DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

Production of Sustainable Aviation Fuels from Corn Stover via NREL's Deacetylation and Mechanical Refining Technology
"Project SAFFiRE"

WBS: **3.5.3.103**

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Systems Development and Integration Session B

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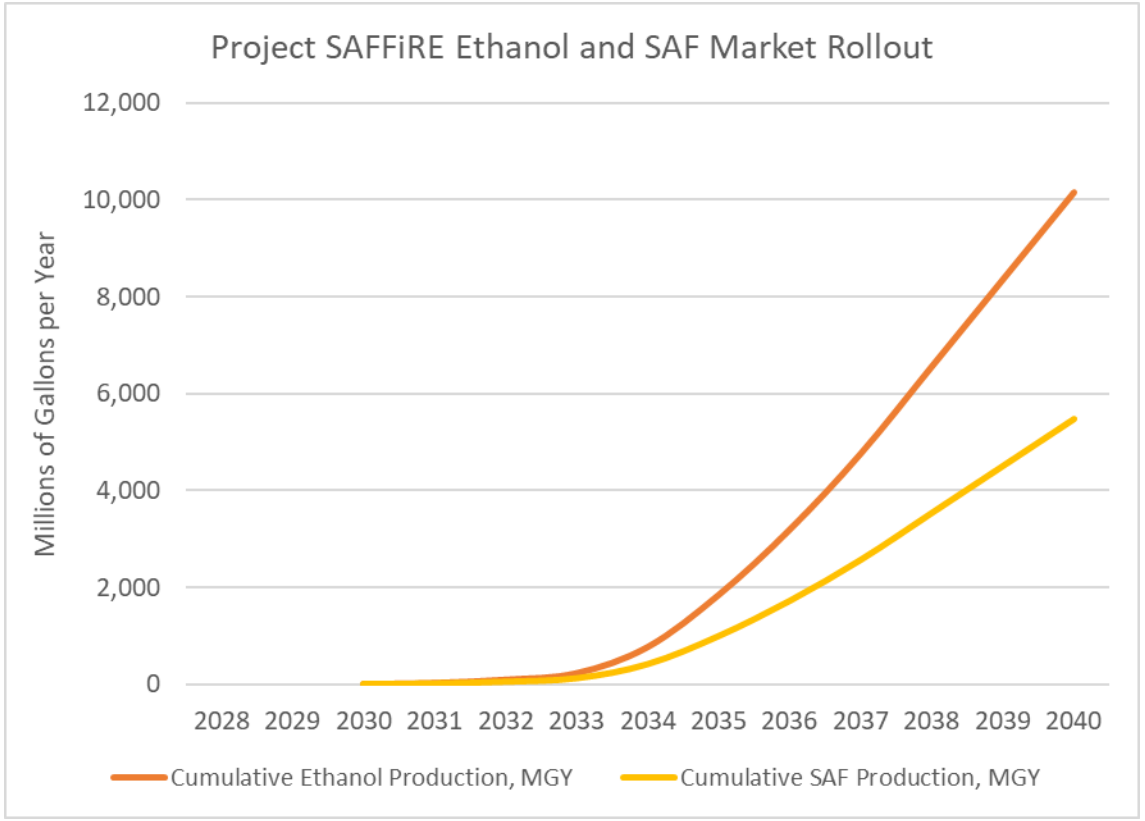
Project Overview

- Project SAFFiRE will demonstrate reliable, low-GHG production of ethanol from corn stover in a fully integrated, 10 ton per day pilot facility; the ethanol will be upgraded to Sustainable Aviation Fuel (SAF) by LanzaJet at their commercial Alcohol-to-Jet (AtJ) facility in Soperton, Georgia
- Meeting the global aviation industry's 2050 net zero GHG emissions goal will require massive amounts of SAF from many sources; 100+ billion gallons globally and 35 billion gallons in the U.S.
- Yet today, SAF's deployment has been limited by its high cost – due primarily to high feedstock and production costs
- Currently, SAF is produced primarily from supply-constrained, and thus expensive, fats, oils, and greases
  - Ultimately, more sources of lower-cost feedstocks are required to meet SAF demand
  - Agricultural residues and energy crops, such as corn stover, wheat straw and switchgrass, are a very large, underutilized, non-food resource for the production of ethanol for conversion to low carbon SAF
- Production costs must also be lowered over time to make SAF more affordable and more widely deployed
  - Utilizing existing ethanol infrastructure in the U.S. to facilitate SAF production could lower this cost
  - Alone, conversion of Generation 1 (Gen 1) ethanol to SAF cannot meet U.S. and global SAF demand, necessitating coupling with Gen 2 ethanol to SAF to help further these goals

Project SAFFiRE – Supporting BETO's Goals

- Our project supports the SAF Grand Challenge and BETO's goal to accelerate the bioeconomy and, in particular, the production of low-carbon fuels for the aviation industry
- Our goal is to produce 5.5 billion gallons of low-carbon SAF per year by 2040
- Our project also supports BETO's goal to leverage first generation ethanol plants in the U.S. to produce renewable hydrocarbons
- We estimate that co-locating SAFFiRE plants with Gen 1 ethanol plants will reduce the capital investment for each plant by ~30% and reduce labor costs by more than 80%

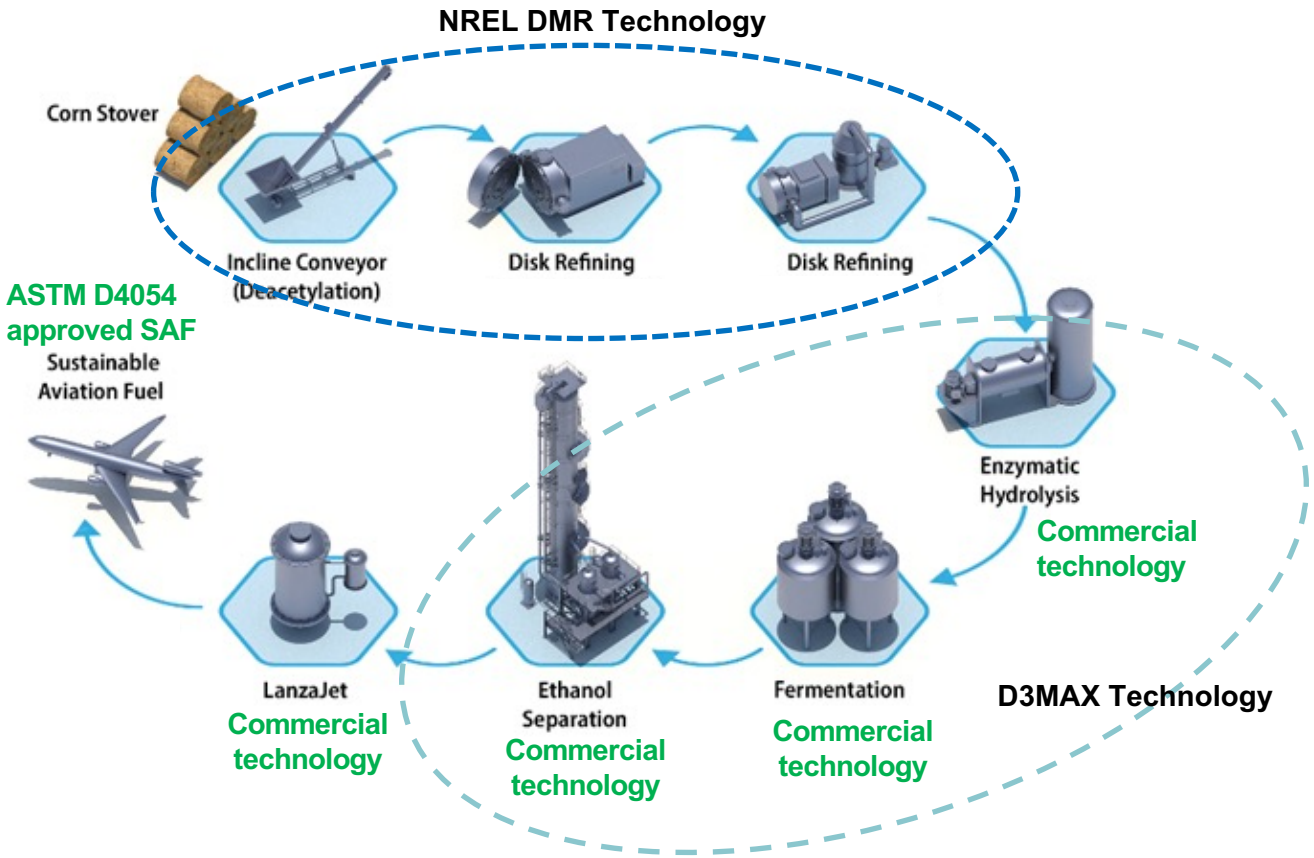


Approach – A new and improved pretreatment process from NREL

- Pretreatment is the key step in producing ethanol from corn stover; previous attempts to make ethanol from corn stover failed due, in part, to issues related to dilute acid pretreatment
- NREL's patent-pending, deacetylation and mechanical refining (DMR) pretreatment avoids the operational and capex challenges of dilute acid pretreatment by virtue of the following:
  - DMR is an alkaline pretreatment (high pH), eliminating corrosion issues and high cost alloys associated with dilute acid pretreatment
  - Dilute acid pretreatment solubilizes hemicellulose (primarily xylan) in biomass, whereas DMR solubilizes lignin, ash, and acetic acid; this is a completely different approach to pretreatment
  - Removing lignin, ash, and acetic acid during deacetylation, drastically improves enzymatic hydrolysis and fermentation performance
  - DMR operates at low temperatures (<100°C) and atmospheric pressure, reducing capex and eliminating issues related to feeding biomass into a high pressure reactor
  - DMR's low temperature does not produce fermentation inhibitors
  - DMR's low temperatures and deacetylation preserve valuable lignin properties, making lignin upgrading possible
  - DMR does not create lignin fouling, improving reliability and downstream operations

Approach – Low Technology Risk

- NREL and D3MAX technologies will be combined to produce ultralow carbon ethanol from corn stover (CI = 0)
- NREL has repeatedly demonstrated DMR pretreatment at pilot scale but in a batch mode; we will modify the NREL DMR design for continuous operation
- D3MAX has commercialized all remaining unit operations to produce cellulosic ethanol
- LanzaJet's first commercial-scale AtJ facility will be operational in 2024
- LanzaJet has received ASTM D4054 approval for its SAF



Approach – Project Goals

- Our primary goal for Phase 1 is to design a reliable, fully-integrated, 10 ton per day (tpd) pilot facility that will produce ethanol from corn stover for upgrading to SAF (in Phase 2)
- Additional Phase 1 goals include:
  - The pilot plant must demonstrate the technology that we plan to use in a commercial plant
  - Develop a Business Plan and corn stover supply chain for the pilot as well as a commercialization strategy
  - Update the Life Cycle Analysis (LCA) and Technoeconomic Analysis (TEA) that we submitted in our proposal to the 2021 Scale-up FOA
  - Complete all Phase 1 milestones and deliverables per our SOPO and Project Management Plan
- The Phase 1 pilot design and additional Phase 1 work must support BETO's goals:
  - The Phase 1 LCA and TEA must demonstrate >70% GHG reduction and <$2.75/GGE for SAF
  - In Phase 2 the pilot must operate 500 hours continuously with at least 1000 hours total run time

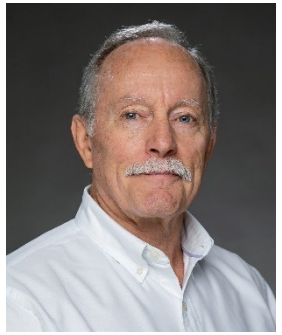
Approach – Key Strategies

- Use NREL's alkaline DMR pretreatment which solves the issues caused by dilute acid pretreatment seen in past projects
- Our technical approach includes developing a complete FEL 3 design package (with P&IDs) so that we can get accurate bids for the Phase 2 pilot fabrication
- Our pilot plant is large enough so that scale-up to our planned demonstration plant is reasonable; our pilot plant will be 10 tons/day of corn stover and our demonstration plant will process 200 tons/day: a reasonable 20:1 scale-up
  - Past commercial cellulosic ethanol plants were much too large (scale-ups exceeding 100:1) contributing to their failure
  - To reduce risk, our strategy is to start with a small demonstration plant after the pilot testing is complete, then double the plant size until we reach 1,600 ton/day (45 mgy ethanol; 24 mgy SAF)
  - We plan to grow without straining the feedstock supply in a given region (and eventually use other feedstocks such as wheat straw and switchgrass)

Approach – Key Strategies – continued

- Our pilot project is focused on demonstrating the SAFFiRE technology and seeks to avoid R&D as much as possible; use of commercially-available technologies, equipment, enzymes and yeasts will help further this strategy
- Co-location of the pilot and commercial plants with Gen 1 ethanol plants strategically reduces capex and opex costs
  - D3MAX pioneered this “co-location” strategy to reduce the capex and opex of the D3MAX cellulosic ethanol plant at Ace Ethanol in Stanley, WI; this plant converts the cellulose and hemicellulose in corn fiber to cellulosic ethanol
  - We estimate that the Ace Ethanol co-location resulted in ~30% capex savings and opex labor savings of more than 80%

Approach – Experienced Project Management Team



Mark Yancey
D3MAX CTO, Project Principal Investigator

- 30+ years of experience in the ethanol industry including project development and technology commercialization
- Developed seven bioenergy plants
- Successful commercialization of corn fiber cellulosic ethanol technology

Tom Nealon
SAFFiRE Renewables CEO, Executive Team Member

- Southwest Airlines Senior Advisor
- Former President and EVP of Strategy and Innovation at Southwest Airlines
- 30+ years of driving results at the executive level at Southwest Airlines, JCPenney, and Frito Lay

Michael AuBuchon
Southwest Airlines Co. Managing Director Fuel Strategy & Management

- 23 years' experience at Southwest Airlines
- Responsible for Southwest's planning and ultimate deployment of sustainable aviation fuel
- Manages billions of gallons of jet fuel for Southwest, including planning, scheduling, logistics, on- and off-airport storage and more

Mike Himmel
Co-PI and NREL Senior Fellow

- 40 years' experience in biofuels R&D; PhD in Biochemistry
- Published 500 papers and cited ~40,000 times.
- Mike has designed and supervised applied research in all aspects of the proposed work. Mike also built the first NREL biofuel pilot plant in 1983

Approach – Experienced Project Team

- To achieve our Phase 1 goals we have assembled a very experienced and capable project team with the skills needed to address all of the Phase 1 goals, milestones and deliverables

Approach – Challenges

- SAFFiRE's primary technical challenge is to ensure that the following success criteria for the pilot plant are met: ***reliability*, *throughput* and *yield***
  - Reliability – the process must be designed to facilitate the reliable processing of corn stover; to demonstrate this, the Phase 1 pilot plant design goals are 500 hours of continuous operation and at least 1,000 hours of total pilot plant operating time
  - Throughput – the process must meet the design throughput of 10 dry ton/day of corn stover
  - Yield – the process must meet the design yield of 80 gallons of ethanol per dry ton of corn stover
- A key risk for Project SAFFiRE is designing a pilot with reliable solids handling from receiving stover bales through saccharification (sugar production) where high viscosity is reduced to an easy to pump and mix liquid stream
- Additional challenges include:
  - Modifying NREL's batch pilot-scale DMR process to a continuous, integrated process
  - Lignin valorization ($350/ton target price) in a large market with sequestration of the lignin carbon
  - High process reliability (8,400 hour/year target for commercial plants) at design throughput
  - Designing and executing a feedstock supply chain for corn stover (for commercial plants)

Approach – Go/No-Go Decision Points

- Phase 1 has two Go/No-Go Critical Decision (CD) points:
  - Go/No-Go CD-1: Review Verification Outcome – complete
  - Go/No-Go CD-2: Approve Phase 2 Project Scope – occurs at the end of Phase 1 (Aug 31, 2023)
- NREL submitted the Task 1 Verification Report to DOE for review on Oct 2, 2022; approval was received to proceed with Budget Period 2 (BP-2) on Dec 2, 2022
- For CD-2, D3MAX must demonstrate that the project has all required plans in place, cost share funds available, and the expertise required to successfully execute Phase 2
- We believe the key issue for receiving approval to proceed with Phase 2 is the pilot plant design; the design must demonstrate that past issues for ethanol production from corn stover have been addressed:
  - Corn stover bale processing: we plan to use an established and reliable commercial design
  - Pretreatment: NREL has demonstrated DMR in batch pilot-scale tests; we will convert this to a continuous process with reliability of solids processing of upmost importance
  - All processes downstream of pretreatment are commercial and low technology risk; the high risk areas are processing the corn stover bales and high solids prior to enzymatic hydrolysis

Approach – Phase 1 Risks and Mitigation

Risk	Probability	Impact	Mitigation Plan
Corn stover not available	Low	High	A detailed corn stover supply plan will be developed; work with growers to address corn stover harvest issues; have multiple sources for corn stover; collect corn stover early and collect more than is needed
Stover bales are wet (wet stover can plug bale processing equip.)	Medium	Low	Have contingency plan to collect stover from an area where the stover has dried in the field (higher transportation costs); cover bales once collected and prevent condensation on bales; arrange for the use of a bale dryer
Bale processing is unreliable	Low	High	Use demonstrated technology; develop multiple sources for key equipment like the de-stringer and bale shredder, and be prepared to replace pilot equipment if necessary
Pretreatment is unreliable	Low	High	Test key equipment during Phase 1; minimize the possibility of equipment failure and plugging though attention to equipment/material selection and piping design and layout
Low ethanol yield	Medium	Low	Increase DMR chemical dose, increase enzyme dose, increase saccharification/fermentation time, pay attention to piping layout and CIP design
No market for lignin	Low	Medium	We will investigate using lignin in kraft mills, adhesives, asphalt, & concrete; our fallback plan is to pelletize the lignin and sell it in the fuel pellet market

Approach – Communication and Collaboration

- To disseminate information and progress to the SAF and ethanol industries, we will present at conferences and meetings such as the Commercial Aviation Alternative Fuels Initiative (CAAFI) meetings, the National Ethanol Conference, the Growth Energy Executive Leadership Conference, and the Fuel Ethanol Workshop
- Mark Yancey is the Executive Chair of the Industrial Advisory Committee for the ARPA-e LignoCrete project at NREL; Project SAFFiRE will collaborate with this project to develop a very large market for SAFFIRE's lignin
- We are also creating samples of our lignin streams that will be provided to strategic partners in the adhesives, asphalt, bio-plastics, and animal feed industries
- We have several stakeholders on our project team: Southwest Airlines will be a very large user of SAF, LanzaJet is building the first commercial-scale AtJ facility; Lignolix is developing technology to use lignin in adhesives and other products
- We have established a SAFFiRE Renewables website (www.saffirerenewables.com) to provide information to the public

Approach – DEI Plan

- In Phase 1, D3MAX and all subcontractors without Diversity, Equity, and Inclusion (DEI) programs will have the opportunity to receive DEI training
- The bid package issued in Phase 1 for the pilot plant EPC contract will include DEI instructions for bidders including requiring bidders to identify opportunities for the EPC contract to serve disadvantaged communities
- The DEI Plan for Phase 2 will identify minority business enterprises, minority owned businesses, woman owned businesses and veteran owned businesses to solicit as vendors and subcontractors for Phase 2 bids on supplies, services, and equipment
- The Phase 2 DEI Plan will include hiring an intern that is selected from groups that are underrepresented in the fields of science, technology, engineering, and mathematics (STEM)

Progress and Outcomes

- NREL's Verification work demonstrated our claim that DMR pretreatment can produce a very clean sugar stream; the verification fermentation utilized all glucose and xylose in just 28 hours which is extremely fast when fermenting xylose
- We are making good progress on the FEL 3 design for the pilot plant with 2 of the 3 design milestones complete; P&IDs, equipment specs and plot plans to be completed by 5/31/23
- Work on the pilot Feedstock Supply Plan is underway and on schedule to be complete by 5/1/23
- We have identified multiple viable host sites for the pilot and are in discussions to finalize our pilot location

Progress and Outcomes – continued

- We have negotiated and signed an Intellectual Property Management Plan with NREL to license NREL's DMR technology
- The Freedom to Operate analysis is underway (patent search and analysis that shows the SAFFiRE process will not infringe another party's intellectual property rights)
- Development of our project Permitting Plan is underway; this plan will identify all permits required for the pilot plant and provide a plan to obtain those permits
- We are working with PNNL to develop our Risk Management Plan
- We are developing plans for additional tests to support the pilot design (additional ethanol fermentations, decanter tests, enzyme tests, and lignin tests)

Progress and Outcomes – Milestones

- The Task 1 Verification milestone is complete (CD-1)
- The Design Basis for the pilot plant is complete; this is milestone M 2.1.1; the Design Basis sets the key variables for each step of the SAFFiRE process
- Rev A Process Flow Diagrams (PFDs) are complete; this is milestone M 2.1.2; PFDs show major equipment and the flow of material through the SAFFiRE process; each PFD drawing includes a mass balance for that drawing
- There are four more Phase 1 milestones to be completed:
  - P&IDs Complete – this work is in progress
  - Business Plan Complete – this work is in progress
  - LCA and TEA Update Complete – not started
  - Award at least one contract to a woman, minority, or veteran owned business – not started

Progress and Outcomes – Status of Phase 1 Milestones

blue = complete

Task, Milestone, and Go No/Go Decision Points	Tasks, Milestones, and Go No/Go Decision Pts	Performer	Start Date	Planned Completion Date	Actual Completion Date
Task 1	Verification of Application Data	NREL	07/21/22	09/30/22	10/2/22
CD-1	Review Verification Outcome (Approve Budget Period 2)	DOE	10/2/22	12/2/22	12/2/22
Task 2	Design Basis Definition	D3MAX	12/02/22	8/31/23	
M 2.1.1	Design Basis Documents Complete	AdvanceBio	12/2/22	1/31/23	1/9/23
M 2.1.2	Process Flow Diagrams Complete	AdvanceBio	1/3/23	2/28/23	2/9/23
M 2.1.3	P&IDs Complete	AdvanceBio	2/10/23	5/31/23	
M 2.3	Business Plan Complete	D3MAX	1/3/23	6/30/23	
M 2.4	LCA and TEA Update Complete	D3MAX	3/1/23	6/30/23	
M 2.5	Award contract to woman, minority, or veteran owned business	D3MAX	4/1/23	08/31/23	
CD-2	Approve Phase 2 Project Scope	DOE	9/1/23	11/01/23	

Impact

- If we are successful we will reduce the cost of SAF significantly allowing for wider use of SAF; the projected SAF cost in our proposal was $2.72/GGE; this cost estimate will be updated in Phase 1
- If we are successful we will enable the production of billions of gallons of SAF from cellulosic ethanol; our goal is to produce 5.5 billion gallons of SAF with SAFFiRE technology by 2040
- If we are successful we will help the airline industry to decarbonize by producing SAF with >70% GHG reduction compared to Jet A; the GHG reduction estimate in our proposal was 84%; this will be updated in Phase 1
- We have strong industry involvement with Southwest Airlines as a team member and investor in SAFFiRE Renewables; LanzaJet, Novozymes (largest enzyme producer) and Lallemand (major global yeast producer) are also team members

Summary

- NREL's DMR pretreatment is a game changer; NREL has demonstrated > 90% sugar yields from corn stover at pilot scale with very low enzyme loading (10 mg cellulase per gram of glucan) making low cost production of SAF from corn stover possible
- During Verification testing NREL demonstrated complete utilization of glucose and xylose in small scale fermentations resulting in 70 g/L ethanol production in less than 28 hours indicating the lack of fermentation inhibitors and the excellent performance of the Lallemand C5FUEL™ yeast
- The key challenge for Project SAFFiRE is the design of the front-end of the pilot; deconstructing corn stover bales and processing high solids/high viscosity liquids is difficult; once the viscosity has been reduced in saccharification, processing the resulting low viscosity liquids becomes more routine
- D3MAX has demonstrated its enzymatic hydrolysis, fermentation and distillation technology at commercial scale with corn fiber; this commercial design will be used for Project SAFFiRE
- LanzaJet is building its first commercial-scale AtJ facility and its SAF has been certified for use in commercial airliners
- Our goal is to produce 5.5 billion gallons of SAF with SAFFiRE technology by 2040

Quad Chart Overview

Timeline

- *10/1/2021*
- *8/31/2023 (end of Phase 1)*

	FY22 Costed	Total Award
DOE Funding	*$2,073 (plus $10,811 for NREL)*	*$142,988 (plus $357,000 to NREL = $499,988 total)*
Project Cost Share	$17,873	$499,988

Project Goal

Demonstrate reliable, low-greenhouse gas (GHG) production of an intermediate ethanol product from corn stover in a fully integrated, 10 ton per day pilot-scale facility and to upgrade the ethanol to Sustainable Aviation Fuels (SAF) at LanzaJet's commercial Alcohol to Jet (ATJ) facility in Soperton, Georgia.

End of Project Milestone (Phase 2)

- *Demonstrate < $2.75/GGE*
- *GHG reduction > 70%*
- *500 hours continuous operation*
- *1,000 hours cumulative operation*
- *60,000 gallons of SAF*
- *Develop plans to finance and build a demo plant*

Funding Mechanism

FY21 BETO Scale-up and Conversion FOA DE-FOA-0002396

TRL at Project Start: 4

TRL at Project End: 6 (end of Phase 2)

Project Partners

- Southwest Airlines, NREL, LanzaJet, AdvanceBio, Lallemand, Novozymes, Lignolix, Equinox, Merjent, Life Cycle Associates, Dorsey & Whitney

Additional Slides

Publications, Patents, Presentations, Awards, and Commercialization

- Mark Yancey presented Project SAFFiRE at the 2022 Fuel Ethanol Workshop
- Tom Nealon is scheduled to discuss Project SAFFiRE on a panel at the Growth Energy Executive Leadership Conference in March 2023
- A project update will be presented at the 2023 Fuel Ethanol Workshop
- Three project Subject Inventions have been documented
- Southwest Airlines has retained Equinox (corn stover supply expert) to begin developing a commercial corn stover Feedstock Supply Chain
- Southwest Airlines is holding discussions with future AtJ producers for the upgrading of cellulosic ethanol produced by commercial SAFFiRE plants