DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

Project LOTUS

Monday, April 3

Systems Development and Integration –
Scale-up Portfolio

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Project Overview

SKYNRG

What: Develop a scalable SAF production pathway

- 3 billion gallon per year SAF Grand Challenge
- RINs Eligible Feedstock
- Scalable

"To meet projected future aviation demands, new SAF production pathways and feedstock sources are needed"

How: Integrate commercial process steps

- Renewable natural gas (RNG): from landfills and dairy digesters
- Syngas: Linde hot oxygen burner (HOB) for partial oxidation (POx) of RNG
- Ethanol: LanzaTech gas fermentation of syngas
- SAF and RD: LanzaJet commercial alcohol-to-jet (AtJ)

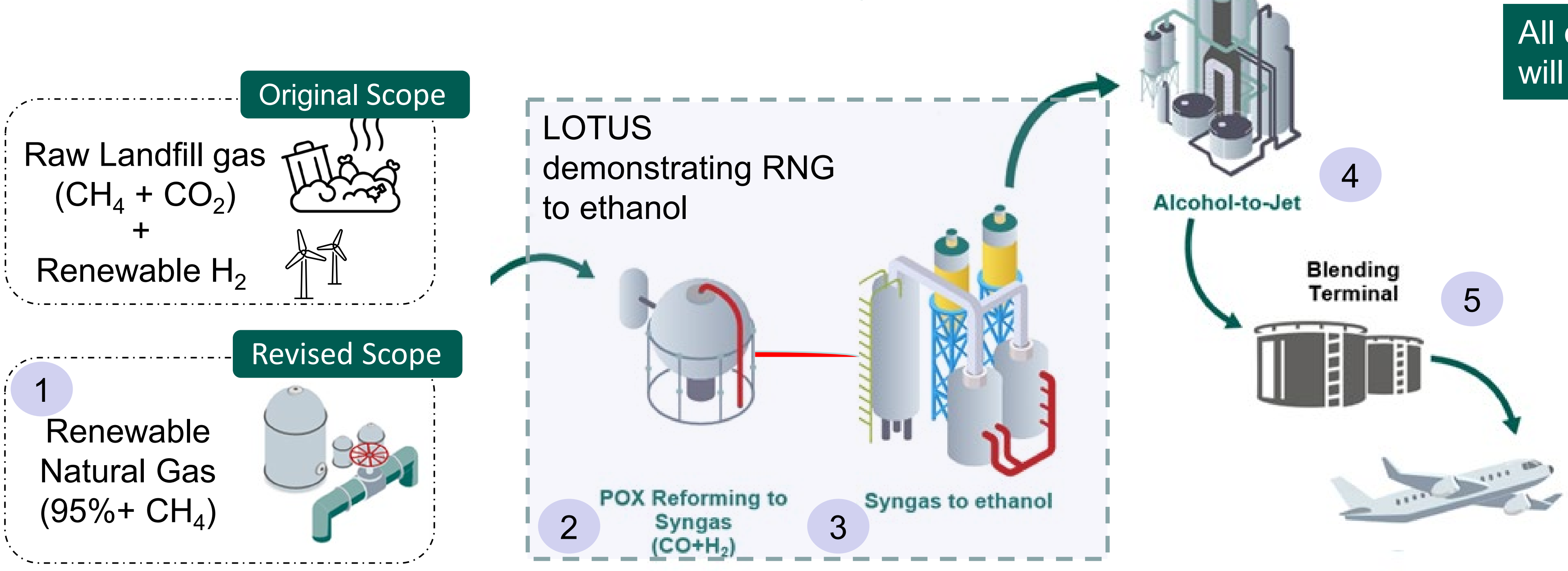
Why: Highly efficient, implementable route to SAF

- Selective: 90% SAF and 10% RD (not broad range of products)
- Usable today: qualified under ASTM D7566 Annex A5 (SAF) and ASTM D975 (diesel)
- Simple: removes risks of solids handling and gasification
- Scalable: RNG infrastructure in place
- Next generation: Incorporate CO_2 as renewable H_2 comes available

Project Overview – Technology Integration

Develop a scalable SAF production pathway

All ethanol from project will be converted to SAF



1. Renewable natural gas sourced from pipeline and local suppliers
2. Linde HOB partial oxidation gas reformer converts RNG to syngas
3. LanzaTech gas fermentation converts syngas to fuel-grade ethanol
4. Ethanol converted to SAF at commercial LanzaJet facility
5. SAF qualified under ASTM D7566 Annex 5
   blended with conventional jet for direct delivery to fueling facilities

LOTUS: RNG to ethanol

LanzaJet uses fuel grade ethanol

Project Overview – Project Goals

SKYNRG

Project LOTUS uses waste and under-utilized carbon feedstocks, provides a final fuel lower in aromatics, has a minimum ~85% GHG reduction (SAF), all at a price competitive in the sustainable fuels marketplace.

FOA Goal	Relevance of Project LOTUS
Delivering an equitable, clean energy future with a path to achieve net-zero emissions, economy-wide, by 2050	▪ New cost-effective route to SAF ▪ Contribute to net-zero aviation emissions ▪ Reduce criteria pollutants near airports.
Mobilize clean energy investment in reducing cost and technical risk	▪ Reduce technical and financial risk hurdle for private investment in commercializing and technology adoption
Produce [SAF] at $2.75 GGE, with >70% lifecycle GHG emissions reductions	▪ Can be achieved by purchasing long-term RNG contracts ▪ >85% GHG reduction for demonstration scale
Advance equity for all (diversity, equity, and inclusivity)	▪ Reduces air pollution that disproportionately impacts low-income neighborhoods ▪ Provides stable, well paid jobs in depressed rural areas.
Allow use of waste or underutilized carbon feedstocks as resources	▪ Utilizes RNG produced from landfill, agriculture, and other waste sources
Novel process technologies, tested and verified at engineering scale	▪ Novel integration of HOB & gas fermentation allows feedstock flexibility at capital cost lower than alternatives

Project Overview – Syngas Production

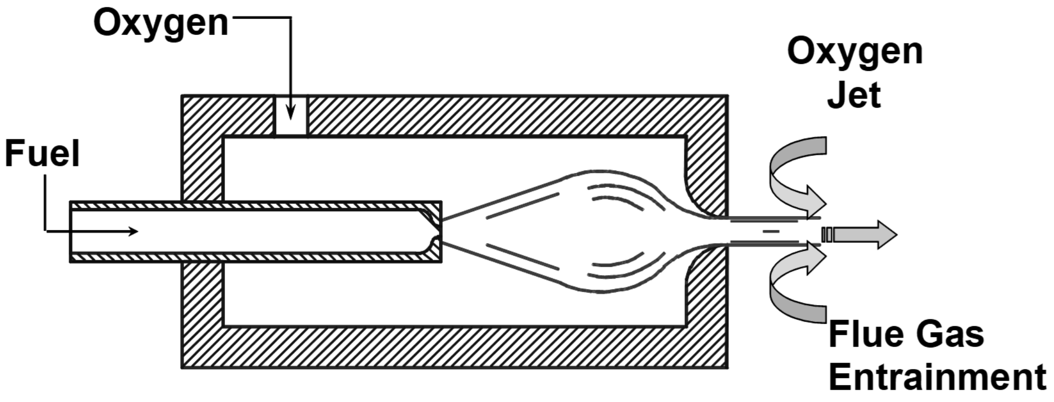
Linde HOB advancement for POx

- HOB produces a jet of high temperature, high momentum oxygen (combusting fuel with excess oxygen)
- The "hot oxygen" is accelerated through a nozzle to velocities ranging from 500-800 m/s

Highly reactive jet with exceptional mixing

- Feedstock gases rapidly entrained into the reactive jet
- Exceptional stability in starting the reforming reactions
- All feedstock is entrained, eliminating any risk of higher hydrocarbons (such as tars) from slipping through unreacted
- Easily tolerates variation in feedstock composition and flowrate
- Enable large amounts of turndown without sacrificing performance

Linde has operated commercial natural gas POx for more than 25 years; HOB represents the next innovation in POx



HOB Specs

- Operating temp: 1000-1800°C
- Methane slip: <0.8%
- Syngas output ratio H_2-to-CO: ~1.7:1

Project Overview – Gas Fermentation

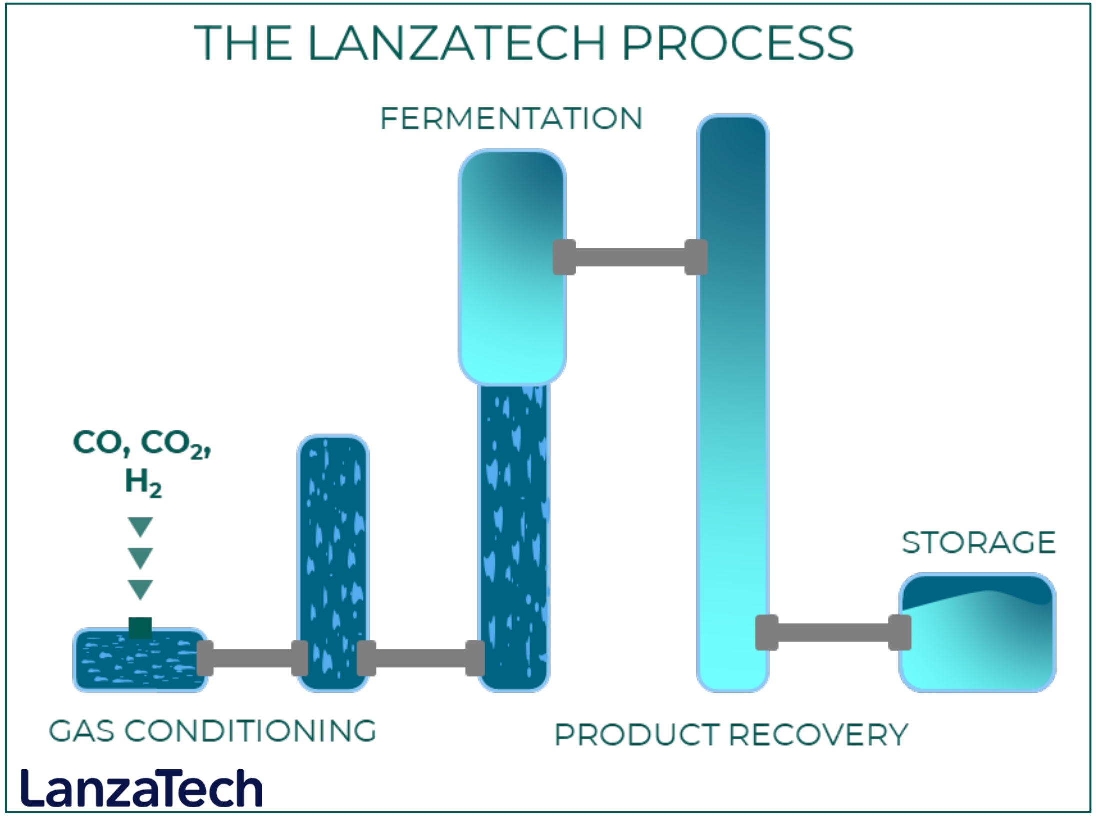
LanzaTech has 3 commercial operating plants and several more in construction that span the syn gas ratios in project LOTUS

LanzaTech Gas Fermentation

- Syngas from Linde HOB fed directly to LanzaTech Gas Fermentation
- Biocatalyst, *Clostridium autoethanogenum,* assimilates energy and carbon from a mixture of CO, H_2, and CO_2
- Any ratio of H_2:CO can be used
- At 2:1 ratio of H_2:CO, CO_2 is not a product
- With excess H_2, CO_2 is a reactant (converted)

Gas Fermentation Process

- *Gas Conditioning* – Feed gas from the HOB reactor is cooled and cleaned prior to fermentation
- *Fermentation* – The biocatalyst converts CO, CO_2 and H_2 into ethanol in a continuous fermentation process
- *Product Recovery* – Ethanol continuously removed, separated from water, and stored for transport to ATJ



Project Overview – Alcohol-to-Jet

LanzaJet ATJ

- Catalytic process converting ethanol to Synthetic Paraffinic Kerosene (SPK) and Synthetic Paraffinic Diesel (SPD)

LanzaJet ATJ Process

Follows the four steps outlined in ASTM D7566

- *Dehydration*
- *Oligomerization*
- *Hydrogenation*
- *Fractionation*

Fuels

- SAF (ASTM D7566)
  Drop in fuel blended with conventional jet up to 50%
- Renewable diesel (ASTM D975)
  No blending wall

ATJ is being de-risked in another BETO-sponsored project in this session

https://www.lanzajet.com/news-and-insights/

Project Overview – Phase 1

Phase 1

- Two Budget periods

Verification addresses risks of coupling HOB with Gas Fermentation

Budget Period 1. Verification

- Verification at Linde's facility using biogenic RNG with a LanzaTech portable pilot unit connected to Linde's large HOB pilot
- Verification test completed Dec 12, 2022 and test report currently under review by IE

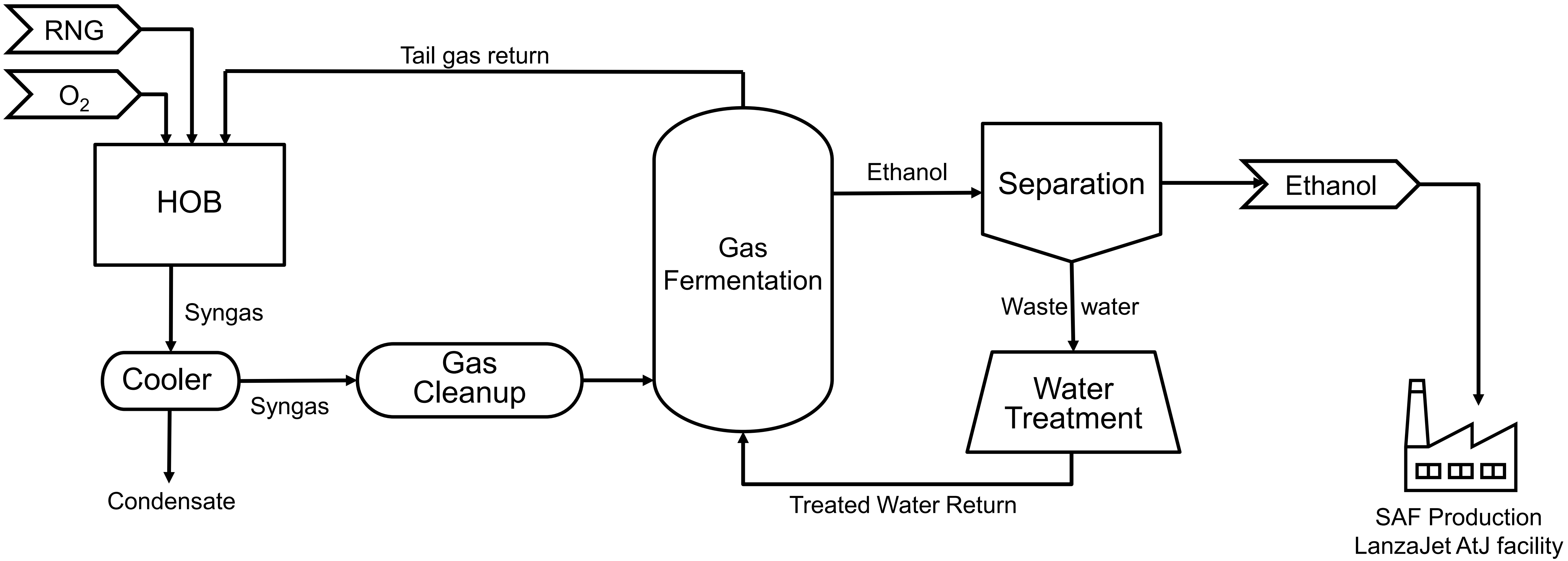
Budget Period 2. Engineering and Business case

- Engineering for a +30/-15% design basis
- LCA, TEA, Proforma, and other business case documents

Linde HOB

LanzaTech GTS

Project Overview – Block Flow Diagram

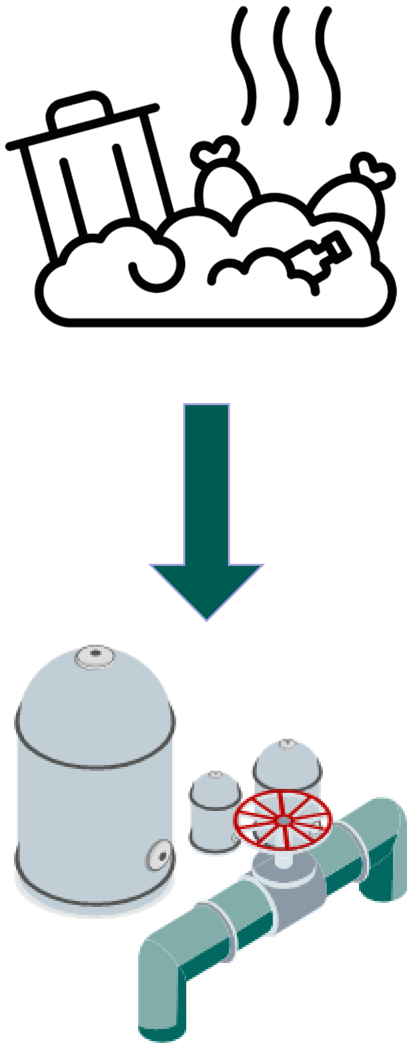


- RNG (CH_4) and O_2 inputs are converted to syngas ($CO + H_2$) in the HOB
- Syngas is cooled, cleaned, and fed to fermentation unit
- Ethanol is separated from produced broth and sent to offsite AtJ facility for SAF production
- Process design efficiencies allow for re-use of fermentation tail gas and wastewater

Approach – Why Change Scope

Market and policy changes dictate new feedstock

- In 2021 Q4, shortly after Project LOTUS was approved – EPA RVO definitive position that biogenic CO_2 as a feedstock is not eligible for generating RIN credits[1]
  - Eliminated RFS credits on ~40-50% of product = losses of ~$4 per gallon
- Landfill owners opt for RNG production
  - Project LOTUS team, working with industry consultants, encountered resistance from landfill owners siting an unproven technology at their facilities
  - Few landfills have sufficient gas for a large SAF facility



Switch to RNG

- Best business case for SAF production in the US
- RNG infrastructure allows larger plants

1. December 7, 2021 6560-50-P RIN 2060-AV11; EPA proposes that to be eligible for RIN the mass, volume, and energy must be from biomass, biogenic CO2 does not contain energy and would require bio-derived energy be used which is neither cost competitive nor make technical sense to do (e.g., bio-derived carbon would be lost to make H_2)

Approach – Why Change Scope (con't)

Benefits of RNG as a feedstock

- RNG is a RIN eligible feedstock (today generate RINs for production of CNG/LNG)

- RNG allows aggregating biogas collection and distribution using existing infrastructure
  - Fully fungible commodity
  - Enables aggregating smaller landfills and digesters (either via truck for local aggregation or pipeline)
  - Nationwide and inexpensive transport logistics in place

- RNG diversifies supply strategy
  - Current sourcing from landfills, anerobic digesters and wastewater treatment facilities
  - New sourcing from ag residues, food and other waste

- RNG is competitively priced and readily available
  - Long term contracts desired by RNG suppliers
  - Significant new RNG production planned

Approach – Pathway to PtL

US policy doesn't yet support power-to-liquids (PtL) pathways

- Technology of original scope is sound
- LanzaTech has a commercial scale plant with CO_2+CO+H_2 (India)
- As US policy adapts, CO_2 + green H_2 can be added to future plants

Example of Commercial plant processing CO_2 as a component

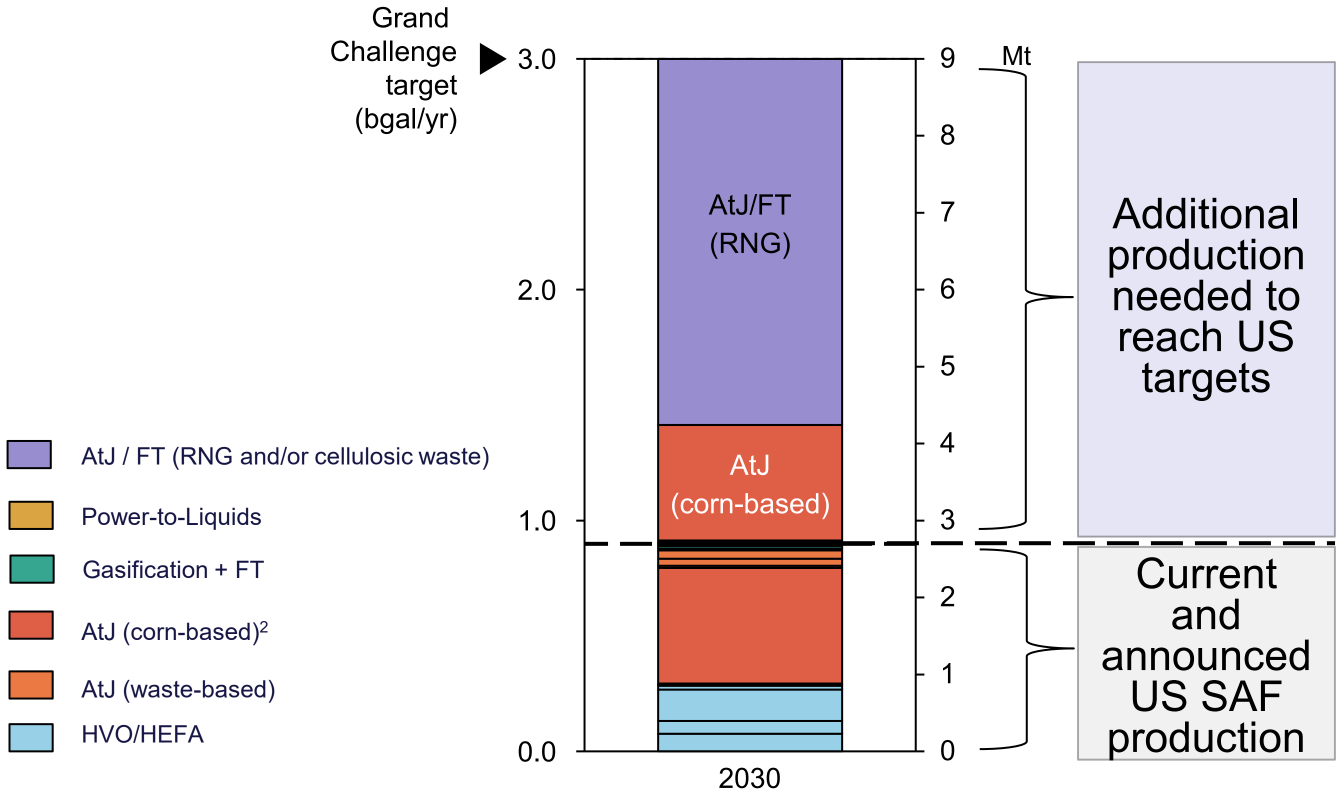
- Synthetic fuels (CO_2 and H_2) not likely to play significant role until 2030[1]
- US policy mechanisms currently incentivize biomass-based pathways
- CO_2 does not fit into the RFS
- As US Policy adopts, CO_2 as a feedstock can be commercialized
- Today, CO_2 feedstock fits CORSIA
- IRA (H_2 credit, BTC) and 45Q help close the gap

[1] Source: SkyNRG internal analysis from May 2022

Approach

The case for new US-based SAF production pathways

US SAF outlook towards 2030[1]



- Announcements of new SAF capacity in the US is about 900 Mgal (2.6 Mt) SAF by 2026–2030[1].
- Another 500 Mgal of corn-based SAF could theoretically be added by 2030[2].
- Due to feedstock limitations and market dynamics HVO/HEFA and corn-based AtJ capacity is limited to 1.4 bgal, **requiring other cellulosic pathways to fill the 1.6 bgal gap towards 2030.**
- **Synthetic fuels from CO_2 and H_2 are not likely to play significant role up until 2030** due to technical and economics limitations. US policy mechanisms currently incentivize biomass-based pathways and do not support synthetic pathways such as PtL.

[1] Source: SkyNRG internal analysis from May 2022 – [2] Significant modifications are needed on-farm or at the ethanol plant to achieve the required GHG reduction of 50%

Potential Challenges

Scale-up

- LOTUS has completed a successful verification of integrated HOB-gas fermentation
- Technologies need to be integrated at scale
  - Syngas from HOB using RNG has lower impurity levels than LanzaTech's commercial plants
  - Both technologies are independently deployed at production scales we're targeting
- Budget Period 2 engineering design focus is on integration and outside battery limit costs

Market and Policy Uncertainty

- Changes in market dynamics and supporting policy affect every project as they move towards commercialization
- LCA, TEA, and proforma efforts need to show profit at market-relevant price / different conditions
- Efficiencies of scale help (Phase 2)
- Recent legislative incentives and flexibility in feedstock sourcing also help

Approach

Risk Analysis and Mitigation

Work started before BP2 (3 Elements)

- LanzaTech ran their internal Risk assessment
- Coupled with PNNL Risk Management Tool (pilot program for BETO)
- And, SkyNRG contracted feasibility study with a leading EPC (independent look at risk)

Summary

- Robust risk register and risk matrix in place; guiding document for project development

Description	Cause	Consequence	Risk Level	Mitigation
RNG seasonal price volatility	Colder months, increasing demand, higher prices leading to unviable business case.	OPEX		1. Assess coldest month in Walla Walla region to align with annual maintenance period. 2. Assess potential hedging mechanisms, internally or externally.
Climate related event impacts the the supply and /or operations of the plant	Draught (most likely), wild fires, earthquakes, etc..	CAPEX		1. High-level scan performed; location is not vulnerable for any natural disasters. 2. Incoporate language in contracts to minimize external liability.
Unable to hire the right team in a timely manner.	Skilled workforce not available in the region under the right conditions	Increaed DevEx, Opex and potential delay		1. Develop HR strategy 2. Develop budgets which allow to attract the right workforce under attractive conditions
Permits on critical path	Permit process takes longer than expected	Project delay and DevEx increase		1. Start EPA application as soon as possible 2. Perform due diligence on site prior to purchase 3. Engage external contractors for support

Sample of LOTUS risk register items

Diversity, Equity, and Inclusion in Project LOTUS

SkyNRG Americas and the entire LOTUS team are committed to advancing diversity and inclusion, which is reflected in our Diversity, Equity, and Inclusion (DEI) strategy:

- Our strategic philosophy entails **more than just looking at the demographic numbers** related to diversity, but also focusing on developing leadership competencies that create and maintain an inclusive culture.
- This includes setting an expectation that our managers seek to **effectively address behavior** that is seen as biased, divisive, and in opposition to our values.
- We commit to behaviors, practices, and initiatives which **support a culture of understanding**, inclusion, and collaboration.
- We seek to include **all voices** in order to **achieve our mission** and profoundly impact our professional disciplines.
- Now that project site selected, working to understand DEI from rural Washington community lens

Progress and Outcomes

Current Project Progress

- All BP1 work completed
- Verification Test report delivered to IE and undergoing review
- BP2 work continuing at-risk
- Market and policy evaluations to revise feedstock

Key Milestones

- ***Integrated Technology Demonstration***
  - Successful integration and operation of HOB and gas fermentation technologies
  - Swine- and dairy-derived RNG feedstock, as well as pipeline natural gas
  - Final verification test report delivered to IE
- ***Recovery of produced ethanol***
  - Produced ethanol recovered from fermentation broth
  - Ethanol purity tested and shown to exceed requirements for AtJ process
- ***Project Site Selected***
  - BP2 milestone completion demonstrates at-risk work being performed
  - Signed sales agreement with landowner
  - Site due diligence and permitting continuing

Progress and Outcomes

Important Technical Accomplishments

The most critical technical accomplishment for Project LOTUS so far was the successful integration of the technology units to produce ethanol. This pilot-scale integrated test allowed for IE verification, and it was also the first time the proposed production pathway had been in operation. The successful verification test was the culmination of the BP1 work.

The successful integrated verification test included:

- *Biogas sourcing and transport*
- *Equipment setup and safety reviews*
- *Revised PFDs*
- *Site construction and upgrades*
- *Feedstock evaluation*
- *140 hours of continuous runtime*

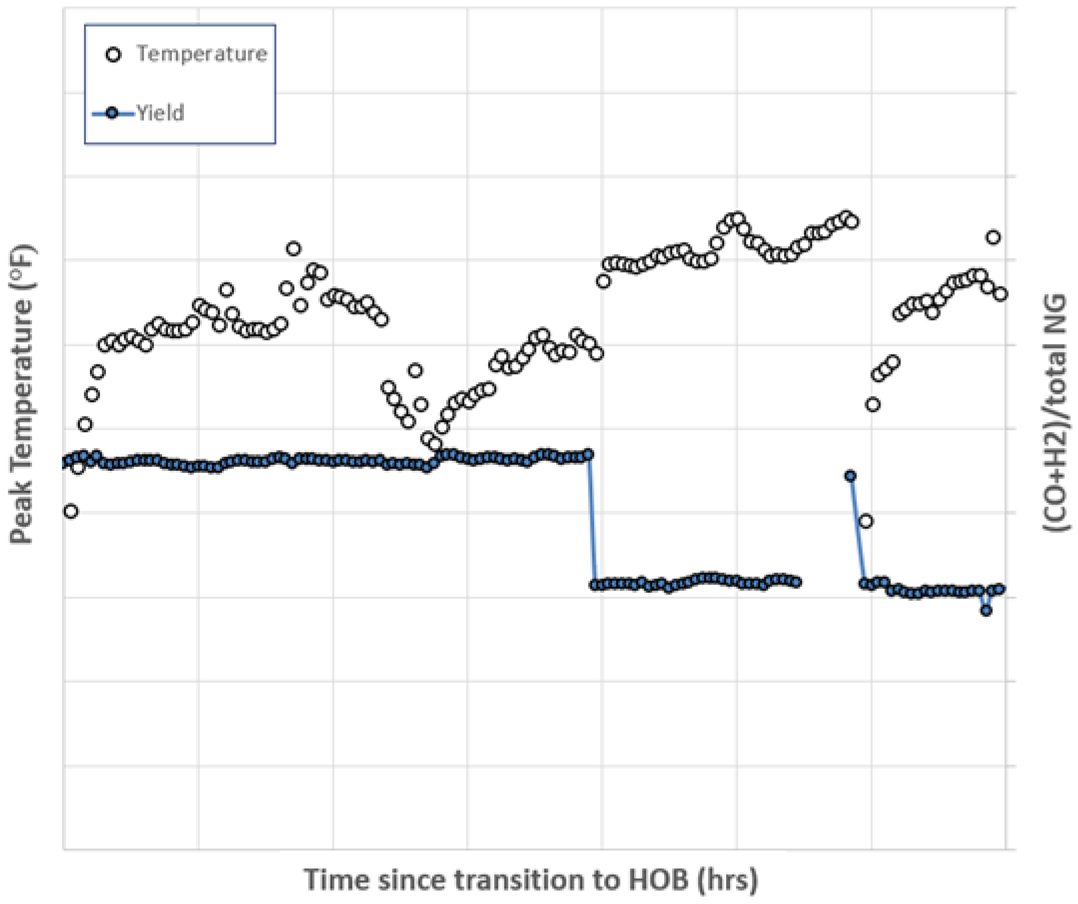
Linde pilot-scale HOB Connected to LanzaTech mobile pilot plant

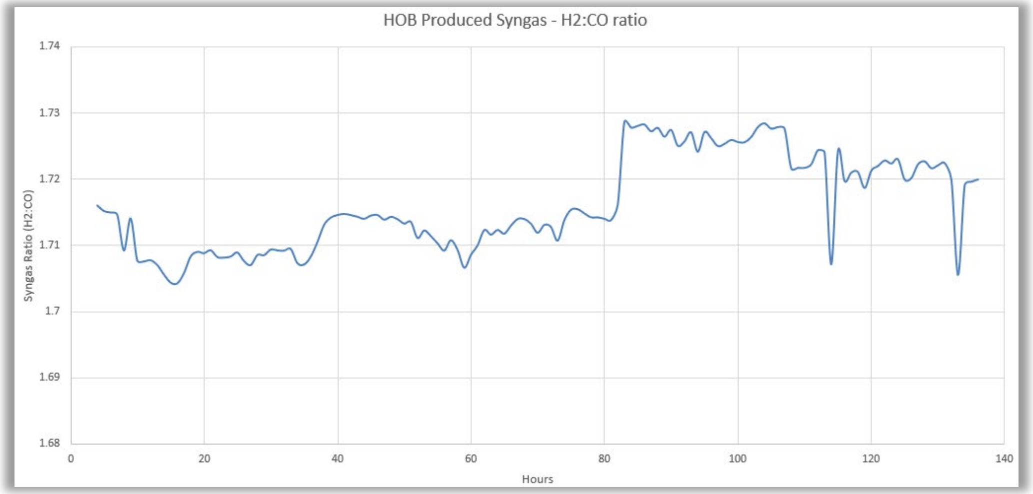
Progress and Outcomes

Verification Test Results - HOB

- HOB unit operated for 140 hours during verification testing
- Transitioned between 3 different feedstocks
  - Dairy & Swine RNG
  - Pipeline natural gas
- Maintained consistent temperature and syngas output
- Maintained consistent syngas composition
  - H2:CO ratio of 1.7

HOB Temp and Yield Over Time

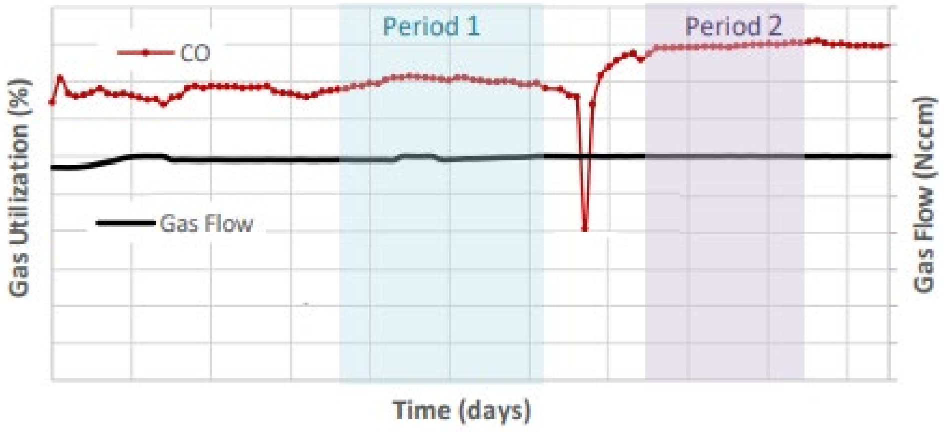




Progress and Outcomes

Verification Test Results – Gas Fermentation

- The LanzaTech gas fermentation system operated on HOB-produced syngas for 64 hours
- Biocatalyst microbe proliferated throughout the test, indicating compatibility with syngas composition
- Produced ethanol exceeded ASTM D4806 specifications, meeting all requirements for AtJ SAF production



Property	Unit	ASTM D4806	Result
Ethanol	vol%	≥92.1	>99
Methanol	mass%	≤0.5	0.009
Solvent-washed gum	mg/100 ml	≤5.0	4.2
Water	mass%	≤1.26	0.78
Inorganic Cl	mg/L	≤6.7	0.6
Copper	mg/kg	≤0.1	<0.1
Acidity as Acetic acid	mg/kg	≤70	5.3
pH_e	-	6.5-9.0	8.9
Sulfur	mg/kg	≤10	6.8
Existent sulfate	mg/kg	≤4	0.5

LOTUS produced ethanol compared to fuel-grade ASTM specifications

Project Impact

Project LOTUS has the potential to open the doors to a new SAF production pathway and serve as a proof case for RNG as a viable feedstock. Current SAF production has taken advantage of the low hanging fruit of HEFA and food crops, but the availability of these feedstocks is already nearing maximum demand.

Project LOTUS SAF production pathway

- Utilizes RNG, a readily available and abundant feedstock
- Uses robust technologies tolerant of volatiles and contaminants in source gas
- Removes the risks of solids handling and gasification
- Is scalable, both for feedstock and technologies
- Selectively makes SAF and RD – not a broad range of hydrocarbons
- Can change product ratio (SAF/RD) at same cost of production
- Can incorporate next-gen processes (PtL, CCU) when policy supports
- Will result in a low-CI fuel with <70% reduction in GHG

Summary

On Schedule

- Completed verification test (BP1)
- Working at-risk on BP2 (while waiting for Go/No Go) to complete BP2 deliverables
  - Switch to RNG caused initial project delays, but doing BP2 at risk, has allowed us to get back on schedule, with important milestones already reached.
  - Three fold risk analysis (LanzaTech, PNNL, EPC) to identify potential risks, opportunities, and challenges
  - Techno-economic, lifecycle analysis and Proforma ensure price competitive in the market.
  - Offtake agreements are in place, with more being negotiated
  - Corporate partners supportive in our efforts to affect sustainable policy

Reduced Project Risk

- Project technologies proven at commercial scale and easily integrated
- No solids handling or gasification steps

Impact

- Unique production pathway tolerant to a wide range of feedstock sources and quality, with no impact on the integrity of the final product
- Flexible RNG sourcing minimizes risk and decreases overall product CI

Quad Chart Review

Timeline

- *Project start date: October 1, 2021*
- *Project end date: September 30, 2027*

	FY22 Costed	Total Award (Phase 1)
DOE* Funding	*$150,845*	*$853,000*
Project Cost Share *	*$188,802*	*$1,000,653*

TRL at Project Start: TRL6
TRL at Project End: TRL7

Project Goal

Construction and operation of a demonstration scale SAF production facility utilizing the integrated technologies of Linde POx and LanzaTech gas fermentation.

End of Project Milestone

- *1,000,000 gallons of SAF produced*
- *70% GHG reduction*
- *1000 hours cumulative time on stream*
- *500 hours continuous time on stream*

Funding Mechanism

FY21 BETO Scale-up and Conversion FOA DE-FOA-0002396; Subtopic Area 1c: Scale-up of Biotechnologies - Demonstration Scale for Biofuels and Bioproducts

Project Partners*

- SkyNRG Americas
- LanzaTech
- Linde

*We are waiting for invoicing from partners (will exceed cost share)

Additional Slides

Responses to Previous Reviewers' Comments

Project LOTUS has not yet gone through any peer review sessions, nor has it reached any Go/No-Go decision points.

Publications, Patents, Presentations, Awards, and Commercialization

Not currently applicable to Project LOTUS