of the new ethanol facilities. The construction of 11 ethanol facilities across Iowa supports an estimated 20,432 jobs and provides a $1.7 billion in total value added within the state over the course of the construction period. If, for example, the buildout period for ethanol facilities was 20 years, this would be an average of 1,021 jobs supported and $87 million in value added in each of those years.

Table 18. Ethanol Construction Impact Summary, Iowa

Impact Summary - New Iowa Ethanol Facility Construction				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	13,710	$ 900.4	$ 1,022.0	$ 1,980.0
Indirect	2,400	$ 170.7	$ 304.2	$ 621.2
Induced	4,322	$ 215.5	$ 418.2	$ 732.0
Total	**20,432**	**$ 1,286.6**	**$ 1,744.4**	**$ 3,333.1**

Table 19 shows the industries most affected by the construction of the new ethanol facilities.

Table 19. Ethanol Construction Top Industries Impacted, Iowa

Top Industries Impacted - New Iowa Ethanol Facility Construction	
Industry	**Total Value Added ($M)**
Construction of new manufacturing structures	$ 1,022.0
Owner-occupied dwellings	$ 76.5
Monetary authorities and depository credit intermediation	$ 28.9
Wholesale - Machinery, equipment, and supplies	$ 28.8
Truck transportation	$ 25.7
Wholesale - Other durable goods merchant wholesalers	$ 20.3
Ready-mix concrete manufacturing	$ 20.0
Hospitals	$ 19.2
Commercial and industrial machinery and equipment rental and leasing	$ 17.8
Other real estate	$ 15.9

10.1.2 HEFA-SAF

Three new HEFA-SAF facilities are projected to be built in Iowa. These three facilities are estimated to directly employ 603 workers and have a value added of $768 million once they are built and operating at capacity. When accounting for indirect and induced effects, the total economic impact of these new HEFA-SAF facilities is 2,691 jobs created or supported, more than $115 million in labor income, and $978 million in value added (Table 20).

Table 20. HEFA-SAF Operations Impact Summary, Iowa

Impact Summary - Iowa SAF Production from New HEFA Facilities

Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	603	$ 23.1	$ 768.0	$ 2,851.2
Indirect	1,477	$ 74.1	$ 174.5	$ 595.1
Induced	611	$ 18.3	$ 35.5	$ 62.5
Total	**2,691**	**$ 115.5**	**$ 977.9**	**$ 3,508.7**

The industries most impacted by HEFA-SAF production are mostly those that provide feedstocks for the HEFA process, such as oilseed farming, oilseed processing, and rendering (Table 21). The "other basic organic chemical manufacturing" industry primarily represents the value added attributable directly to the operations of the HEFA-SAF facilities.

Table 21. HEFA-SAF Operations Top Industries Impacted, Iowa

Top Industries Impacted - Iowa SAF Production from New HEFA Facilities

Industry	Total Value Added ($M)
Other basic organic chemical manufacturing	$ 769.1
Oilseed farming	$ 50.2
Soybean and other oilseed processing	$ 24.6
Truck transportation	$ 12.3
Wholesale - Other nondurable goods merchant wholesalers	$ 11.0
Animal production, except cattle and poultry and eggs	$ 6.5
Animal, except poultry, slaughtering	$ 6.5
Monetary authorities and depository credit intermediation	$ 6.2
Owner-occupied dwellings	$ 6.2
Rail transportation	$ 3.9

The construction of three new HEFA-SAF facilities is estimated to have a total (one-time) impact of 6,069 jobs, $389 million in labor income, $535 million in value added, and $1 billion in total sales (output) on the state economy. This is around $130 million in labor income and $180 million in value added per new facility (Table 22).

Table 22. HEFA-SAF Construction Impact Summary, Iowa

Impact Summary - New Iowa HEFA Facility Construction				
Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	3,919	$ 260.3	$ 295.4	$ 572.3
Indirect	854	$ 64.7	$ 114.5	$ 225.1
Induced	1,296	$ 64.6	$ 125.4	$ 219.5
Total	**6,069**	**$ 389.6**	**$ 535.3**	**$ 1,016.8**

Table 23 shows the industries most impacted by the construction of new HEFA-SAF facilities. As with the construction of ETJ-SAF and ethanol facilities, some of the most affected industries are equipment and other goods providers, transportation, and healthcare services.

Table 23. HEFA Construction Top Industries Impacted, Iowa

Top Industries Impacted - New Iowa HEFA Facility Construction	
Industry	Total Value Added ($M)
Construction of new manufacturing structures	$ 295.4
Wholesale - Machinery, equipment, and supplies	$ 45.3
Owner-occupied dwellings	$ 22.9
Monetary authorities and depository credit intermediation	$ 8.2
Hospitals	$ 5.8
Truck transportation	$ 5.7
Management of companies and enterprises	$ 4.9
Insurance carriers, except direct life	$ 4.8
Other real estate	$ 4.8
Offices of physicians	$ 4.7

10.1.3 PTF-SAF

Eight PTF-SAF facilities that convert CO2 recovered from ethanol plants are projected to be built across Iowa. These facilities are estimated to employ 848 workers with a total labor income of $34 million annually (Table 24). It should be noted that the direct value-added for PTF-SAF is negative reflecting a situation in which costs are much greater than value and the need for large subsidies for PTF-SAF production given current operational relationships.

PTF is an emerging technology that currently exists in experimental and relatively small-scale production and is not considered economically viable at this time for large-scale production. An operations impact for PTF is attempting to model economic relationships that do not currently exist at the magnitude projected for 2050. Because of this, only the direct estimate of SAF production by PTF is shown in the table below. This result reflects only the operations of the PTF plants themselves and does not include further effects produced by input industries.

Table 24. PTF-SAF from Ethanol CO2 Operations Impact Summary, Iowa

Impact Summary - Iowa SAF Production Using Captured Ethanol CO2				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	848	$ 33.9	$ (1,265.9)	$ 2,389.6

The industries likely to be most affected by operations of the PTF-SAF facilities are the manufacturing of renewable (green) hydrogen, electric power transmission and distribution, and electrical generation. If hydrolyzation of renewable hydrogen becomes significantly more efficient than current processes[12], then the economic impacts will change dramatically for PTF-SAF.

The construction of PTF-SAF facilities in the U.S. is estimated to have a total (one-time) direct impact of 66,659 jobs, $4 billion in labor income, and $4.5 billion in value added (Table 25). These values are rough estimates, as the precise requirements to build a large-scale PTF facility are not currently known.

Table 25. PTF Construction Impact Summary, U.S.

Impact Summary - Iowa PTF Facility Construction				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	60,659	$ 4,028.1	$ 4,546.8	$ 8,632.8

10.2 Economic Impact Assessment for the 12 Midwestern States

Table 26 shows the estimated total (annual) operations impact from SAF and associated ethanol production in the Midwest. Once the facilities for SAF production from ETJ, HETA, and PTF are fully operational, the SAF production industry has the potential to support more than 224,000 jobs and provide more than $9 billion in labor income, nearly $20 billion in total value added, and more than $71 billion in total output (sales) within the region.

Table 26. Midwest Operations Impact Summary

Midwest Operations Impact Summary				
Event	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
New Ethanol Production	184,115	$ 7,339.6	$ 15,692.2	$ 56,403.0
SAF from ETJ	22,610	$ 1,140.9	$ 724.3	$ 4,289.3
SAF from HEFA	17,716	$ 840.6	$ 3,277.8	$ 10,449.7
Total	**224,440**	**$ 9,321.1**	**$ 19,694.2**	**$ 71,142.0**

Table 27 shows the estimated total (one-time) impact from the construction of all new ethanol and SAF production facilities in the Midwest. More than $15.5 billion in labor income, $22 billion in value added, and $41.6 billion in output is projected to be generated within the region as these facilities are constructed. If the build-out of SAF (and ethanol) production facilities takes place over 25 years, this

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[12] Bloom Energy has begun generating hydrogen from the world's largest solid oxide electrolyzer installation at NASA's Ames Research Center, the historic Moffett Field research facility in Mountain View, Calif. This high-temperature, high-efficiency unit produces 20-25% more hydrogen per megawatt (MW) than commercially demonstrated lower temperature electrolyzers such as proton electrolyte membrane (PEM) or alkaline. Source: https://www.bloomenergy.com

results in an average impact of $620 million in labor income, $882 million in value added, and $1.7 billion in output each year over that period.

Table 27. Midwest Construction Impact Summary

Event	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
New Ethanol Production	139,066	$ 9,513.6	$ 13,493.0	$ 25,600.3
SAF from ETJ	64,960	$ 4,505.4	$ 6,424.6	$ 12,070.0
SAF from HEFA	21,456	$ 1,490.2	$ 2,127.8	$ 3,990.4
Total	**225,482**	**$ 15,509.2**	**$ 22,045.4**	**$ 41,660.6**

10.2.1 HEFA-SAF

All six of the projected new HEFA-SAF facilities are expected to be built in the Midwest. These six facilities are estimated to directly employ 1,206 workers and provide $46.2 million in labor income annually. When accounting for indirect and induced effects, the total annual economic impact on the Midwest of these new HEFA-SAF facilities is 17,716 jobs created or supported, more than $840 million in labor income, and more than $3.2 billion in value added (Table 28).

Table 28. HEFA Operations Impact Summary, Midwest

Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	1,206	$ 46.2	$ 1,536.0	$ 5,702.3
Indirect	10,829	$ 592.9	$ 1,370.6	$ 4,084.0
Induced	5,681	$ 201.4	$ 371.3	$ 663.4
Total	**17,716**	**$ 840.6**	**$ 3,277.8**	**$ 10,449.7**

As with the results at the national level, the industries most impacted by HEFA-SAF production are largely those that provide feedstocks for the HEFA process, such as oilseed farming, oilseed processing, and rendering (Table 29).

Table 29. HEFA-SAF Operations Top Industries Impacted, Midwest

Top Industries Impacted - Midwest SAF Production from New HEFA Facilities	
Industry	Total Value Added ($M)
Other basic organic chemical manufacturing	$ 1,552.1
Oilseed farming	$ 539.4
Soybean and other oilseed processing	$ 146.0
Truck transportation	$ 83.0
Rendering and meat byproduct processing	$ 50.1
Monetary authorities and depository credit intermediation	$ 49.2
Owner-occupied dwellings	$ 47.2
Wholesale - Other nondurable goods merchant wholesalers	$ 45.0
Other real estate	$ 37.7
Petroleum refineries	$ 28.6

The construction of six new HEFA-SAF facilities is estimated to have a total (one-time) impact of 21,456 jobs, $1.5 billion in labor income, $2.1 billion in value added, and nearly $4.0 billion in total sales (output) (Table 30).

Table 30. HEFA-SAF Construction Impact Summary, Midwest

Impact Summary - New Midwest HEFA Facility Construction				
Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	11,451	$ 801.1	$ 908.0	$ 1,717.0
Indirect	3,712	$ 311.1	$ 532.8	$ 1,052.1
Induced	6,294	$ 378.0	$ 687.0	$ 1,221.3
Total	**21,456**	**$ 1,490.2**	**$ 2,127.8**	**$ 3,990.4**

Table 31 shows the industries most impacted by the construction of new HEFA-SAF facilities. As with the construction of ETJ-SAF and ethanol facilities, some of the most affected industries are equipment and other goods providers, management, and legal services.

Table 31. HEFA-SAF Construction Top Industries Impacted, Midwest

Top Industries Impacted - New Midwest HEFA Facility Construction	
Industry	**Total Value Added ($M)**
Construction of new manufacturing structures	$ 908.0
Wholesale - Machinery, equipment, and supplies	$ 160.7
Owner-occupied dwellings	$ 91.6
Hospitals	$ 40.5
Monetary authorities and depository credit intermediation	$ 37.6
Other real estate	$ 34.7
Management of companies and enterprises	$ 30.4
Offices of physicians	$ 24.3
Employment services	$ 24.1
Truck transportation	$ 23.4

10.2.2 ETJ-SAF

Of the 32 ETJ-SAF facilities projected to be built across the U.S., 30 are projected to be built in the Midwest. Once these facilities are fully operational, they are estimated to directly employ more than 5,600 workers and provide more than $375 million in labor income annually. Once indirect and induced effects are added, the estimated total impact of SAF production from the ETJ pathway on the Midwest is 22,6610 jobs and $724 million in total value added (Table 32). Note that this impact does not include the production of ethanol for these facilities; that impact is estimated separately below.

Table 32. ETJ-SAF Operations Impact Summary, Midwest

Impact Summary - Midwest SAF Production Using Ethanol				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	5,670	$ 375.7	$ (860.1)	$ 1,169.7
Indirect	9,100	$ 486.9	$ 1,071.2	$ 2,202.7
Induced	7,840	$ 278.3	$ 513.1	$ 916.9
Total	**22,610**	**$ 1,140.9**	**$ 724.3**	**$ 4,289.3**

The industries most affected in terms of value added by ETJ-SAF production are largely a part of the energy and transportation sectors (Table 33). Other highly impacted industries include monetary authorities (banking) and owner-occupied dwellings[13].

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[13] The owner-occupied dwellings industry in IMPLAN captures the economic impact of homeownership. It includes property taxes, the interest portion of mortgage payments, and home repair and maintenance.

Table 33. ETJ-SAF Operations Top Industries Impacted, Midwest

Top Industries Impacted - Midwest SAF Production Using Ethanol	
Industry	**Total Value Added ($M)**
Electric power transmission and distribution	$ 155.9
Natural gas distribution	$ 148.8
Monetary authorities and depository credit intermediation	$ 96.5
Electric power generation	$ 88.4
Wholesale - Other nondurable goods merchant wholesalers	$ 73.0
Owner-occupied dwellings	$ 64.6
Truck transportation	$ 43.6
Management of companies and enterprises	$ 35.9
Retail - Nonstore retailers	$ 28.5
Other local government enterprises	$ 27.8

Table 34 shows the impact from the construction of the ETJ-SAF facilities in the Midwest. While operations impacts occur annually, construction impacts are a one-time impact. The construction of 30 ETJ-SAF facilities across the Midwest supports an estimated total 64,940 jobs and provides a total of $4.5 billion in total value added to the economy. If the construction of these new ETJ-SAF facilities occurs across a 25-year time frame, then the average annual impact would be approximately 2,600 new jobs, $180 million in annual labor income, $257 million in value-added activities and increased GDP, and $483 million in increased sales output each year.

Table 34. ETJ-SAF Construction Impact Summary, Midwest

Impact Summary - Midwest ETJ Facility Construction				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	34,835	$ 2,437.2	$ 2,762.2	$ 5,223.3
Indirect	11,096	$ 925.3	$ 1,585.3	$ 3,154.2
Induced	19,029	$ 1,142.9	$ 2,077.2	$ 3,692.4
Total	**64,960**	**$ 4,505.4**	**$ 6,424.6**	**$ 12,070.0**

The industries most impacted by the construction of ETJ facilities equipment providers, management, and healthcare services (Table 35).

Table 35. ETJ-SAF Construction Top Industries Impacted, U.S.

Top Industries Impacted - Midwest ETJ Facility Construction	
Industry	**Total Value Added ($M)**
Construction of new manufacturing structures	$ 2,762.2
Wholesale - Machinery, equipment, and supplies	$ 425.3
Owner-occupied dwellings	$ 276.8
Hospitals	$ 122.6
Monetary authorities and depository credit intermediation	$ 114.4
Other real estate	$ 104.9
Management of companies and enterprises	$ 90.4
Wholesale - Other durable goods merchant wholesalers	$ 74.5
Truck transportation	$ 74.2
Offices of physicians	$ 73.5

The vast majority of the new ethanol plants (63 out of 68) are projected to be built in the Midwest. Once fully operational, these facilities are estimated to directly employ nearly 5,300 workers and provide a labor income of $257.3 million. Once indirect and induced effects are considered, the estimated total impact of new ethanol production on the Midwest is more than 184,000 jobs supported and more than $15 billion in value added (Table 36).

Table 36. Ethanol Operations Impact Summary, Midwest

Impact Summary - New Midwest Ethanol Production				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	5,292	$ 257.3	$ 2,106.8	$ 22,989.6
Indirect	129,400	$ 5,329.8	$ 10,355.4	$ 27,642.3
Induced	49,422	$ 1,752.4	$ 3,230.0	$ 5,771.2
Total	**184,115**	**$ 7,339.6**	**$ 15,692.2**	**$ 56,403.0**

Similar to the impact at the national level, the industry most impacted by new ethanol production is grain farming, with an estimated value-added impact of $3.9 billion (Table 37).

Table 37. Ethanol Operations Top Industries Impacted, Midwest

Top Industries Impacted - New Midwest Ethanol Production	
Industry	**Total Value Added ($M)**
Grain farming	$ 3,910.1
Other basic organic chemical manufacturing	$ 2,141.9
Other real estate	$ 802.8
Wholesale - Other nondurable goods merchant wholesalers	$ 650.2
Monetary authorities and depository credit intermediation	$ 634.0
Natural gas distribution	$ 444.8
Owner-occupied dwellings	$ 410.3
Support activities for agriculture and forestry	$ 359.5
Electric power transmission and distribution	$ 271.0
Pesticide and other agricultural chemical manufacturing	$ 252.5

Table 38 shows the impact from the construction of the new ethanol facilities. The construction of 63 ethanol facilities across the U.S. supports an estimated total 139,066 jobs and provides a total of $9.5 billion in labor income within the Midwest over the course of the construction period. If, for example, the buildout period for ethanol facilities was 20 years, this would be an average of 6,950 jobs supported and $475 million in labor income in each of those years.

Table 38. Ethanol Construction Impact Summary, Midwest

Impact Summary - New Midwest Ethanol Facility Construction				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	76,469	$ 5,291.2	$ 5,996.8	$ 11,340.0
Indirect	22,107	$ 1,790.5	$ 3,076.6	$ 6,404.0
Induced	40,489	$ 2,431.8	$ 4,419.6	$ 7,856.3
Total	**139,066**	**$ 9,513.6**	**$ 13,493.0**	**$ 25,600.3**

Table 39 shows the industries most affected by the construction of the new ethanol facilities.

Table 39. Ethanol Construction Top Industries Impacted, Midwest

Top Industries Impacted - New Midwest Ethanol Facility Construction	
Industry	**Total Value Added ($M)**
Construction of new manufacturing structures	$ 5,996.8
Owner-occupied dwellings	$ 589.1
Hospitals	$ 260.7
Monetary authorities and depository credit intermediation	$ 252.3
Other real estate	$ 222.4
Wholesale - Other durable goods merchant wholesalers	$ 207.9
Wholesale - Machinery, equipment, and supplies	$ 206.6
Truck transportation	$ 195.5
Management of companies and enterprises	$ 175.5
Legal services	$ 172.8

10.2.3 PTF-SAF

Of 31 PTF-SAF facilities that are projected to be built across the U.S., 29 are expected to be built in the Midwest. These facilities are estimated to employ 3,074 workers with a total labor income of $123 million annually. PTF-SAF requires many inputs including carbon dioxide, hydrogen, and substantial amounts of renewable electricity. Note that these estimates do not include the economic impact of additional ethanol production, as those effects were already considered in Table 40.

Table 40. PTF-SAF from Ethanol CO2 Operations Impact Summary, Midwest

Impact Summary - Midwest SAF Production Using Captured Ethanol CO2				
Impact Type	**Employment**	**Labor Income ($M)**	**Value Added ($M)**	**Output ($M)**
Direct	3,074	$ 123.1	$ (4,588.8)	$ 8,662.2

It should be noted that the direct value-added for PTF-SAF is negative reflecting a situation in which costs are much greater than value and the need for large subsidies for PTF-SAF production given current operational relationships.

PTF is an emerging technology that currently exists in experimental and relatively small-scale production and is not considered economically viable at this time for large-scale production. An operations impact for PTF would be attempting to model economic relationships that do not currently exist at the magnitude projected for 2050. Because of this, only the direct estimate of SAF production by PTF is shown in the table below. This result reflects only the operations of the PTF plants themselves and does not include further effects produced by input industries.

The construction of PTF facilities in the Midwest is estimated to have a direct total (one-time) impact of 208,700 jobs, $14.6 billion in labor income, and $16.5 billion in value added (Table 41). If the PTF-SAF construction were to happen over a period of 10 years (roughly 3 facilities per year), this would result in an average annual impact of around 20,870 jobs supported, $1.46 billion in labor income, and $1.65 billion in value added per year over that period. These values are rough estimates, as the precise requirements to build a large-scale PTF facility are not currently known.

Table 41. PTF-SAF Construction Impact Summary, Midwest

Impact Summary - Midwest PTF Facility Construction				
Impact Type	Employment	Labor Income ($M)	Value Added ($M)	Output ($M)
Direct	208,702	$ 14,601.7	$ 16,548.9	$ 31,293.9

10.3 Economic Impact Methodology

The above economic impact analysis was conducted using the IMPLAN modeling system. All operations events were modeled based off the “other basic organic chemical manufacturing” industry in IMPLAN, while all construction events were modeled using the “construction of new manufacturing structures” industry. For the events relating to the production of SAF and construction of relevant facilities, the input industry sales, value added, labor income, and employees were set according to values from the operational models described in Section 5. Additionally, the industry spending pattern for each event was modified to reflect the inputs more closely from the operational models.

The inputs for the ethanol operations and construction events were based off the Iowa State ethanol profitability model. These inputs were adjusted using DIS estimates of ethanol revenue and costs for plants sequestering CO2 and receiving the 45Z tax credit and for plants capturing CO2 for use and receiving the 45Q tax credit. Three ethanol events were analyzed, and the model outputs presented in the report reflect a weighted average of conventional (unadjusted) ethanol production (10%), ethanol production with a 45Z tax credit (45%) and ethanol production with a 45Q tax credit (45%).

All models in IMPLAN were run using the most recent data available (2022). Construction events were run and output in current (2023) dollars. This assumes that the inflation rate for construction costs is roughly similar to the general rate of inflation moving forward until 2050. The operations events are meant to capture the full extent of the SAF production industry once all facilities are fully operational in 2050. These events were output from IMPLAN at dollar year 2050 using the built-in inflation modifiers within IMPLAN and adjusted back to 2023 dollars assuming a 2% average inflation rate.

11 Research Implications/Suggestions for Further Research

Estimation of the interactive aspects of changes in corn supply and demand for multiple years in the future would provide greater understanding of how supply/demand balances would affect other users of corn such as livestock producers and exports as well as how other crops might adjust to the changes occurring in corn production and utilization. A multi-year, general equilibrium or partial equilibrium model would assist in such estimates and reduce some of the uncertainty around long-term forward estimates.

As the SAF production industries advance and more scaled-up production comes online, the uncertainty surrounding the indirect and induced impacts of SAF production should be able to be reduced. Updates with more complete estimates of these impacts could be developed as the industry matures.

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13Appendix

13.1 Jet Fuel Specifications[14]

Jet fuel specifications are defined in ASTM D1655, Standard Specification for Aviation Turbine Fuels (ASTM 2019a). ASTM has defined the steps for qualification and approval of new aviation turbine fuels in ASTM D4054, Standard Practice for Evaluation and Approval of New Aviation Turbine Fuels and Fuel Additives (ASTM 2019b). Finally, there is a specification for SAF, ASTM D7566, Standard Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons (ASTM 2019c). A fuel meeting these specifications is fully fungible. Maintaining jet fuel properties is critical. Meeting the specifications outlined in ASTM D7566 Table 1, Parts 1 and 2, and the associated D7566 annex ensures the necessary performance and operability requirements are met (ASTM 2019c).

Fuel properties needed in SAF must meet three general requirements: (1) performance, (2) operability, and (3) drop-in compatibility.

Figure 53 provides a graphical illustration of the four families of hydrocarbons in jet fuel and a summary of the properties imparted by each hydrocarbon class.

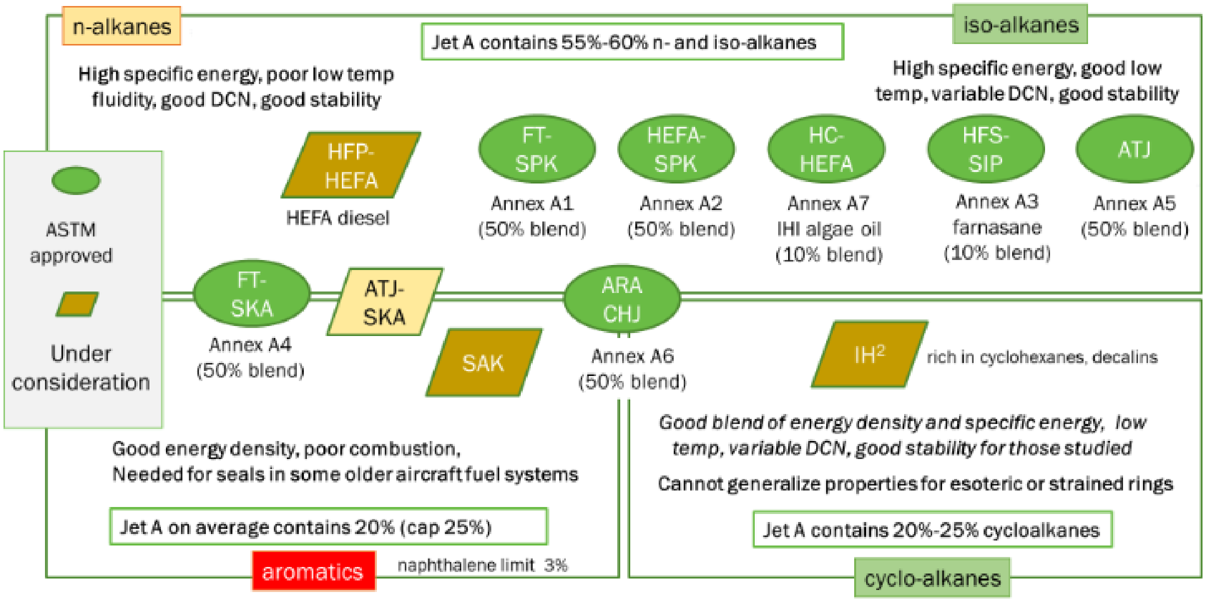

Figure 53. Summary of Four Classes of Hydrocarbons

13.2 How Is Jet Fuel Similar to and Different from Other Transportation Fuels?

Gasoline, jet, and diesel fuels are mostly blended mixtures of several hundred different hydrocarbon molecules. Molecules in gasoline fuel range from those containing 4 carbon atoms to those containing 12 carbon atoms. Gasoline has an initial boiling point at atmospheric pressure of about 35°C and a final boiling point of about 200°C. Molecules in jet fuel range from those containing 8 carbon atoms to those

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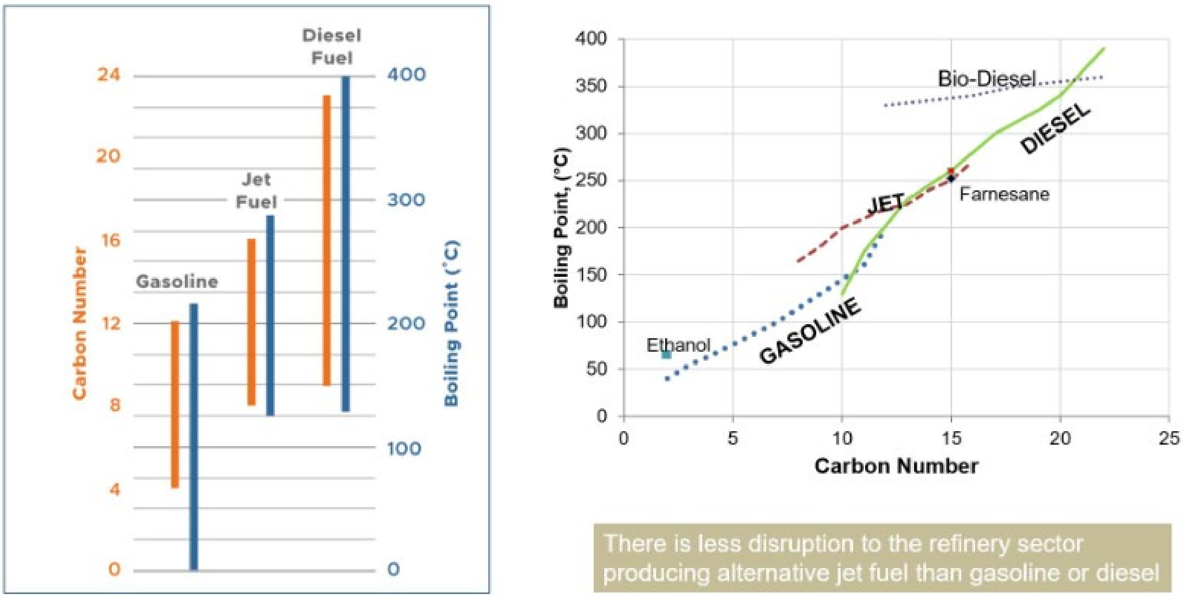
[14] Chapter 2 Jet Fuel Specifications from https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf

containing 16 carbon atoms. Jet fuel has an initial boiling point at atmospheric pressure of about 125°C and a final boiling point of about 290°C. Molecules in diesel fuel range from those containing 8 carbon atoms to those containing 23 carbon atoms. Diesel has an initial boiling point at atmospheric pressure of about 150°C and a final boiling point of about 380°C.

As shown in Figure 54, jet fuel is the middle distillate product between gasoline and diesel. There is significant overlap in the boiling point range of gasoline and jet fuel, and almost complete overlap in the boiling point range between jet fuel and diesel. These overlaps have several implications from the perspective of fuel producers.

First, if a process produces molecules that have a broad range of boiling points spanning those of gasoline, jet, and diesel, then collection of the jet fuel fraction through distillation will need to be done in a way so neither the gasoline nor diesel stream is compromised, which can affect the amount of jet fuel recovered. Otherwise, the gasoline fraction is left with only light volatile components (4–8 carbons in length) and the diesel fraction is composed of a distribution with the heaviest fractions.



There is less disruption to the refinery sector producing alternative jet fuel than gasoline or diesel

Figure 54. Carbon Numbers and Boiling Points for Gasoline, Jet, and Diesel Fuels

Second, the almost complete overlap of the boiling point ranges of jet fuel and diesel allows a refinery to select which product to make depending on market conditions and other incentives. For example, if the market value of diesel is higher than that of jet fuel, then a refinery would be incentivized to produce diesel rather than jet fuel. This would be particularly true if a refinery can have good control of the boiling point range and does not have to distill out the lower-value heavy components. Today, biorefiners are producing renewable diesel at the expense of renewable jet fuel.

Third, if all jet fuel were replaced with SAF (in a long-term scenario), refiners would still have a home for all the fractions they produce. Today, many refineries do not produce jet fuel. Figure 4 shows 2018 domestic biofuel production. U.S. production of renewable diesel exceeded 300 million gallons. SAF, made with the same technology, was two million gallons. While there is some difference in production cost, the difference in renewable diesel production and SAF production is driven by policy.

13.3 SAF Production Pathways

The pathways below from the U.S. Department of Energy, Alternative Fuels Data Center, represent only those currently approved by ASTM. Processes and tests exist for the approval of other feedstocks, fuel molecules, and blending limits, and the types of approved fuels will increase as these are evaluated through this process.

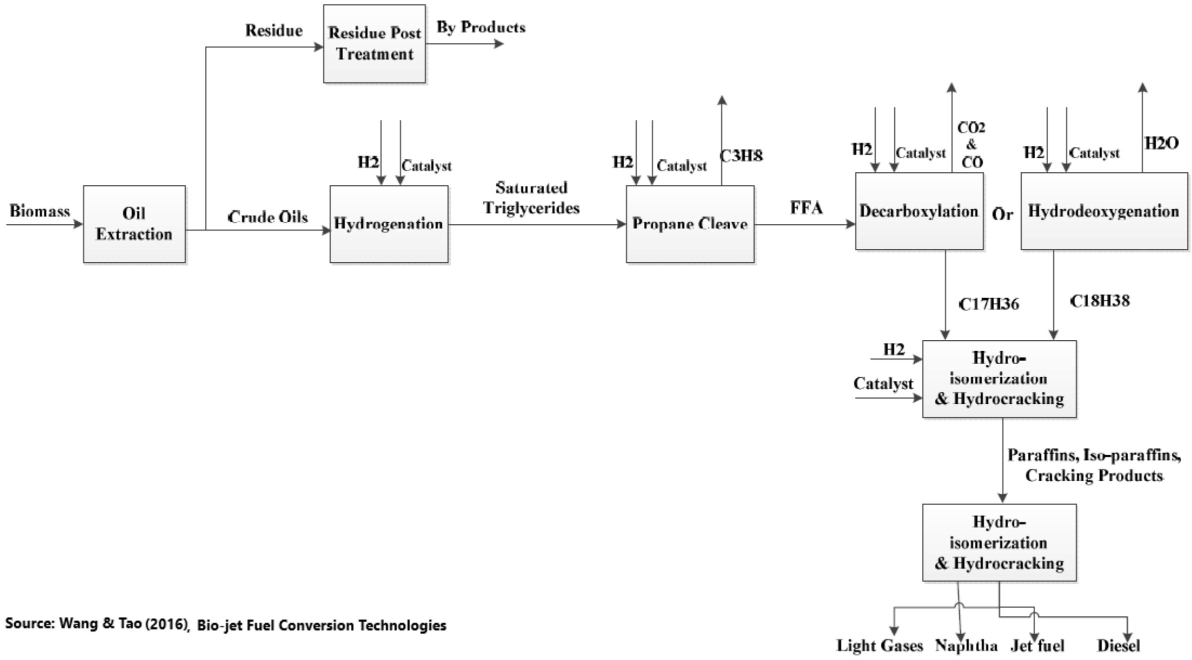
Pathway	Approved Name	Blending Limitation	Feedstocks	Chemical Process
Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)	FT-SPK, ASTM D7566 Annex A1, 2009	50%	Municipal solid waste, agricultural and forest wastes, energy crops	Woody biomass is converted to syngas using gasification, then a Fischer-Tropsch synthesis reaction converts the syngas to jet fuel. Feedstocks include various sources of renewable biomass, primarily woody biomass such as municipal solid waste, agricultural wastes, forest wastes, wood, and energy crops. ASTM approved in June 2009 with a 50% blend limit.
Hydroprocessed Esters and Fatty Acids (HEFA)	HEFA-SPK, ASTM D7566 Annex A2, 2011	50%	Oil-based feedstocks (e.g., jatropha, algae, camelina, and yellow grease)	Triglyceride feedstocks such as plant oil; animal oil; yellow or brown greases; or waste fat, oil, and greases are hydroprocessed to break apart the long chain of fatty acids, followed by hydroisomerization and hydrocracking. This pathway produces a drop-in fuel and was ASTM approved in July 2011 with a 50% blend limit.
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	HFS-SIP, ASTM D7566 Annex A3, 2014	10%	Sugars	Microbial conversion of sugars to hydrocarbons. Feedstocks include cellulosic biomass feedstocks (e.g., herbaceous biomass and corn stover). Pretreated waste fat, oil, and greases also can be eligible feedstocks. ASTM approved by ASTM in June 2014 with a 10% blend limit
FT-SPK with Aromatics	FT-SPK/A, ASTM D7566 Annex A4, 2015	50%	Municipal solid waste, agricultural and forest wastes, energy crops	Biomass is converted to syngas, which is then converted to synthetic paraffinic kerosene and aromatics by FT synthesis. This process is similar to FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components. ASTM approved in November 2015 with a 50% blend limit.

Alcohol-to-Jet Synthetic Paraffinic Kerosene	ATJ-SPK, ASTM D7566 Annex A5, 2016	30%	Cellulosic biomass	Conversion of cellulosic or starchy alcohol (isobutanol and ethanol) into a drop-in fuel through a series of chemical reactions—dehydration, hydrogenation, oligomerization, and hydrotreatment. The alcohols are derived from cellulosic feedstock or starchy feedstock via fermentation or gasification reactions. Ethanol and isobutanol produced from lignocellulosic biomass (e.g., corn stover) are considered favorable feedstocks, but other potential feedstocks (not yet ASTM approved) include methanol, iso-propanol, and long-chain fatty alcohols. ASTM approved in April 2016 for isobutanol and in June 2018 for ethanol with a 30% blend limit.
Catalytic Hydrothermolysis Synthesized Kerosene	CH-SK or CHJ, ASTM D7566 Annex A6, 2020	50%	Fatty acids or fatty acid esters or lipids from fat oil greases	(Also called hydrothermal liquefaction), clean free fatty acid oil from processing waste oils or energy oils is combined with preheated feed water and then passed to a catalytic hydrothermolysis reactor. Feedstocks for the CH-SPK process can be a variety of triglyceride-based feedstocks such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil. ASTM approved in February 2020 with a 50% blend limit.
Hydrocarbon-Hydroprocessed Esters and Fatty Acids (HEFA)	HC-HEFA-SPK, ASTM D7566 Annex A7, 2020	10%	Algal oil	Conversion of the triglyceride oil, derived from *Botryococcus braunii*, into jet fuel and other fractionations. *Botryococcus braunii* is a high-growth alga that produces triglyceride oil. ASTM approved in May 2020 with a 10% blend limit.
Fats, Oils, and Greases (FOG) Co-Processing	FOG Co-Processing ASTM D1655 Annex A1	5%	Fats, oils, and greases	ASTM approved 5% fats, oils, and greases coprocessing with petroleum intermediates as a potential SAF pathway. Used cooking oil and waste animal fats

				are two other popular sources for coprocessing.
FT Co-Processing	FT Co-Processing ASTM D1655 Annex A1	5%	FT biocrude	In association with the University of Dayton Research Institute, ASTM approved 5% Fischer-Tropsch syncrude coprocessing with petroleum crude oil to produce SAF.
Source: U.S. Department of Energy, Alternative Fuels Data Center				

13.3.1 HEFA (Hydro-processed Esters and Fatty Acids)

HEFA-SPK, is an important type of sustainable aviation fuel produced from lipids. In a chemical process (Figure 55), triglyceride feedstocks including plant oil; animal oil; yellow or brown greases; or waste fat, oil, and greases are hydroprocessed to break apart the long chain of fatty acids. The next steps in the process are hydroisomerization and hydrocracking. The HEFA pathway manufactures a drop-in fuel, which was ASTM approved in July 2011 with a top blend of 50% (Alternative Fuels Data Center: Sustainable Aviation Fuel (energy.gov)).



Source: Wang & Tao (2016), Bio-jet Fuel Conversion Technologies

Figure 55. Hydro-processed Renewable Jet HRJ, Also Known as HEFA, Process[15]

Based on SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel Report (energy.gov), the lipids feedstocks to produce SAF through the HEFA pathway will make up the bulk of the feedstock used to reach the US. goal of 3 billion gal/year by 2030. Yet, other pathways such as starch-and-sugar-based feedstocks are arising as prospective near-term feedstock for SAF thought the ATJ pathway.

13.3.2 Ethanol to Jet (ETJ)

Pathway: Alcohol-to-Jet Synthetic Paraffinic Kerosene

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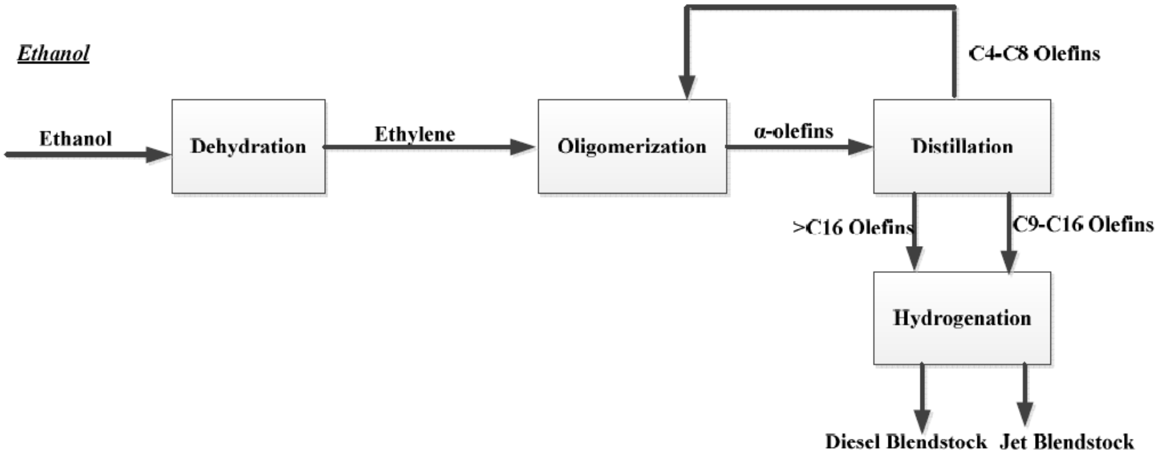
[15] Source: Wang & Tao (2016). Bio-jet fuel conversion technologies (sciencedirectassets.com)

Alcohol to Jet (ATJ fuel), also called alcohol oligomerization, is fuel converted from alcohols, such as methanol, ethanol, butanol, and long-chain fatty alcohols. The maximum use of ethanol is 10-15% for the majority of gasoline-powered vehicles on the road today, which creates a blend wall that makes it difficult to achieve further market penetration of ethanol as a blend stock for gasoline. Therefore, upgrading ethanol to jet fuel blend stock presents a potential pathway for developing drop-in or fungible fuels for the jet fuel market.

The process (Figure 56) of producing ethanol to jet fuel involves the conversion of cellulosic or starchy alcohol (isobutanol and ethanol) into a drop-in-fuel by a series of chemical reactions. The alcohols are obtained from cellulosic feedstock or starchy feedstock via fermentation or gasification reactions. Favorable feedstocks to produce ethanol and isobutanol are lignocellulosic biomass (e.g., corn stover) and the maximum blend ratio is 30%. ASTM specification D7566 Annex A4 (Alternative Fuels Data Center: Sustainable Aviation Fuel (energy.gov)). The pathway was approved in 2015.

The process includes alcohol dehydration, oligomerization, distillation, and hydrogenation. According to Wang & Tao (2016), all the steps in the ethanol to jet fuel process described below have been demonstrated on a commercial relevant scale and the risk of scale-up is expected to be reduced.



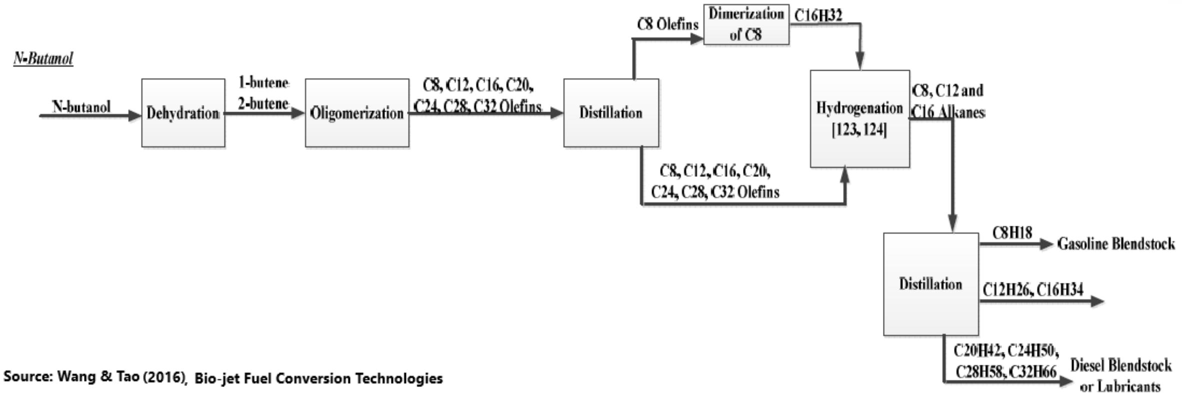
Source: Wang & Tao (2016), Bio-jet Fuel Conversion Technologies

Figure 56. Ethanol to Jet Fuel Process

According to U.S. Department of Energy's Sustainable Aviation Fuel Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel report, the current corn ethanol industry has large potential in the short run to expand SAF production quantities using the ATJ pathway if carbon capture and sequestration is enabled. Lowering the carbon intensity and expanding the carbon efficiency of corn ethanol are important hurdles to overcome to accomplish this potential.

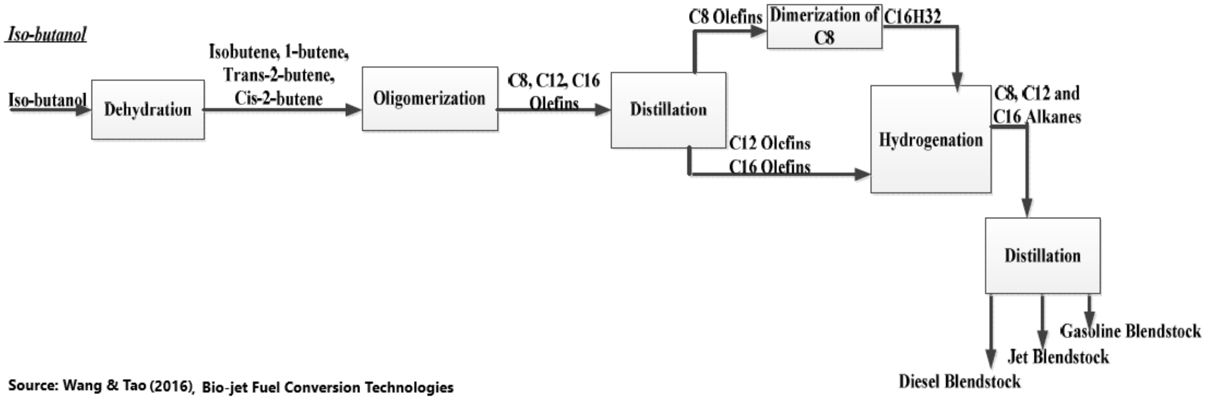
13.3.3 Other alcohol to Jet processes

There are two other alcohol-to-jet (ATJ) processes that have been approved. One is taking N-Butanol (Figure 57) to Jet and the other is taking isobutanol (Figure 58) to jet fuel.



Source: Wang & Tao (2016), Bio-jet Fuel Conversion Technologies

Figure 57. N-Butanol to Jet Process



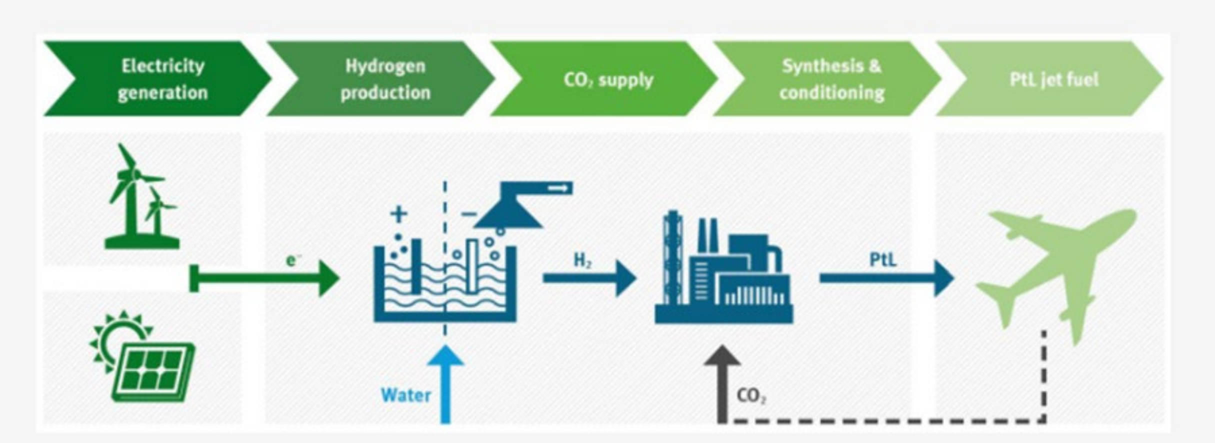
Source: Wang & Tao (2016), Bio-jet Fuel Conversion Technologies

Figure 58. Iso-butanol to Jet Process

13.3.4 Power-to-Fuel (PTF) – from CO2 and Renewable Energy

The power-to-Fuel (PTF) also called Power-to-Liquid jet fuel (PtL) process produces fuels using electrolysis of renewable electricity and direct-air capture and conversion of atmospheric CO2. The process involves large volumes of electricity from low carbon sources such as solar and wind power to bring down emissions (Taheripour et al (2023)). The resulting fuel is a lower carbon intensity alternative to conventional fuels. The PTF simplified diagram is shown in Figure 59. Using renewable energy, the mixing of carbon captured CO2 and hydrogen produces SAF.

According to Taheripour et al (2023), increasing renewable sources of energy could potentially lead to an increase in land demand and result in land use changes and generate land use change emissions, which should be considered as it has been considered for biofuel production[16].

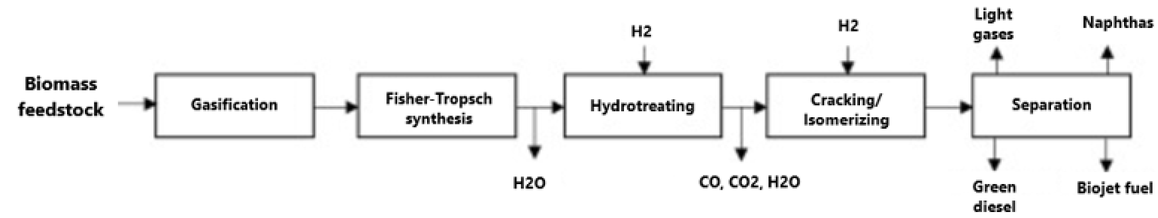


Power to Liquid Fuel Process | Source: https://www.icao.int/environmental-protection

Figure 59. Simplified Description of Power-to-Liquid Fuel for SAF[17]

13.3.5 Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)

In this process of producing jet fuel, woody biomass is converted to syngas using gasification. The Fischer-Tropsch synthesis reaction converts syngas to jet fuel (Figure 60 and Figure 61). There are several feedstocks used in this process including various sources of renewable biomass, particularly woody biomass such as municipal solid waste (MSW), agricultural wastes, forest wastes, wood, and energy crops. ASTM approved in June 2009 and there is a 50% blend limit *(*Alternative Fuels Data Center: Sustainable Aviation Fuel (energy.gov)).



Source: Chong & Ng (2021), Biojet fuel production pathways (in Biojet fuel in aviation applications

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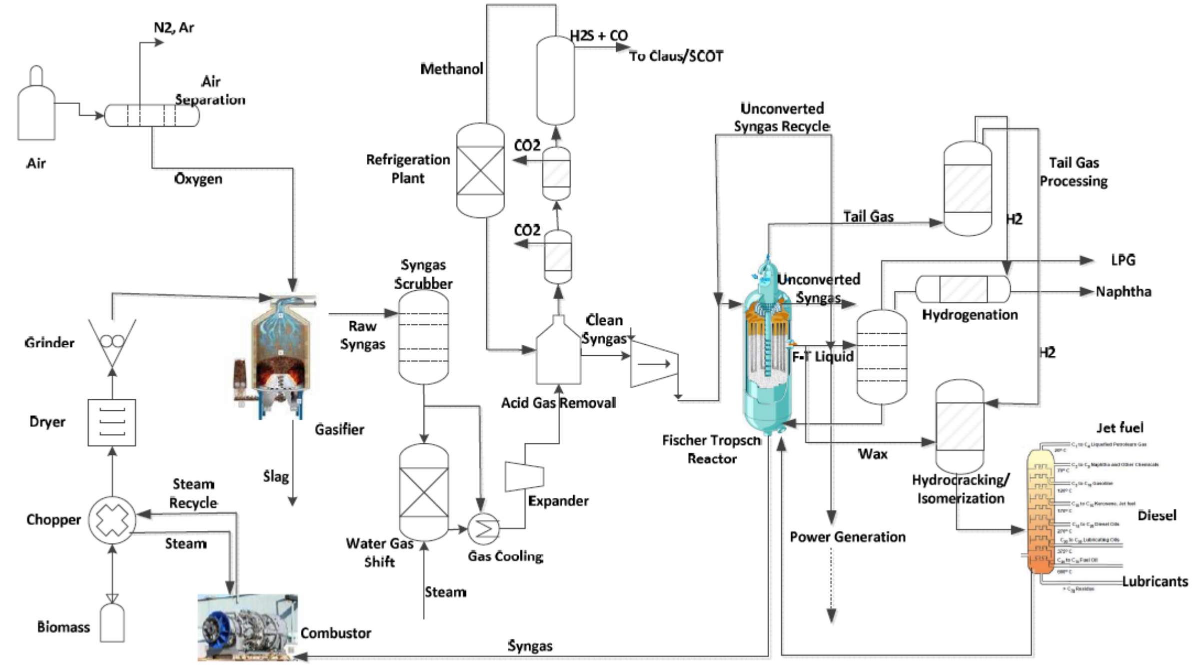
[16] Land use change implications of Power-to-Liquid Fuels (umn.edu)

[17] Chart source: Sustainable Review. Power-to-Liquid Fuel for Sustainable Aviation — Sustainable Review

Figure 60. Fisher Tropsch Biomass to Liquid Fuel Process: Simplified Diagram[18]



Source: Wang & Tao (2016), Bio-jet Fuel Conversion Technologies

Figure 61. Fisher Tropsch Biomass to Liquid Process[19]

13.3.6 Gasification and Pyrolysis

Using lignocellulosic feedstock from MSW, woody biomass, forest operation residuals, mill waste, agricultural residuals have the possibility to add marginally to the 2030 feedstock pool utilizing the gasification and pyrolysis SAF conversion pathways (SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel Report (energy.gov)).

The following table from Wang & Tao (2016) research shows a list of flight test with bio-jet fuels using different conversion pathways by commercial airlines (Table 42). As the table indicates, the most commonly used conversion pathway in these tests was based on oil to jet fuel.

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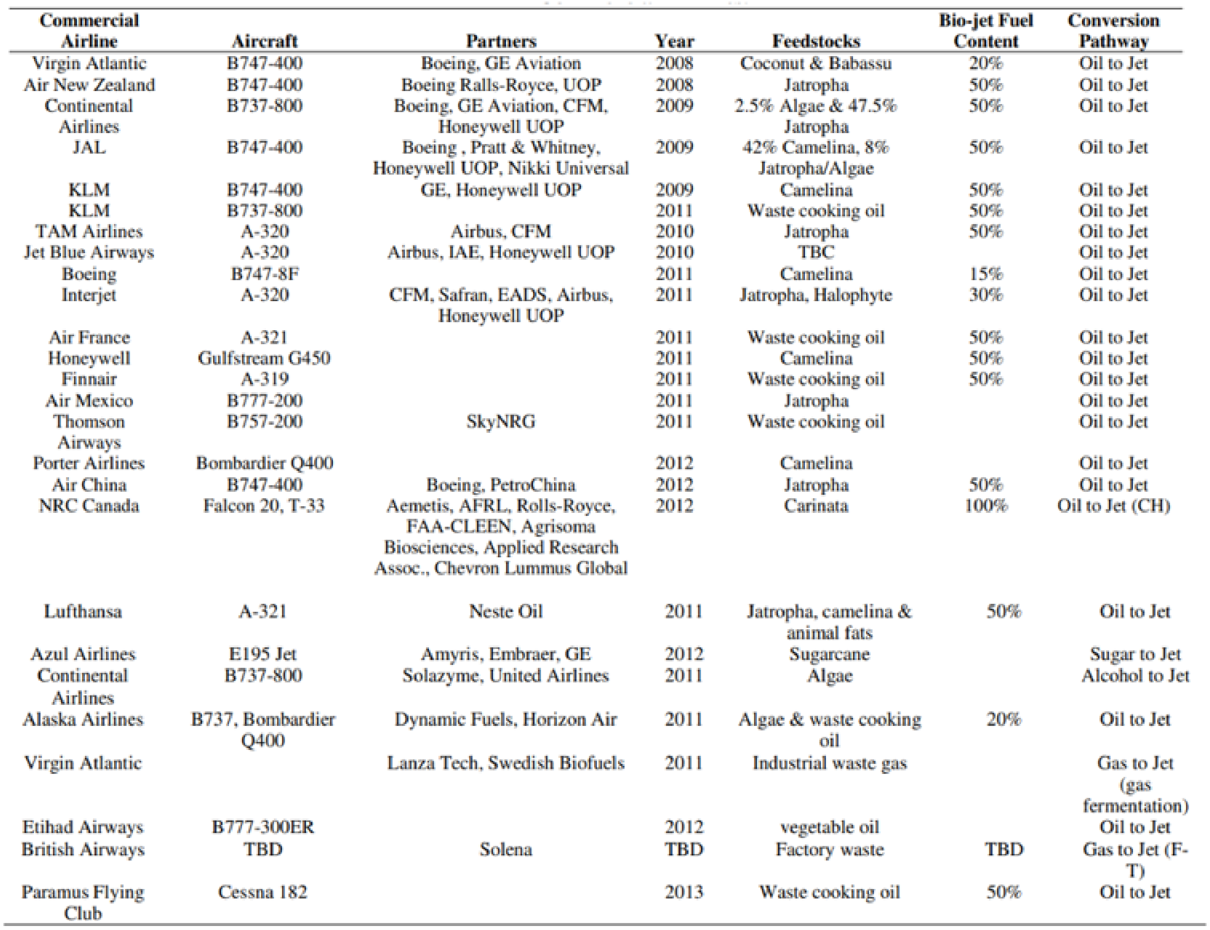
[18] Chong & Ng (2021). Biojet Fuel Production Pathways. https://www.sciencedirect.com/topics/engineering/fischer-tropsch-process

[19] Source: Wang & Tao (2016). Bio-jet fuel conversion technologies (sciencedirectassets.com)

Table 42. Flight Tests with Bio-Jet Fuels Through Different Conversion Pathways by Commercial Airlines



Commercial Airline	Aircraft	Partners	Year	Feedstocks	Bio-jet Fuel Content	Conversion Pathway
Virgin Atlantic	B747-400	Boeing, GE Aviation	2008	Coconut & Babassu	20%	Oil to Jet
Air New Zealand	B747-400	Boeing Ralls-Royce, UOP	2008	Jatropha	50%	Oil to Jet
Continental Airlines	B737-800	Boeing, GE Aviation, CFM, Honeywell UOP	2009	2.5% Algae & 47.5% Jatropha	50%	Oil to Jet
JAL	B747-400	Boeing , Pratt & Whitney, Honeywell UOP, Nikki Universal	2009	42% Camelina, 8% Jatropha/Algae	50%	Oil to Jet
KLM	B747-400	GE, Honeywell UOP	2009	Camelina	50%	Oil to Jet
KLM	B737-800		2011	Waste cooking oil	50%	Oil to Jet
TAM Airlines	A-320	Airbus, CFM	2010	Jatropha	50%	Oil to Jet
Jet Blue Airways	A-320	Airbus, IAE, Honeywell UOP	2010	TBC		Oil to Jet
Boeing	B747-8F		2011	Camelina	15%	Oil to Jet
Interjet	A-320	CFM, Safran, EADS, Airbus, Honeywell UOP	2011	Jatropha, Halophyte	30%	Oil to Jet
Air France	A-321		2011	Waste cooking oil	50%	Oil to Jet
Honeywell	Gulfstream G450		2011	Camelina	50%	Oil to Jet
Finnair	A-319		2011	Waste cooking oil	50%	Oil to Jet
Air Mexico	B777-200		2011	Jatropha		Oil to Jet
Thomson Airways	B757-200	SkyNRG	2011	Waste cooking oil		Oil to Jet
Porter Airlines	Bombardier Q400		2012	Camelina		Oil to Jet
Air China	B747-400	Boeing, PetroChina	2012	Jatropha	50%	Oil to Jet
NRC Canada	Falcon 20, T-33	Aemetis, AFRL, Rolls-Royce, FAA-CLEEN, Agrisoma Biosciences, Applied Research Assoc., Chevron Lummus Global	2012	Carinata	100%	Oil to Jet (CH)
Lufthansa	A-321	Neste Oil	2011	Jatropha, camelina & animal fats	50%	Oil to Jet
Azul Airlines	E195 Jet	Amyris, Embraer, GE	2012	Sugarcane		Sugar to Jet
Continental Airlines	B737-800	Solazyme, United Airlines	2011	Algae		Alcohol to Jet
Alaska Airlines	B737, Bombardier Q400	Dynamic Fuels, Horizon Air	2011	Algae & waste cooking oil	20%	Oil to Jet
Virgin Atlantic		Lanza Tech, Swedish Biofuels	2011	Industrial waste gas		Gas to Jet (gas fermentation)
Etihad Airways	B777-300ER		2012	vegetable oil		Oil to Jet
British Airways	TBD	Solena	TBD	Factory waste	TBD	Gas to Jet (F-T)
Paramus Flying Club	Cessna 182		2013	Waste cooking oil	50%	Oil to Jet

Source: Wang & Tao (2016), Bio-jet Fuel Conversion Technologies

13.4 SAF Production Pathways - Categorization

LEK categorized the four predominant production pathways for sustainable aviation fuels with each pathway characterized by different constraints on either technological readiness, feedstock availability and current limitations on blending.

13.4.1 HEFA

On a scale of 1 to 10, HEFA-SAF is rated 8-9 for technological maturity. The processes are known, and the technology exists to convert hydroprocessed esters and fatty acids into SAF. The most limiting factor for HEFA-SAF will be feedstock availability. Plant-based oil production (soybeans, canola, palm, etc.) can be increased, but the level of such increase is quite limited. Animal fat production supplements the available fat supplies but growth in animal-based fats is even more limited than plant-based oils.

13.4.2 ATJ

Alcohol to Jet as defined by LEK includes both alcohols from cellulosic production and corn-based ethanol. LEK characterizes the technological maturity of alcohol-to-jet as 7-8. In the U.S. the corn-based ethanol production of alcohol probably rates a technological maturity of 9-10 with the primary limitation technology-wise being the permitting of CO2 capture and sequestration via pipelines. Again, this is not so much a technological limiting factor as it is a geo-political factor. For cellulosic alcohol to jet, the limitations are more cost-related as the processes that now exist are technologically feasible, but they are generally not cost competitive with corn-based alcohols. Feedstock availability is a limiting factor for both corn-based ETJ and for cellulosic ATJ, although corn yields are likely to increase sufficiently to allow current uses of corn with trend line use increases to continue with enough "extra" corn to eventually provide enough ethanol for nearly 9 billion gallons of ETJ-SAF by 2050. Feedstock limitations for other ATJ (cellulosic-based alcohols) include cost of transport and limitations on agricultural and forest residuals.

13.4.3 FT

LEK characterizes gasification through Fischer-Tropsch processes as a 6-7 for technological maturity. While technically feasible, somewhat similar to cellulosic ATJ, the cost of the process tends to be higher than making fuels from HEFA or from corn-based ethanol. Feedstock supplies are limited and tend to be costly to transport or can lead to environmental degradation if the residuals are fully removed from the land. Use of municipal solid waste does offer some expansion of the available feedstocks but even this supply stream has a number of logistical limitations.

13.4.4 PtL or PTF

Power-to-Liquid or PTF-SAF has the lowest technological maturity rating according to LEK with a rating of 6. With technological advances it is expected that PTF-SAF will become much more cost competitive in the next 15-20 years. The technology to extract hydrogen via electrolysis and combine that hydrogen with CO2 that is either captured (such as from ethanol production or other industrial streams) offers great promise. In the short term, CO2 captured from ethanol production offers the most cost-effective supply of CO2 although this supply route needs development of advanced carbon capture to enable sufficient scale. In the long term, the supply of industrial-based CO2 is limited but a nearly unlimited supply of CO2 can be obtained through direct air capture. The technology for direct air capture of CO2 is very immature at present.

13.5 Global SAF Pathway(s)

Prior to the COVID pandemic, jet fuel demand globally was running very close to 8 million barrels per day (bpd) which converts to approximately 122 billion gallons per year (gpy). Total commercial flights have returned to pre-pandemic levels, but improvements in fuel efficiency of the jet fleet and higher average load capacity of the planes in use has jet fuel consumption running nearly 13% below the levels of late 2019, early 2020. S&P Global Commodity[20] Insights expects daily jet fuel consumption to return to 8 million bpd in 2027.

Thunder Said Energy[21] projects a quicker recovery of jet fuel use to pre-pandemic levels with 2023 consumption being projected slightly above 2019 consumption levels. Thunder Said Energy projects growth in jet fuel use by nearly every region of the globe with the greatest absolute consumption increases arising from China and other Asian countries. Their projection of jet fuel use in 2050 is just under 18 million barrels per day which is approximately 274 billion gallons per year.

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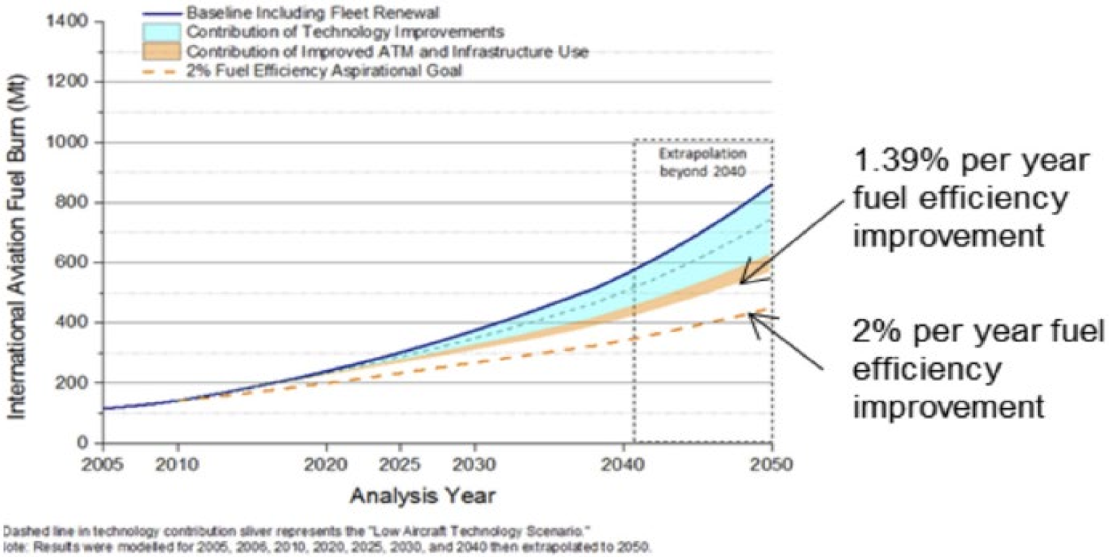
[20] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/oil/051923-global-jet-fuel-recovery-lags-air-travel-as-flights-return-to-pre-pandemic-levels

[21] https://thundersaidenergy.com/downloads/global-jet-fuel-demand-by-region-and-forecasts/

For the forecasts of jet fuel use globally by 2050, one of the major factors that affects the level of consumption in 2050 is the assumption regarding technological improvements as expressed in per-year fuel efficiency improvements. As shown in Figure 62, the baseline for total jet fuel consumption reaches approximately 840 million metric tons (mmt) [277 billion gallons] of consumption by 2050. With a 1.39% per year improvement in fuel efficiency, the consumption only rises to 580 mmt [192 billion gallons] and if a 2% per year annual improvement in fuel consumption efficiency is achieved then consumption only rises to 139 billion gallons. The greater the fuel efficiency achieved, the more likely that biojet fuels such as SAF can replace a significant portion of jet fuel use by 2050.



Dashed line in technology contribution sliver represents the "Low Aircraft Technology Scenario."
Note: Results were modelled for 2005, 2006, 2010, 2020, 2025, 2030, and 2040 then extrapolated to 2050.

Figure 62. Full Flight Fuel Burn[22]

13.6 Distribution of SAF

SAF must be blended with Jet A prior to use in an aircraft. If SAF is co-processed with conventional Jet A at an existing petroleum refinery, the fuel would flow through the supply chain in a business-as-usual model via pipeline to terminals and/or airports (Figure 63). It is expected that SAF produced at biofuels facilities would be blended with Jet A at existing fuel terminals and then delivered to airports by pipeline. There would be no change to airport fuel operations as the investment and blending would occur upstream at a fuel terminal. While it is possible to blend fuels at an airport, it is not ideal due to the need for additional equipment, staff, and insurance. Due to strict fuel quality standards, it is preferable to certify SAF as ASTM D1655 upstream of an airport.

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[22] Environmental Trends in Aviation to 2050, Gregg G. Fleming, USDOT, https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2016/ENVReport2016_pg16-22.pdf

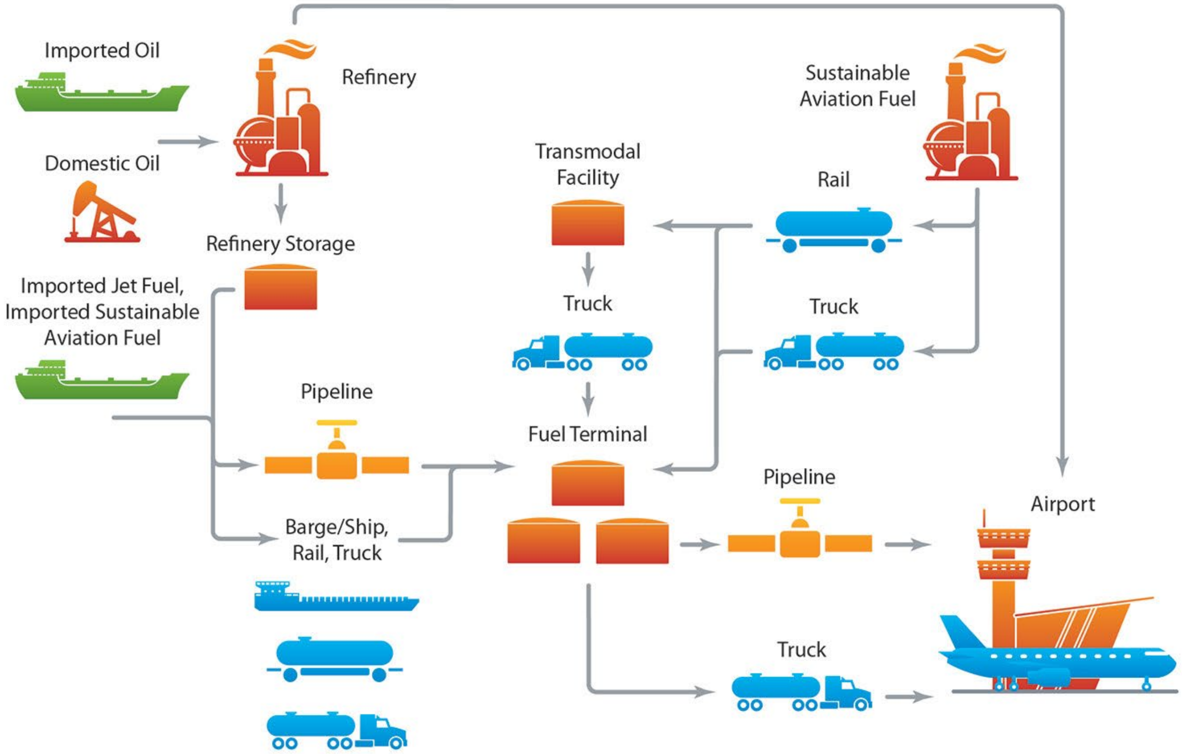


Figure 63. Distribution Model for SAF to Airports; Source: Alternative Fuels Data Center

Figure 64 shows the map of current major jet fuel pipelines that send jet fuel to major airports.

Figure 64. Pipeline Distribution of Jet Fuels; Source: https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf

Railways are also expected to be instrumental in the distribution of SAF. In 2023, Montana Renewables was the largest producer of SAF in North America and uses rail to distribute SAF to major airports in the western U.S. and in western Canada (Figure 65). SAF production that is being planned for southeastern Kansas will also use rail as a primary delivery mechanism for its SAF.

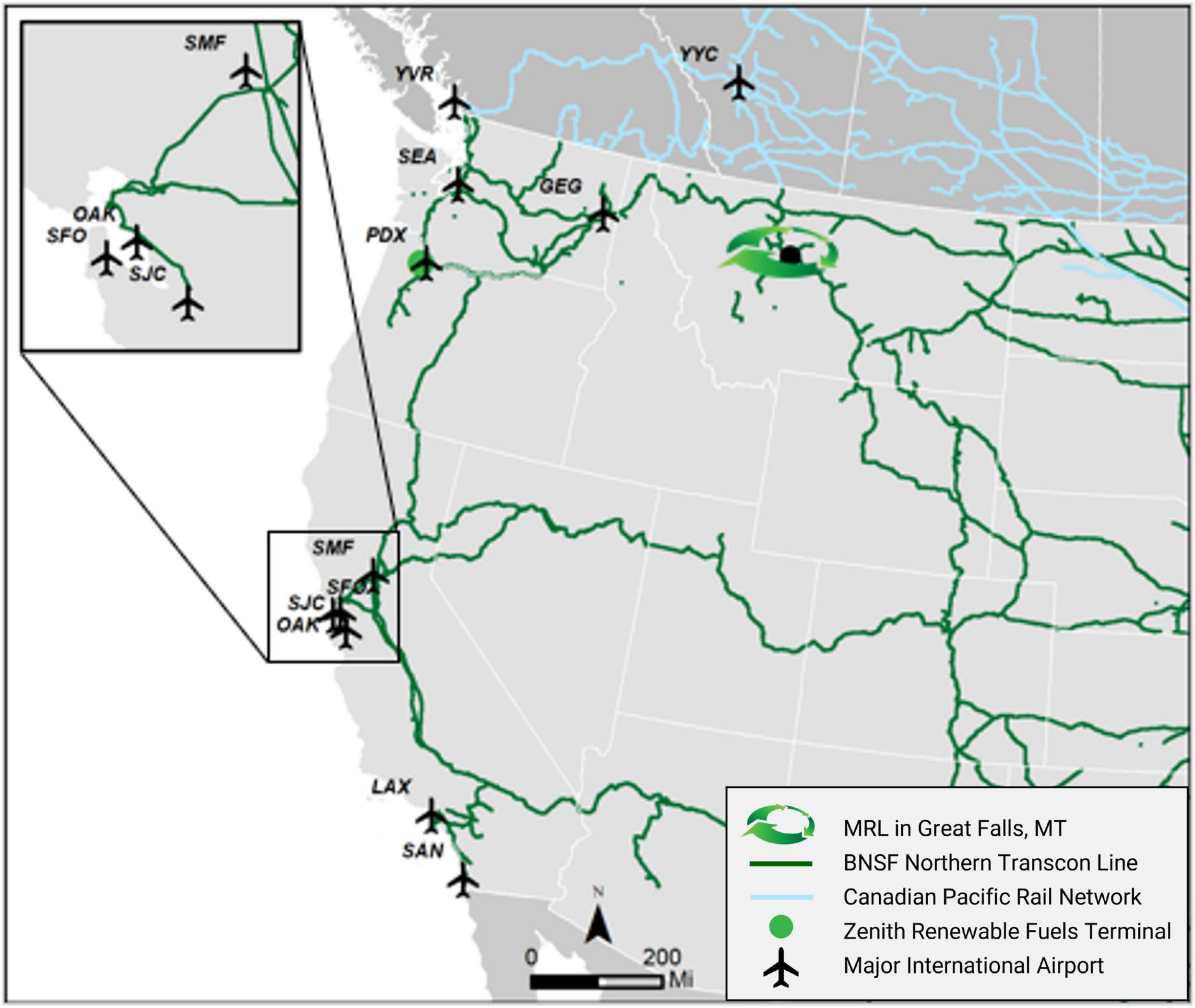
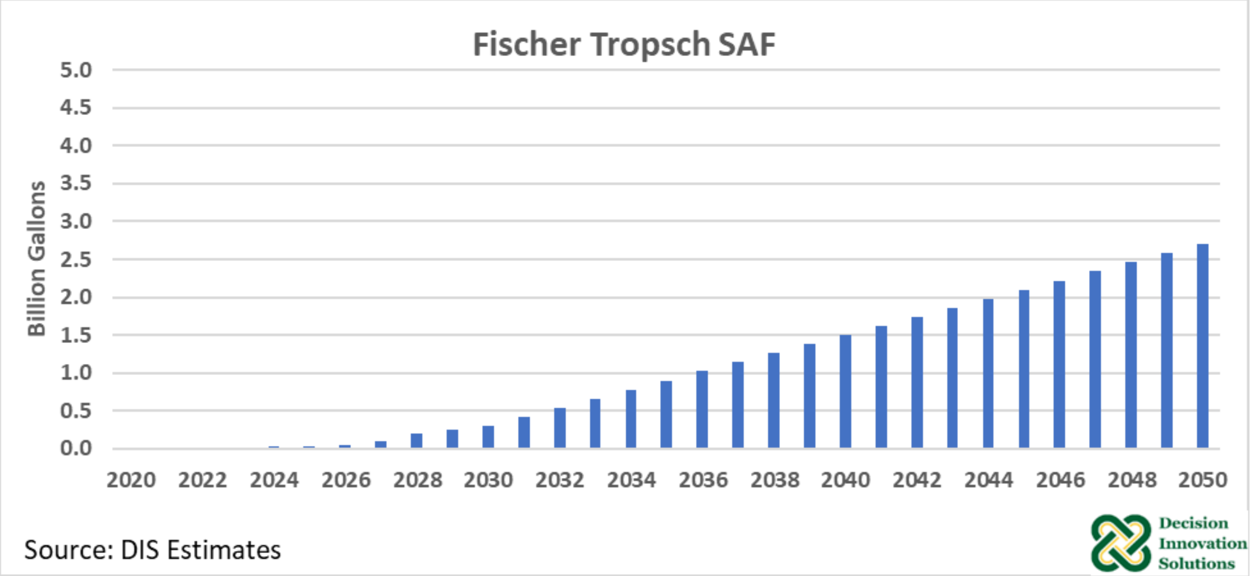


Figure 65. Railway Distribution of SAF from Montana Renewable Fuels

13.7 Fischer-Tropsch SAF (FT-SAF) Pathway

There are currently 3 approved FT-SAF processes. These processes convert solid biomass (including residual waste) into a synthetic gas and then processes the gas into a mixture of hydrocarbons including road and aviation fuels (often referred to as Biomass-to-Liquid - BtL). The feedstocks for FT-SAF are limited and the process of collecting, transporting, and processing solid biomass into a syngas and then into FT-SAF can be relatively costly compared to other pathways. McCurdy and ICF in a presentation at the 2023 SAF Leadership Summit presented a pathway for FT-SAF that begins with less than 10 million gallons of FT-SAF in 2023 and grows to about 300 million gallons of FT-SAF om 2030 and then rises to approximately 2.7 billion gallons of FT-SAF by 2050. For this report we have modeled the DIS FT-SAF pathway similar to the pathway presented by McCurdy and ICF at the 2023 SAF Leadership Summit (Figure 66).



Source: DIS Estimates

Figure 66. Fischer Tropsch SAF

13.8 Other Alcohol to Jet (ATJ-SAF) Pathway

There are a variety of global projections on the adoption of ATJ-SAF from non-corn ethanol feedstocks. McCurdy – ICF in their presentation at the 2023 SAF Leadership Summit presented a global pathway for SAF fuels that a very rapid expansion of ATJ-SAF after 2040 and nearly 14 billion gallons of ATJ-SAF by 2050 and suggested that ATJ-SAF could represent more than 50% of global SAF by 2050. We believe that pathway is too aggressive for ATJ-SAF adoption. Most of these pathways assume that cellulosic ethanol or cellulosic alcohols will be readily available and cost competitive with HEFA-SAF and ETJ-SAF.

The history of cellulosic alcohol production from agricultural wastes (corn stalks, grasses, straw), wood chips and other lignocellulosic materials has been one of under-performance, especially relative to corn-based alcohol production. In the Energy Independence and Security Act of 2007 (EISA), the original target was for cellulosic biofuel to reach 16 billion gallons of production by 2022. EPA has consistently reduced the cellulosic biofuel RIN volumes and the final RIN volume for cellulosic biofuels in 2023 is 0.84 billion RINs. Assuming a crediting rate of 1.7 D3 or D7 RINs for each gallon of cellulosic biofuels, this implies that there will be about 500 million gallons of cellulosic biofuels produced in 2023. This suggests that cellulosic biofuels make up about 2.4% of biofuels in 2023.

LanzaJet has developed an ATJ technology for commercial production of both sustainable aviation fuel and renewable diesel. Their process converts ethanol to Synthetic Paraffinic Kerosene (SPK) and Synthetic Paraffinic Diesel (SPD) (Figure 67). Their process is an approved pathway to produce SAF. The LanzaJet ATJ technology can process any source of sustainable ethanol, including ethanol produced from municipal waste, agricultural residues, industrial off-gases, and biomass. The Lanzajet flagship commercial facility, Freedom Pines Fuels located in Soperton, GA, is a 10 million gallon per year facility scheduled to be completed in late 2023 and begin fuel production in 2024.

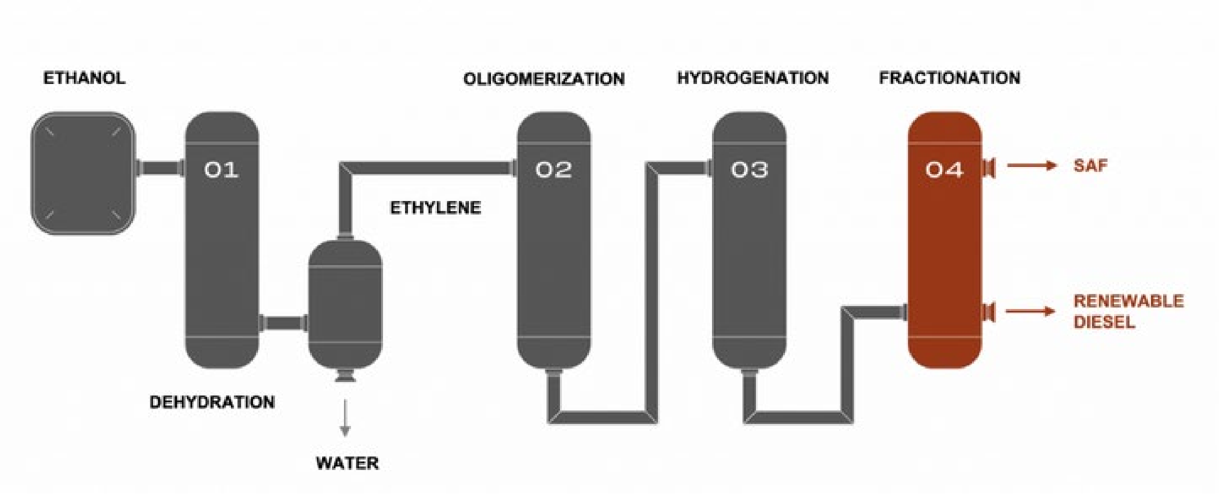


Figure 67. LanzaJet Process for Conversion of Alcohol to SAF and RD; Source: https://www.lanzajet.com/what-we-do/#technology

The DIS pathway for other ATJ_SAF Is significantly less aggressive with regards to inclusion of ATJ-SAF in our pathway to 2050 than the pathway put forward by McCurdy & ICF. DIS projects that 10 million gallons of ATJ-SAF will be produced in 2024 and that production of ATJ-SAF increases slowly to 70 million gallons of ATJ-SAF by 2040 and then increases to 100 million gallons of ATJ-SAF by 2033 and then stays at that level through the 2050 time period (Figure 68).

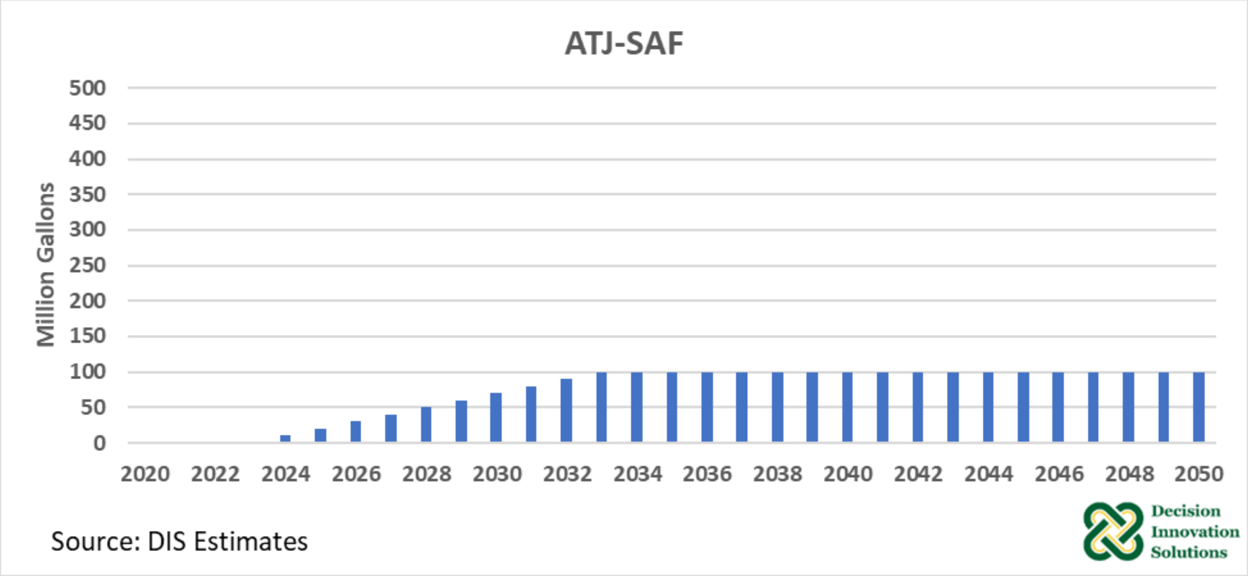
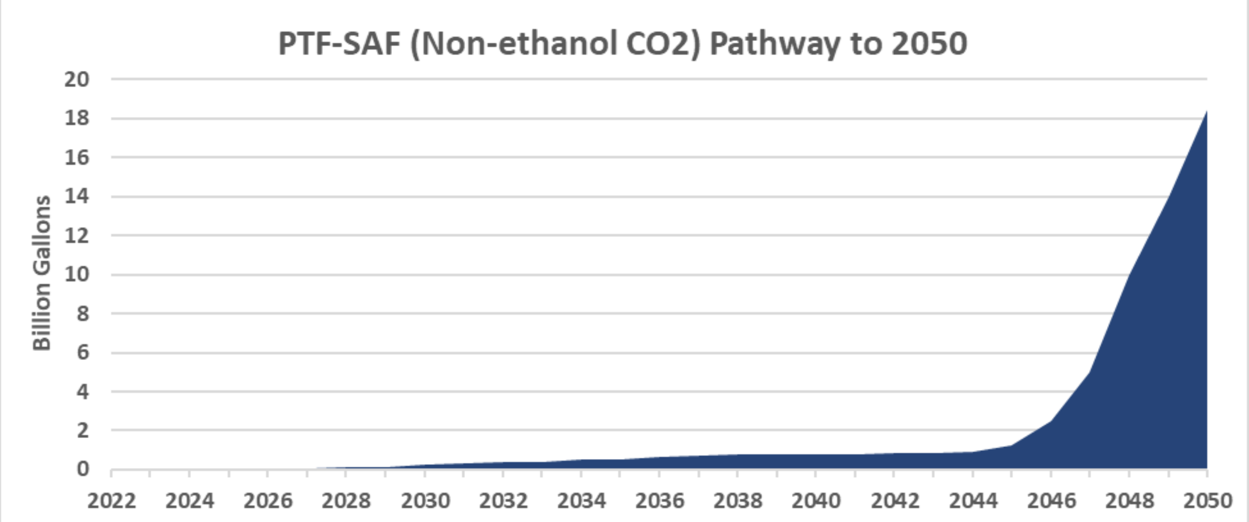


Figure 68. ATJ-SAF

13.9 PTF-SAF from non-corn ethanol feedstock sources

Air Company, Brooklyn, NY is currently producing small quantities of alcohols, chemicals, and fuel products from their trademarked process. The CO2 they use is captured from industrial plants prior to it being emitted into the atmosphere. Currently, it arrives at their facility in tanks after it has been cooled, pressurized and liquified. They create their own green hydrogen through on-site electrolysis with renewable energy. They use an electrolyzer to split water into hydrogen and oxygen with the oxygen gas being released as clean air into the atmosphere and the hydrogen gas being fed into a reactor with the captured CO2 and converted into reactor liquid that is composed of alcohols, alkanes and water. They then distill the reactor liquid into alcohols (ethanol and methanol), alkanes, and water. The alcohols and alkanes can then be converted into PTF-SAF.

Figure 69 depicts the DIS projected pathway for PTF-SAF from non-ethanol sourced CO2. Dis projects that 4 million gallons per year of PTF-SAF (non-ethanol) can come online in 2024, grow to 85 million gallons per year by 2030, and really begin to ramp up in 2042 as the supplies of CO2 from ethanol plants reaches utilization maturity and non-ethanol sources of CO2 are needed. DIS expects CO2 capture at ethanol plants to be relatively less costly than generation of CO2 from the atmosphere or capture of CO2 at other industrial facilities.



Source: DIS

Figure 69. PTF-SAF (Non-ethanol CO2) Pathway to 2050