CO_2 Reduction and Upgrading for e-Fuels Consortium

U.S. DEPARTMENT OF ENERGY

DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Carbon Dioxide Utilization

Markets, Resources, and Environmental and Energy Justice (MarkeRs-EEJ)

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2 Argonne National Laboratory

Project Overview

The project will **quantify resource availability and costs** for CO_2 utilization (CO2U) in sustainable aviation fuel (SAF) production to inform industry, technology communities, and policymakers on location-specific economic and societal impacts.

It will provide insights to guide R&D efforts to achieve BETO's **decarbonization** goals, **SAF cost and production targets**, while meeting DOE's **energy justice** objectives.

We will learn about:

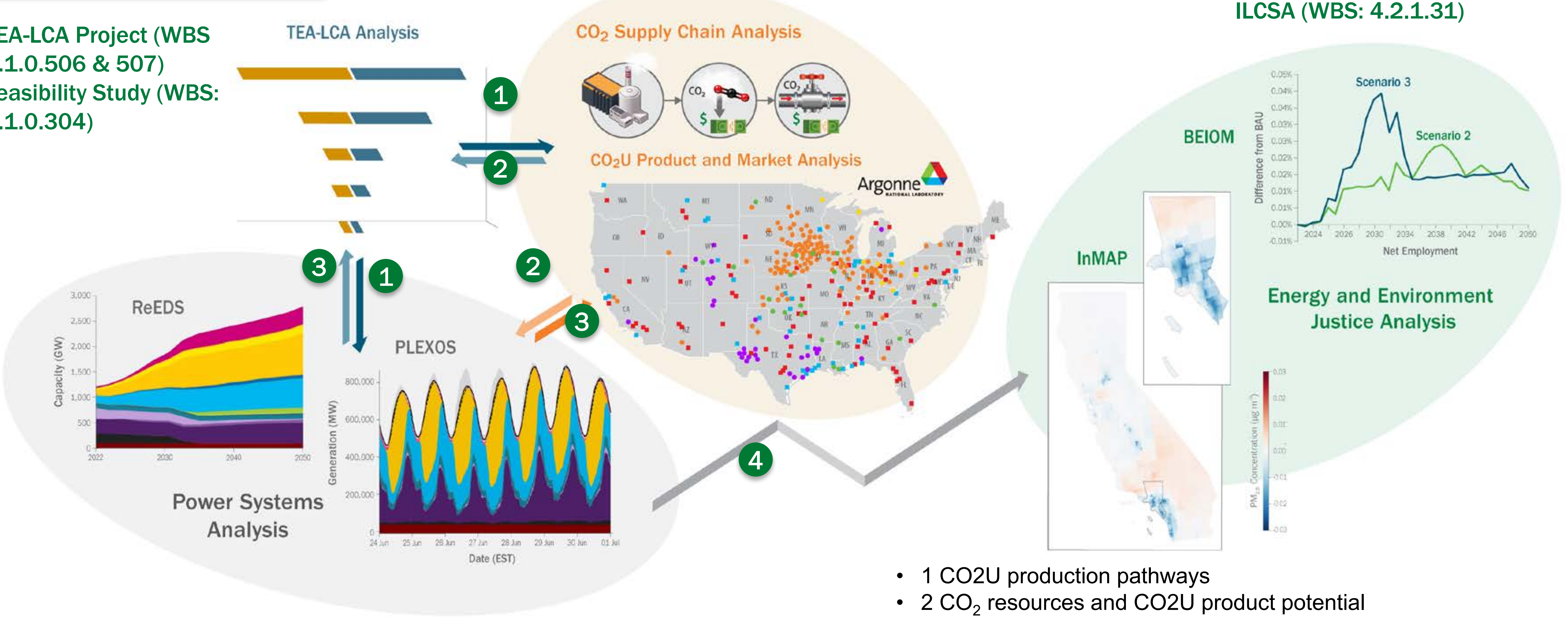
- Future electricity sources, their costs and carbon intensity
- Future CO_2 sources (assuming economic-wide decarbonization) and H_2 sources, their costs and delivery
- CO2U deployment strategies to achieve better energy justice outcomes

1. Approach: Cross-Sector Modeling Framework

Close collaboration with other projects and Consortium advisory board

TEA-LCA Project (WBS 2.1.0.506 & 507) Feasibility Study (WBS: 2.1.0.304)

ILCSA (WBS: 4.2.1.31)



- 1 CO2U production pathways
- 2 CO_2 resources and CO2U product potential
- 3 Electricity grid information such as emission and electricity cost
- 4 CO2U resources, deployment scenarios, and locations

1.1a CO_2 Supply Chain and SAF Market

Examine Current and Future CO_2 Sources in 2030 and 2050

- Estimate industrial high-/mid-purity CO_2 (e.g., bioethanol, ammonia, and natural gas processing).
- Estimate CO_2 using in-house calculation (GREET), EPA GHGRP, and EIA AEO reference case.

Analyze Cost of CO_2 Capture and CO_2 Pipeline Transport

- Capture cost by sources and amounts: NETL reports (Herron et al. 2014, Hughes et al. 2022).
- Calculate transportation cost using ANL CO_2 pipeline transport model

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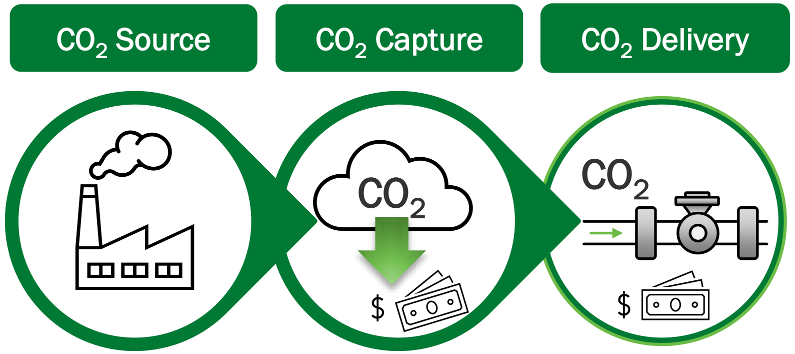
- **Available CO_2 for CO2U products**
- **Costs of CO_2 capture and transportation**



1.1b CO_2 Supply Chain and SAF Market

Sustainable Aviation Fuel

- Current jet fuel market analysis
- Market and consumption outlook (by region)

Estimate SAF Production Potential

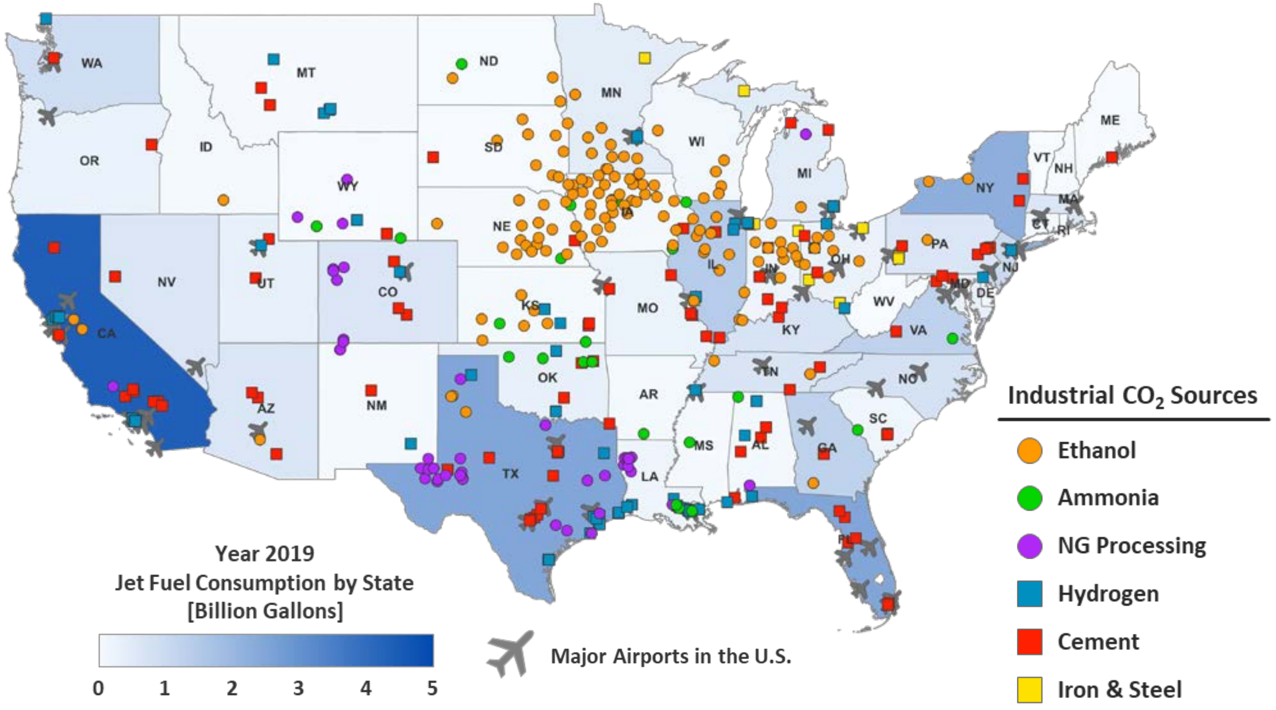
- SAF technology selection: TEA-LCA project (WBS 2.1.0.506 & 507)
- Regional SAF production capability with available CO_2 sources
- Regional energy demand for SAF production

- Market size of SAF
- Regional CO2U production capability

CO2U Product Market

Regional CO_2 Source

CO2U Production Potential



1.2. Power System Analysis

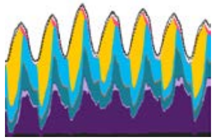
- Build CO2U representation in state-of-the-art power system models to provide insights on the changes needed in power system planning and operation to meet future CO2U demands.
- Outputs include hourly electricity costs, generation mix, transmission needs, carbon emissions, etc. for the contiguous United States at high temporal and geographical resolution.

ReEDS → PLEXOS BY ENERGY EXEMPLAR

NREL's state-of-the-art power system planning model

- Optimizes deployment of generation, transmission, and end-use demand technologies to meet load and reserves while abiding technical and policy constraints

Commercial power system operation model

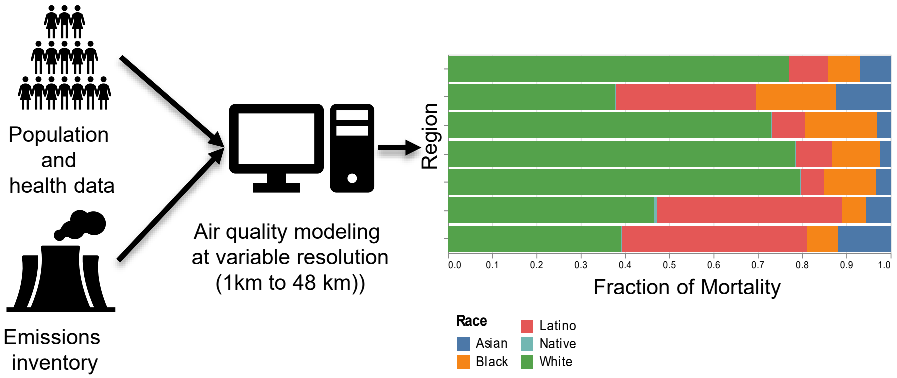


- Performs economic dispatch for ReEDS-built system
- Verifies system is resource-adequate and reliable at hourly level

1.3. Energy and Environmental Justice (EEJ)

Air Quality and Health Impact Assessment:

- Sector- and location- specific emission estimates
- Health impacts and exposure disparity analysis
- Leverage InMAP (a reduced reduced-complexity air quality model)



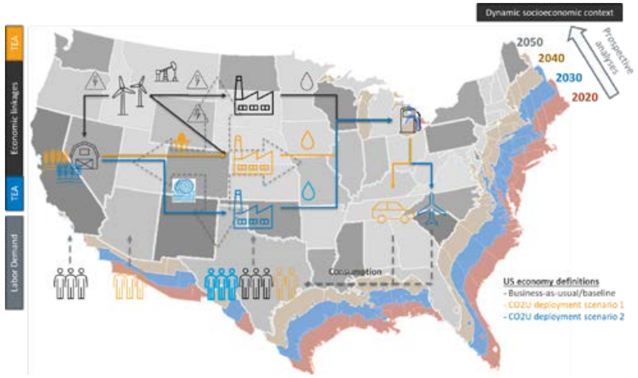
Population and health data

Emissions inventory

Air quality modeling at variable resolution (1km to 48 km))

Socioeconomic Analysis:

- Total jobs
- Occupations (type, skills, education, and wages)
- Value-added by state and by sector
- Leverage BEIOM (WBS: 4.2.1.31)



1.4 Additional Information on Approach

Risk Mitigation

- Uncertainties in future technology development and demand growth are captured through scenario analysis.
- Actively seek feedback and inputs from other projects, industry representatives, and the advisory board through monthly Consortium meetings.

Go/No-Go

- Sufficient information available for the 2050 analysis: conversion pathways ✓, potential CO_2 sources ✓, electricity cost-to-CO2U price profiles ✓

Diversity, Equity, and Inclusion

- Research focuses heavily on the energy and environmental justice implications of CO2U deployment and will examine various equity-related impacts (e.g., air pollution, health, and jobs) to different regions and demographic groups.
- The research results can be used to inform equitable deployment of CO2U deployment and strategies to improve equity and energy justice outcomes.
- Dissemination of research findings will incorporate diversity, equity, and inclusion. The team will participate in the CO_2 Consortium's outreach efforts and provide accessible, age-appropriate materials (e.g., a video recording) explaining our findings after analyses are completed.
- Project team includes members from diverse racial, ethnic, and educational backgrounds.

2. Progress and Outcomes

Investigated 2030 CO_2 resources and their capture and delivery costs

FY22 Q2

Evaluated electricity purchasing options and costs for CO2U sites in 2030

FY22 Q3

Identified 2030 market sizes and three regions for SAF production and market via CO2U

FY22 Q4

Published report on CO_2 sources, electricity costs, generation mix, carbon emissions for CO2U sites in 2030

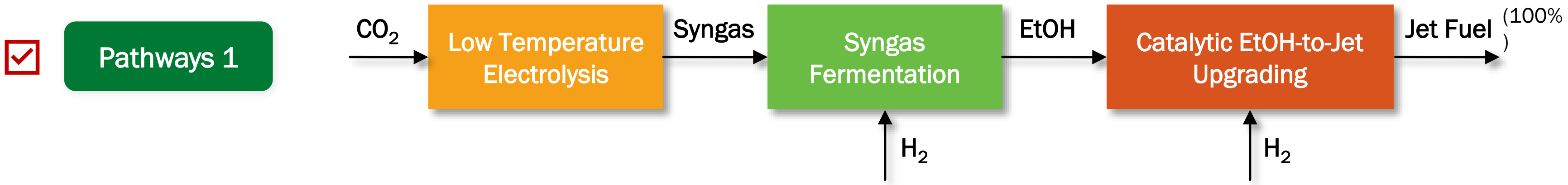
FY23 Q1

Estimated 2050 CO2 resources and SAF production potential

FY23 Q2

2.0 SAF Technology Pathways*

Focus on **Pathways 1 and 3** for CO_2 to jet fuel from the TEA-LCA project



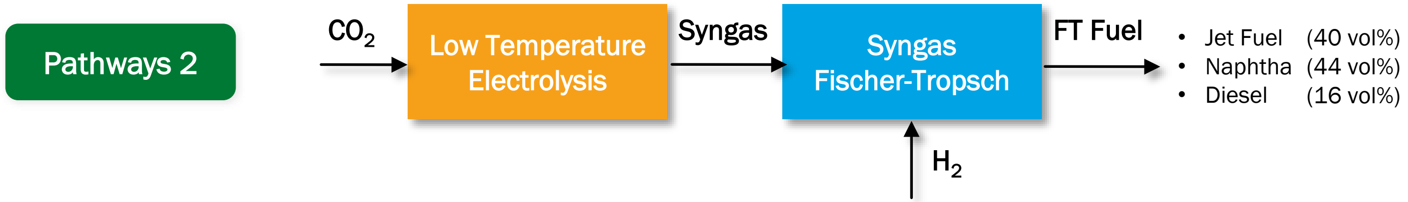
☑ **Pathways 1**

CO_2 → Low Temperature Electrolysis → Syngas → Syngas Fermentation → EtOH → Catalytic EtOH-to-Jet Upgrading → Jet Fuel (100%)

H_2 → Syngas Fermentation

H_2 → Catalytic EtOH-to-Jet Upgrading

Low temperature electrolysis - syngas fermentation - ethanol to SAF (LTE-SF-ETS)

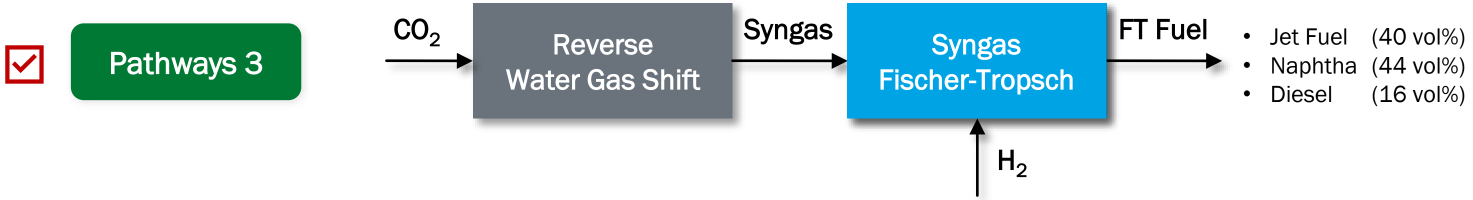


Pathways 2

CO_2 → Low Temperature Electrolysis → Syngas → Syngas Fischer-Tropsch → FT Fuel →

H_2 → Syngas Fischer-Tropsch

Jet Fuel	(40 vol%)
Naphtha	(44 vol%)
Diesel	(16 vol%)



☑ **Pathways 3**

CO_2 → Reverse Water Gas Shift → Syngas → Syngas Fischer-Tropsch → FT Fuel →

H_2 → Syngas Fischer-Tropsch

Jet Fuel	(40 vol%)
Naphtha	(44 vol%)
Diesel	(16 vol%)

Reverse water gas shift - Fischer Tropsch to SAF (RWGS-FTS)

* For SAF pathway details, see next presentation: Economics and Sustainability of CO_2 Utilization Technologies with TEA and LCA (WBS 2.1.0.506 & 507).

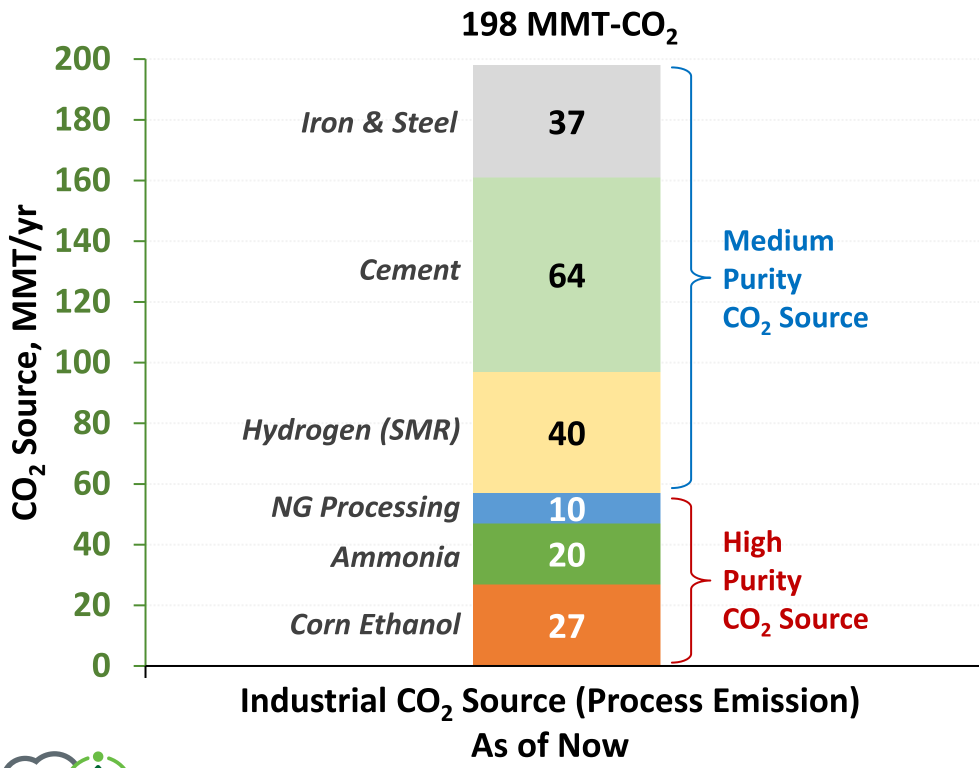
2.1 SAF Production Potential in 2030 (FY22 Q2)

~200 MMT-CO_2 high-/mid- purity CO_2 sources available in 2030 from similar sources to today

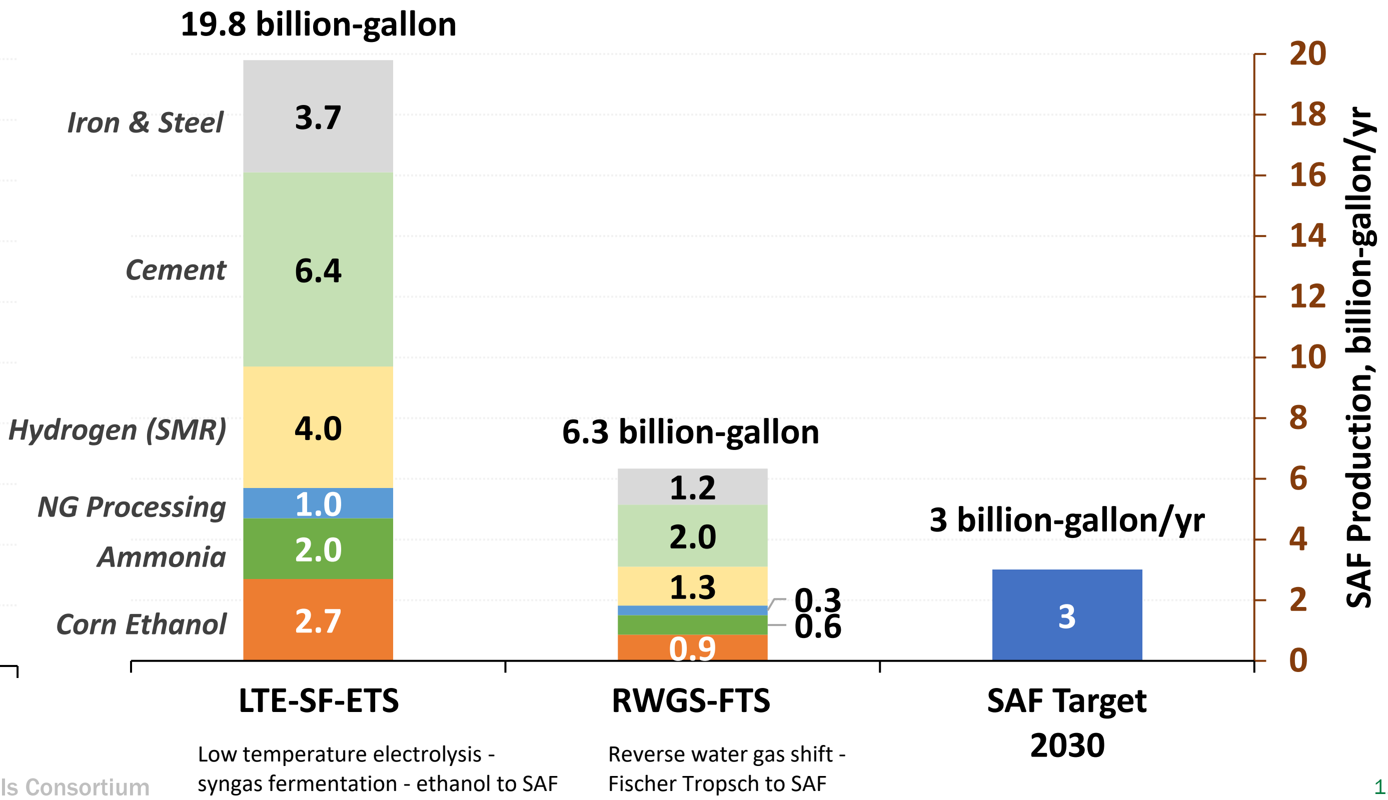
Potential SAF production capability:

- LTE-SF-ETS = ~20 billion-gallon
- RWGS-FTS = ~6 billion-gallon

2030 CO_2 Sources



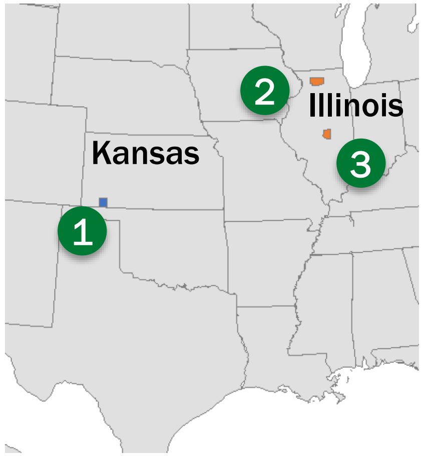
CO2U SAF Production Potential in 2030



2.2 Electricity Purchasing Options for Initial Selected Locations (FY22 Q3)

- Published NREL report on electricity costs and carbon implications for CO_2-to-fuels (Li et al. 2022)
- Identified three preliminary locations for proof-of-concept purposes, based on
  - 1) representation of three wholesale power markets (MISO, PJM, and SPP)
  - 2) vicinity to large existing ethanol plants
- Evaluated costs for various electricity purchasing options for each site: retail rate, financial PPA, physical PPA, real-time pricing

Selected Locations

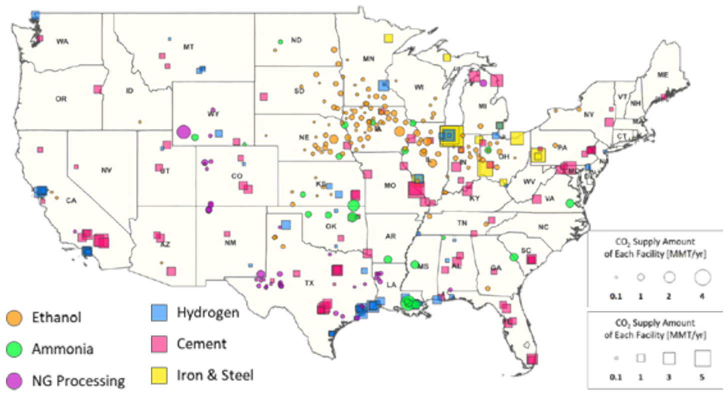


Electricity Purchase Options and Cost (Li et al. 2022)

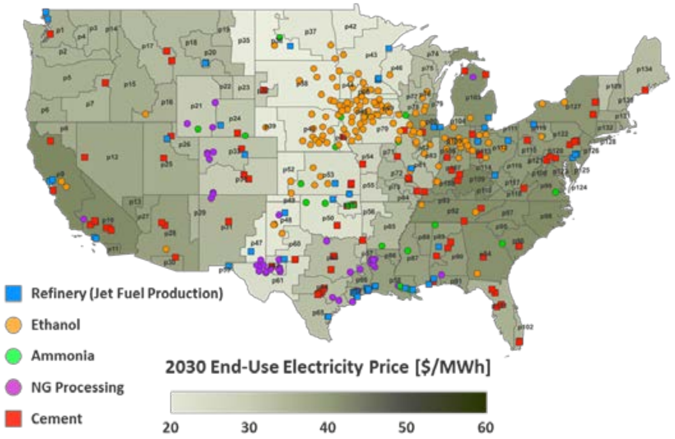
Plant (Location)	CO_2 Supply (MMT/yr)	Electricity for CO2U (TWh/yr)	Retail Rate (¢/kWh)	Financial PPA (¢/kWh)
Liberal, Kansas	0.19	1.5	8.3	2.7–3.6
Rochelle, Illinois	0.15	1.2	5.6	3.3–4.4
Decatur, Illinois	0.63	4.8	3.4	3.3–4.4

2.3 Analysis of Three Potential SAF Facility Regions in 2030 (FY22 Q4)

Current Industrial CO_2 Source Distribution

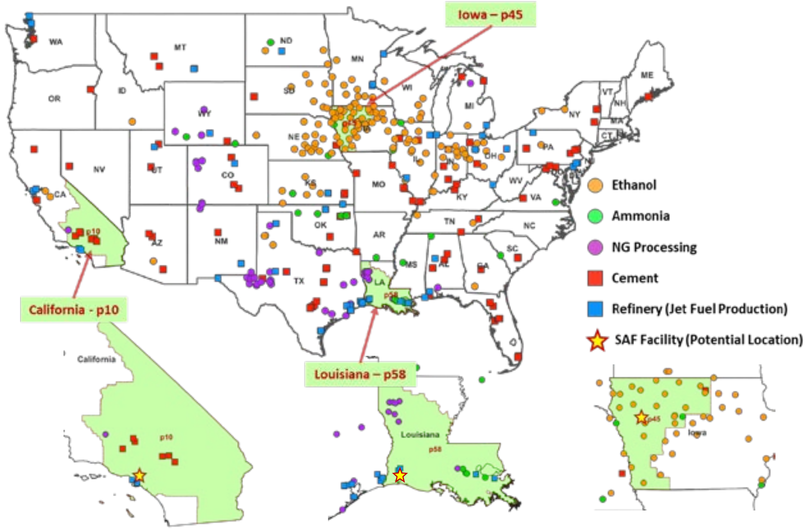


Simulated 2030 Electricity Price
(Low Renewable Cost scenario)



Identify regions by
1. Electricity cost in 2030
2. Proximity to CO_2 sources
3. Proximity to jet fuel refineries

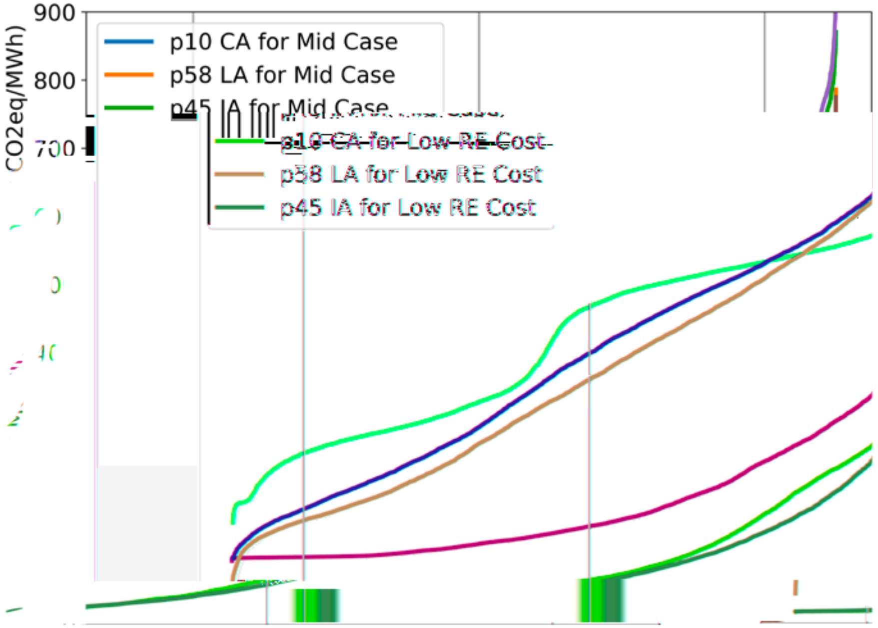
Three Identified Regions



Quantify CO_2 source and electricity demand
- Estimate CO_2 sources from 200-mile radius
- Produce expected SAF production amount and electricity demand (inputs to the FY23 Q1 Milestone)

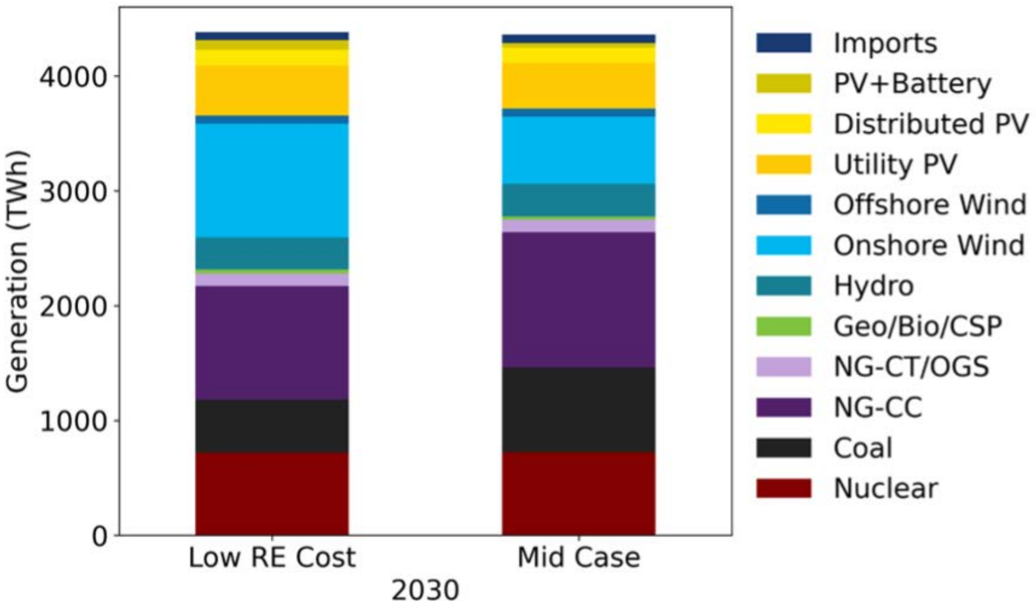
2.4a Generation Mix, Carbon Emissions, and Electricity Purchasing Options for Identified Regions (FY23 Q1)

- Published NREL report (Li et al. 2023): *Near-Term Electricity Requirement and Emission Implications for Sustainable Aviation Fuel Production with CO_2-to-Fuels Technologies*



Cumulative Average Long-run Marginal Greenhouse Gas Emissions in Select Locations

National Generation Mix in 2030
(adapted from Cole and Carag 2022)



- Assessed CO_2 sources, carbon emissions, and electricity generation mix in three locations and quantified costs for various electricity purchasing options (next slide)

2.4b Generation Mix, Carbon Emissions, and Electricity Purchasing Options for Identified Regions (FY23 Q1)

- PPAs, where available, can often provide cost advantage to other purchasing options.
- Utility tariffs typically include demand charges which can be reduced if the CO2U facility can operate flexibly. A utility may also charge distribution upgrade costs to large new loads that trigger a network upgrade, adding to project costs.

Purchase Options and Electricity Cost Ranges (Li et al. 2023)

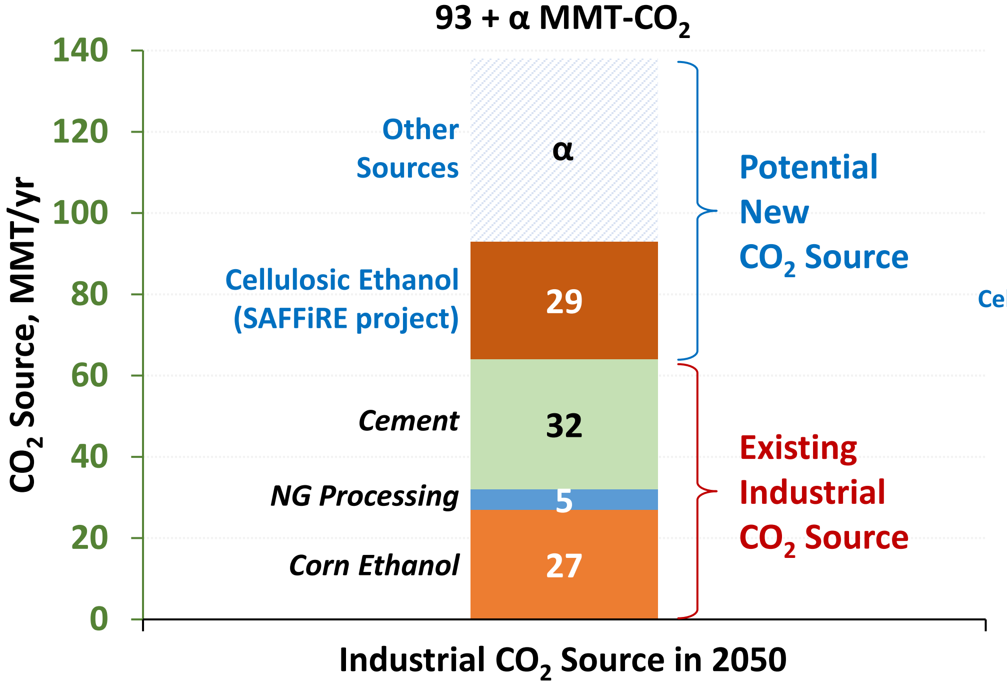
Facility Location	Energy Demand (TWh/yr)	SAF Production (million gallons/yr)		Retail Rate ($/MWh)	Financial PPA ($/MWh)
		LTE-SF-ETS	RWGS-FTS		
El Segundo, California	5.8	67	22	35	35–48
Sulphur, Louisiana	4.5	52	17	49–51	33–45
Arthur, Iowa	11.2	131	42	71	26–36

2.5 CO_2 Sources for SAF Production in 2050 (FY23 Q2)

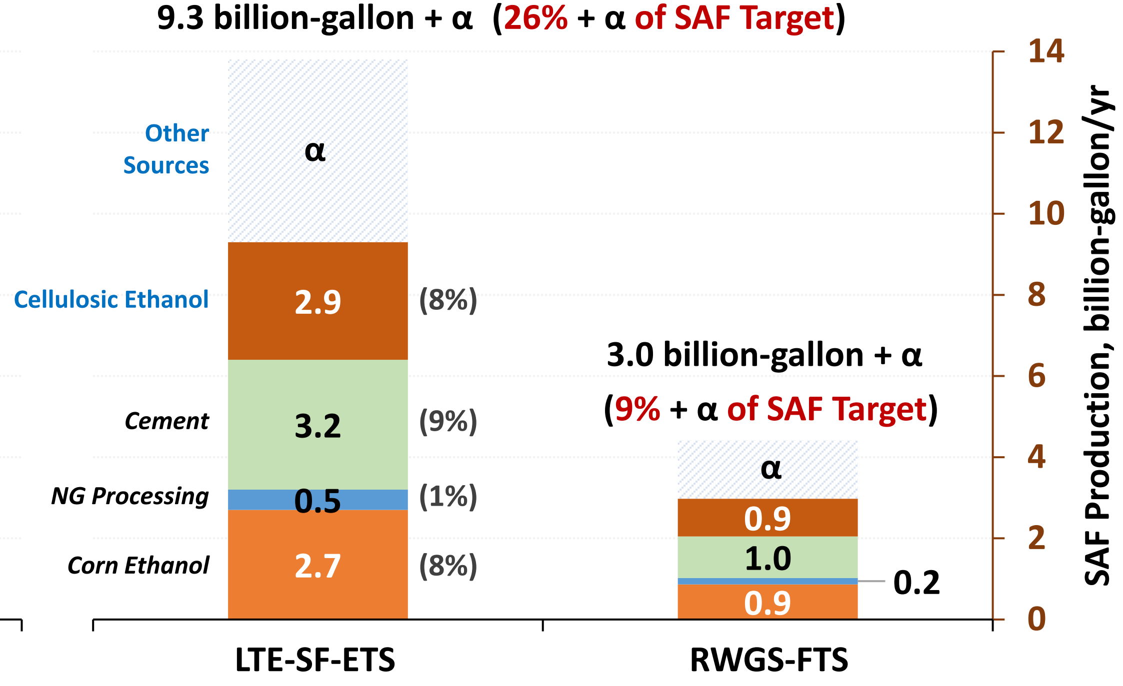
- **64 MMT-CO_2** from selected industrial CO_2 sources
- **29 MMT-CO_2** from new cellulosic ethanol plants
- Other sources (e.g., direct air capture, carbon capture and storage) may be available but the analysis does not depend on them.

- Potential SAF production from the 93 MMT-CO_2
  - LTE-SF-ETS = ~9 billion-gallon (26% of SAF Target)
  - RWGS-FTS = ~3 billion-gallon (9% of SAF Target)

2050 CO_2 Sources



CO2U SAF Production Potential in 2050



Low temperature electrolysis - syngas fermentation - ethanol to SAF

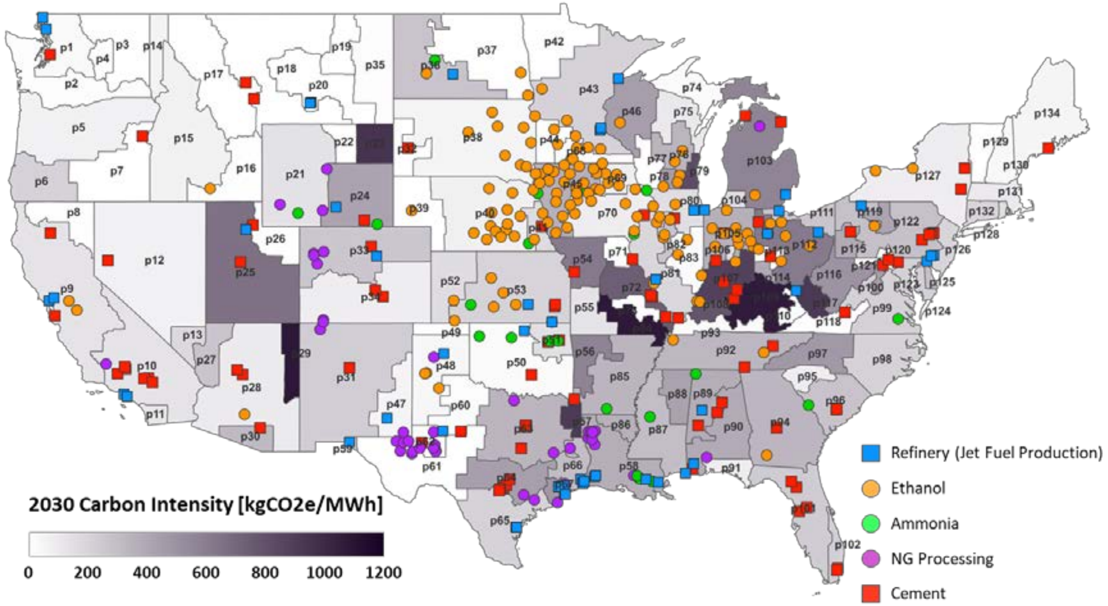
Reverse water gas shift - Fischer Tropsch to SAF

2.6 Future Milestones

Date	Milestone Name/ Description	Type
6/30/2023	Determine whether sufficient 2050 data is available	Go/No-Go ✓
6/30/2023	Joint with WBS#2.1.0.504, conduct grid modeling and CO2U conversation pathways analysis; Estimate delivery and storage cost of CO2 and intermediates	Quarterly Progress Measure
9/30/2023	Develop data sources and approach for emission inventory; Estimate hydrogen delivery and storage costs	Quarterly Progress Measure
9/30/2023	Evaluate the potential of CO2U in 2050, including market locations and sizes, CO2 sources, electricity prices, emissions, and EEJ impacts	Annual Milestone

3.1 Impact for DOE and BETO

- Provide detailed analysis on **CO2U's potential contribution** towards the 2030 and 2050 SAF production targets.
- Inform DOE's R&D roadmap by providing a holistic analysis of economic, carbon, and energy justice metrics.
- **Support BETO's cost target analysis by providing location-specific costs for CO_2, H_2, electricity, resource availability and transportation costs.**
- Support BETO decarbonization goals by assessing various sustainability metrics associated with CO2U **deployment that utilizes low-carbon electricity**
- Provide insights on the impacts of site and technology selection on various EEJ metrics for different demographic groups to inform equitable DOE investment.

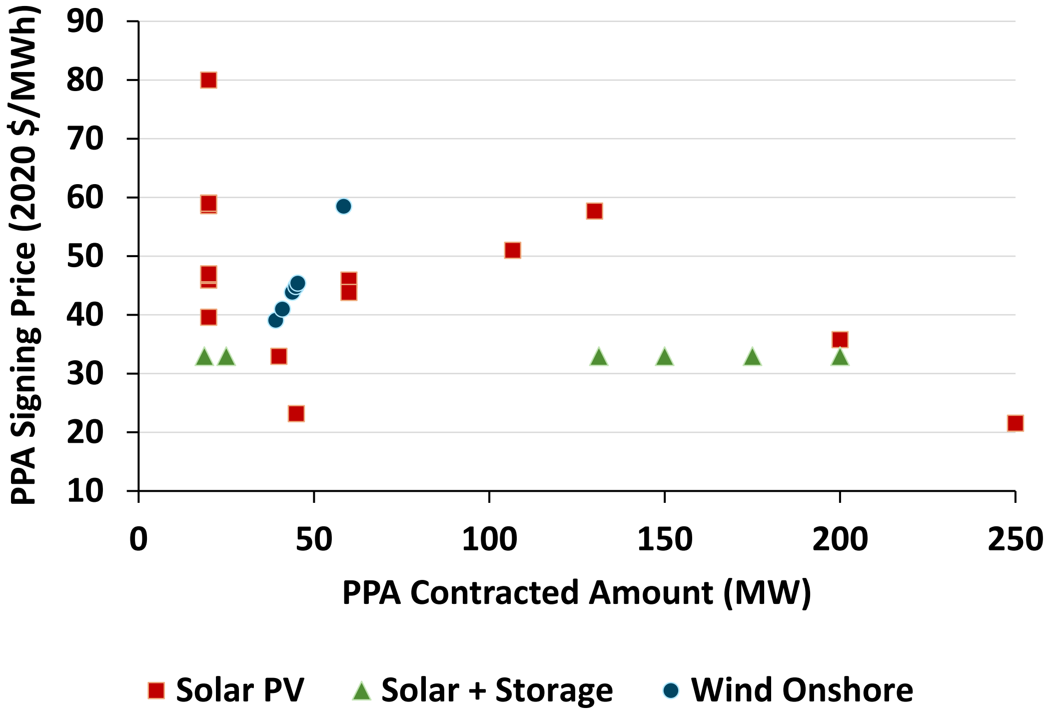


CO_2 Sources and Estimated Power System Carbon Intensities ($kg\ CO_2e/MWh$) in Low Renewable Energy Cost Scenario in 2030 (Li et al. 2023)

3.2 Impact for Industry

- Facilitate project selection and feasibility assessment by providing location-specific costs and availability for CO_2, H_2, delivery infrastructure, and low-carbon electricity.
- Provide insights on the costs, carbon intensities, and risks of various electricity purchasing options for key markets (CA, LA, IA, KS, and IL).
- Inform industry development by providing information on near- and long-term resource availability, SAF markets, electricity cost and carbon intensity projections.
- Provide insights related to corporate sustainability, including potential impacts on air quality, carbon emissions, and energy justice.

< Example: Electricity Purchasing Options Analysis>



Historical PPA Prices and Contract Sizes in California (Li et al. 2023)

3.3 Impact for the Research Community

- Developed a multisector, multidisciplinary modeling framework that evaluates the interactive impacts between the power system and the CO2U industry as well as their associated environmental and energy justice outcomes.
- Inform R&D efforts and improve sustainability assessment by providing estimates of CO_2 and H_2 sources, delivery costs, electricity costs, and environmental impacts.
- Provide detailed data on CO_2 availability and costs, electricity price, generation mix, and carbon intensity of the CO2U products for other research efforts, such as the TEA-LCA Project (WBS 2.1.0.506 & 507) and the Feasibility Study (WBS: 2.1.0.304)
- Assessment of environmental and energy justice (EEJ) for the 2050 scenarios, accounting for CO2U industry-induced changes in the power system, will be provided to the broader community of interests.
- Published two technical reports
- Additional project results will be disseminated through Consortium websites, journal articles, conference talks and/or webinars.

Summary

Today's production and market locations for fuels and chemicals are largely determined by fossil fuel resources and existing infrastructure (e.g., natural gas and petroleum oil).

To achieve DOE's decarbonization and energy justice objectives, at-scale investment in CO2U technologies needs to be informed by detailed analyses of CO_2 and H_2 resources and costs, non-fossil electricity availability and prices, air emissions, job and GDP impacts, and other factors.

This project informs the development of the CO2U industry by (1) assessing the resource potential, market potential, and infrastructure requirements for near-term (2030) and long-term (2050) deployment of CO2U technologies; and (2) evaluating the EEJ implications. The insights can be used across a large portfolio of CO2U technologies so stakeholders can make decisions according to both economic and societal factors.

Markets, Resources, and EEJ of CO_2-to-Fuels Technologies/2.1.0.504

01/01/2022 – 09/31/2024

	FY22 Costed	Total Award
DOE Funding	\$700,000 (NREL)	\$2,025,000 (NREL); \$600,000 (ANL)

Project Partners

- Economics and Sustainability of CO_2 Utilization Technologies with TEA and LCA (WBS: 2.1.0.506/ 2.1.0.507)
- Feasibility Study of Utilizing Electricity to Produce Intermediates from CO_2 and Biomass (WBS: 2.1.0.304)
- Integrated life cycle sustainability analysis (ILCSA) (WBS: 4.2.1.31)

Project Goal

Quantify location-specific H_2 and CO_2 resources and costs of their delivery and electricity demand; assess CO_2 utilization product market sizes and values. Evaluate the environmental and energy justice (EEJ) implications of deploying CO2U technologies in the near term and long term and identify alternative system developments and deployment options required to achieve DOE's EEJ goals.

End of Project Milestone

Draft report summarizing the potential for a CO2U industry in 2050, including market locations and sizes, CO_2 sources, electricity availability and prices, and air quality & associated health impacts, and socioeconomic factors.

Funding Mechanism

Annual Operating Plan FY22

List of Abbreviations and Acronyms

AEO	Annual Energy Outlook
ANL	Argonne National Laboratory
BEIOM	Bio-based circular carbon economy Environmentally-extended Input-Output Model
BETO	Bioenergy Technologies Office (DOE)
CO_2	carbon dioxide
CO2e	carbon dioxide equivalent
CO2U	carbon dioxide utilization
DOE	U.S. Department of Energy
EEJ	environmental and energy justice
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EtOH	ethanol
FT	Fischer–Tropsch
GHGRP	Greenhouse Gas Reporting Program (U.S. Environmental Protection Agency)
GREET (model)	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
H2	hydrogen
ILCSA	Integrated life cycle sustainability analysis
InMAP	Intervention Model for Air Pollution
kWh	kilowatt-hours

List of Abbreviations and Acronyms

LCA	life cycle assessment
LTE-SF-ETS	Low temperature electrolysis - syngas fermentation - ethanol to SAF
MMT	million metric tons
MWh	megawatt-hour
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
$PM_{2.5}$	particulate matter, 2.5 microns or less
PPA	power purchase agreement
R&D	research and development
ReEDS	Regional Energy Deployment System Model
RWGS-FTS	Reverse water gas shift - Fischer Tropsch to SAF
SAF	sustainable aviation fuel
TEA	techno-economic assessment
TM	technical monitor
TWh	terawatt-hours

References

Cole, Wesley, J., and Vincent Carag. 2022. *2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-80641. https://doi.org/10.2172/1834042.

Herron, Steve, Zoelle, Alexander, and Summers, Wm Morgan. 2014. *Cost of Capturing CO2 from Industrial Sources*. Pittsburgh, PA: National Energy Technology Laboratory. NETL-2013/1602. https://doi.org/10.2172/1480985

Hughes, Sydney, Zoelle, Alex, Woods, Mark, Henry, Samuel, Homsy, Sally, Pidaparti, Sandeep, Kuehn, Norma, Hoffman, Hannah, Forrest, Katie, Fout, Timothy, Summers, William, Herron, Steve, and Grol, Eric. 2022. *Industrial CO2 Capture Retrofit Database (IND CCRD).* Pittsburgh, PA: National Energy Technology Laboratory. NETL-2022/3319.

Li, Yijin, Bethany Frew, Mark Ruth, and Ella Zhou. 2022. *Electricity Costs and Carbon Implications for CO_2-to-Fuels in Selected Locations in 2030*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-82573. https://doi.org/10.2172/1899988.

Li, Yijin, Ella Zhou, Ling Tao, Kwang Hoon Baek, Pingping Sun, and Amgad Elgowainy. 2023. *Near-Term Electricity Requirement and Emission Implications for Sustainable Aviation Fuel Production with CO_2-to-Fuels Technologies.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-84838. https://www.nrel.gov/docs/fy23osti/84838.pdf.

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