DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

USDRIVE Net Zero Carbon Fuels Technical Team (NZTT)

April 4, 2023
DMA

Ling Tao – NREL
Uisung Lee and Peter Chen – ANL
Wenqin Li and Hannah Goldstein – LLNL
Aye Meyer – PNNL

Project Overview

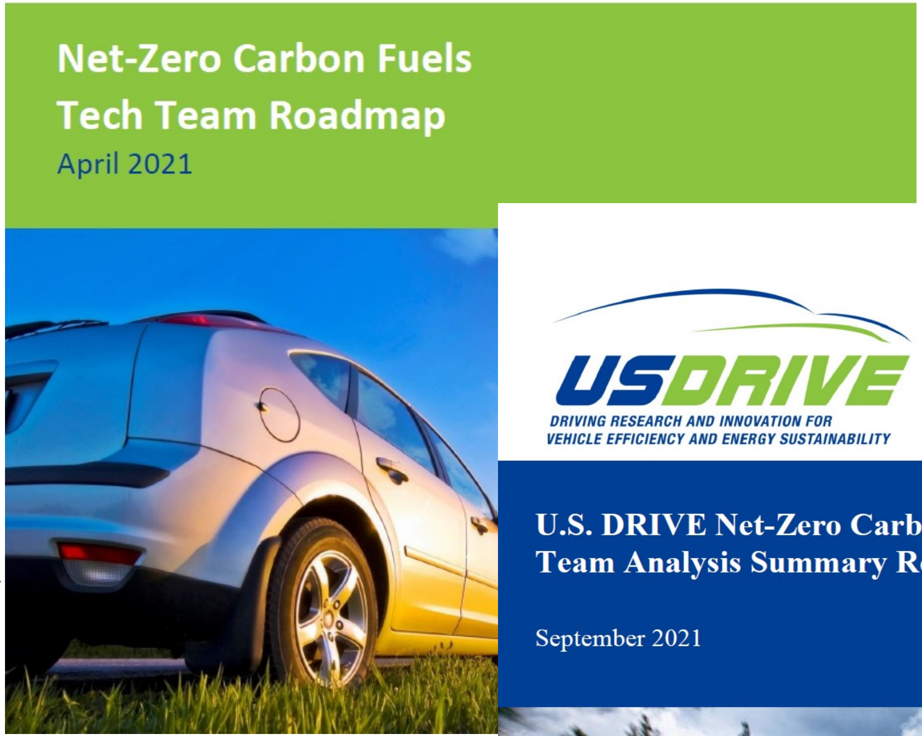
USDRIVE stands for **D**riving **R**esearch and **I**nnovation for **V**ehicle efficiency and **E**nergy sustainability. It is a non-binding and voluntary U.S. government-industry partnership focused on advanced automotive and related energy infrastructure technology R&D.

Net Zero Carbon Fuels Technical Team (NZTT) Project Scope: Investigate options for generating liquid carbon-based fuels with a reduced carbon intensity (CI) such that, from a life cycle carbon accounting standpoint, they have a net carbon emissions profile approaching zero.

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Roadmap Report:
https://www.energy.gov/sites/default/files/2021-04/NZTT_Roadmap_v202010401_FINAL.pdf

FY20 Report :
https://www.energy.gov/eere/vehicles/articles/us-drive-net-zero-carbon-fuels-technical-team-analysis-summary-report-2020



1. **Approach:** Project Management

USDRIVE

DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Executive Steering Group

Joint Operations Group

Technical Teams

- Advanced Compute
- Batteries
- Electric-Drive
- Materials

Joint Technical Teams*

- Fuel Cells
- Grid Integration
- Hydrogen
- Integrated Systems Analysis
- Net-Zero Carbon Liquid Fuels
- Vehicle and Mobility Systems Analysis

*technical teams are joint with the 21st Century Truck Partnership

USDRIVE NZTT: US Department of Energy, Fuels Industry, Electric Utilities, Automotive Industry, Associate members, national lab analysis team.

Analysis Team:

- ***NREL:*** *Ling Tao (TEA)*
- ***PNNL:*** *Aye (Pimphan) Meyer, Lesley Snowden-Swan and Shuyun Li (TEA)*
- ***ANL:*** *Uisung Lee and Peter Chen (LCA)*
- ***LLNL:*** *Wenqin Li and Hannah Goldstein (LCA)*

Monthly Meetings

Biweekly Meetings

Risk Mitigation Strategies:

- Frequent meetings with the USDRIVE NZTT industrial collaborators and advisors
- Advance and integrate analysis to focus on critical decarbonation issues and solutions

1. **Approach:** Integrate TEA and LCA

Carbon Conversion Pathways

Reducing the carbon dioxide (CO_2) emissions from the transportation industry is a key target for achieving global net-zero carbon goals.

Numerous options exist for decarbonization strategies, what are the tradeoffs between TEA/LCA?

Integrated TEA and LCA

Process models developed in Aspen Plus

Discounted cash-flow rate of return analysis and sustainability assessment conducted

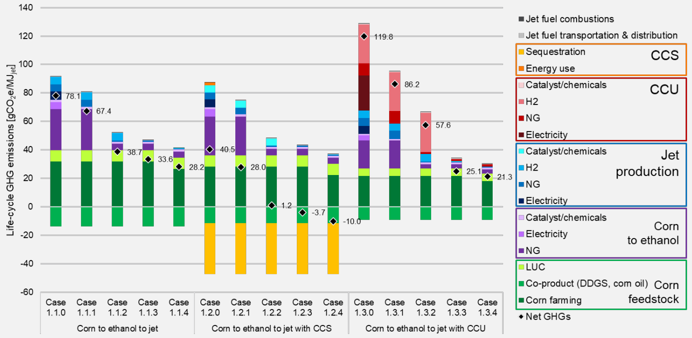
Key metrics identified and leveraged to generate comparative analysis & Regional Analysis

Take an "LCA-first" approach to assessing potential renewable fuel pathways, where the technology is optimized for reduced carbon intensity and the techno-economics of these pathways are assessed to determine the associated cost of carbon mitigation for a given technology solution set.

1. **Approach:** LCA Methodology

- Analyze the life-cycle GHG emissions of various low-carbon fuel production pathways.
- The system boundary includes all supply chain of life-cycle stages including energy and material inputs.
- ANL's GREET model is used to evaluate the supply chains of various fuel production pathways.
- Through close communication with the TEA team, the LCA uses the same assumptions used in TEA so that the results are related each other.

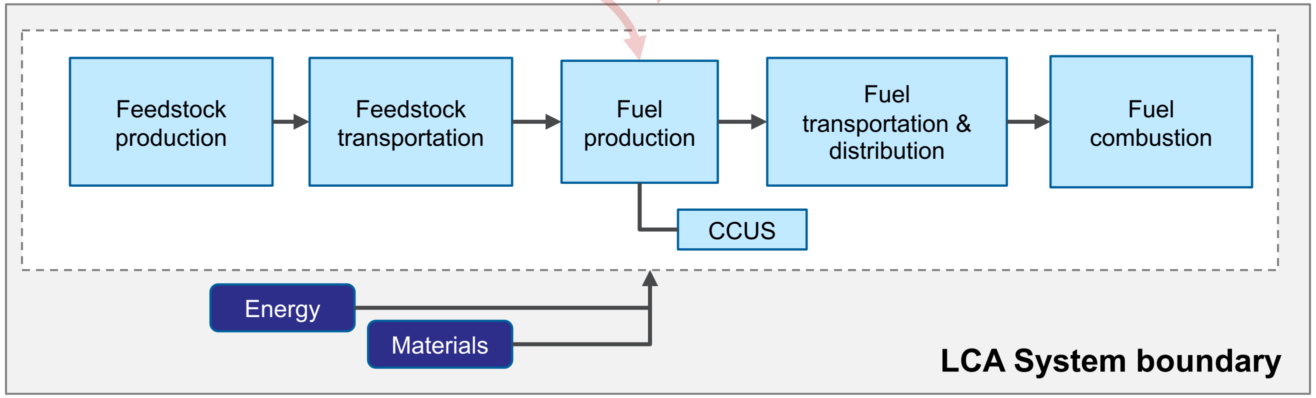
Life-cycle GHG emissions



NREL Process modeling

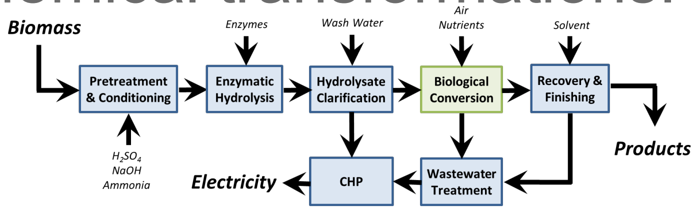
aspentech

ANL GREET

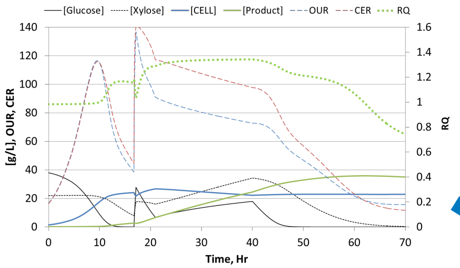


1. **Approach:** TEA Methodology

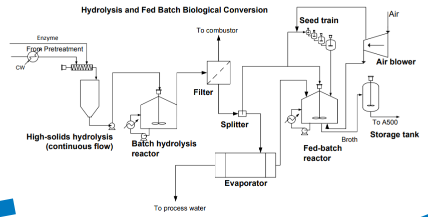
1) Conceptual process is **formulated or refined based on current research** and expected chemical transformations.



2) Individual unit operations are **designed and modeled using experimental data**.



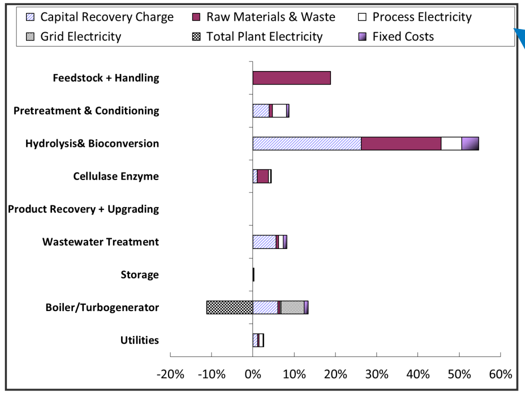
3a) Identify **the major cost drivers**.



GREET LIFE-CYCLE MODEL

3b) Identify **the major sustainability drivers**.

4) Results and **new understanding is fed back** into step 1) and the process iterates.



1. **Approach:** Low-Carbon Scenarios

Evaluates potential emission reduction and corresponding cost by considering renewable energy inputs (renewable electricity, renewable H_2, renewable natural gas, and green ammonia) and carbon capture sequestration (CCS) and carbon capture and utilization (CCU) options.

TEA

Resource	Minimum	Baseline	Maximum
Conventional electricity ($/kWh)		$0.068	
Renewable electricity ($/kWh)	$0.02	$0.068	$0.10
Conventional H_2 ($/kg)		$1.38	
Renewable H_2 ($/kg)	$1.38	$4.50	$6.35
Conventional NH_3 ($/kg)		$0.59	
Renewable NH_3 ($/kg)		$1.37	

	Feedstock	Cost Range ($/MMBtu[a])		
		Minimum	Baseline	Maximum
Anaerobic digestion	Landfill gas	$7.10	$13.05	$19.00
	Animal manure	$18.40	$25.50	$32.60
	Wastewater sludge	$7.40	$16.75	$26.10
	Food waste	$19.40	$23.85	$28.30
	RIN[b]	$7.48	$12.00	$29.44

CCS Parameter	Value
CO_2 sequestration cost	$10/tonne CO_2 (2016 dollars)

LCA

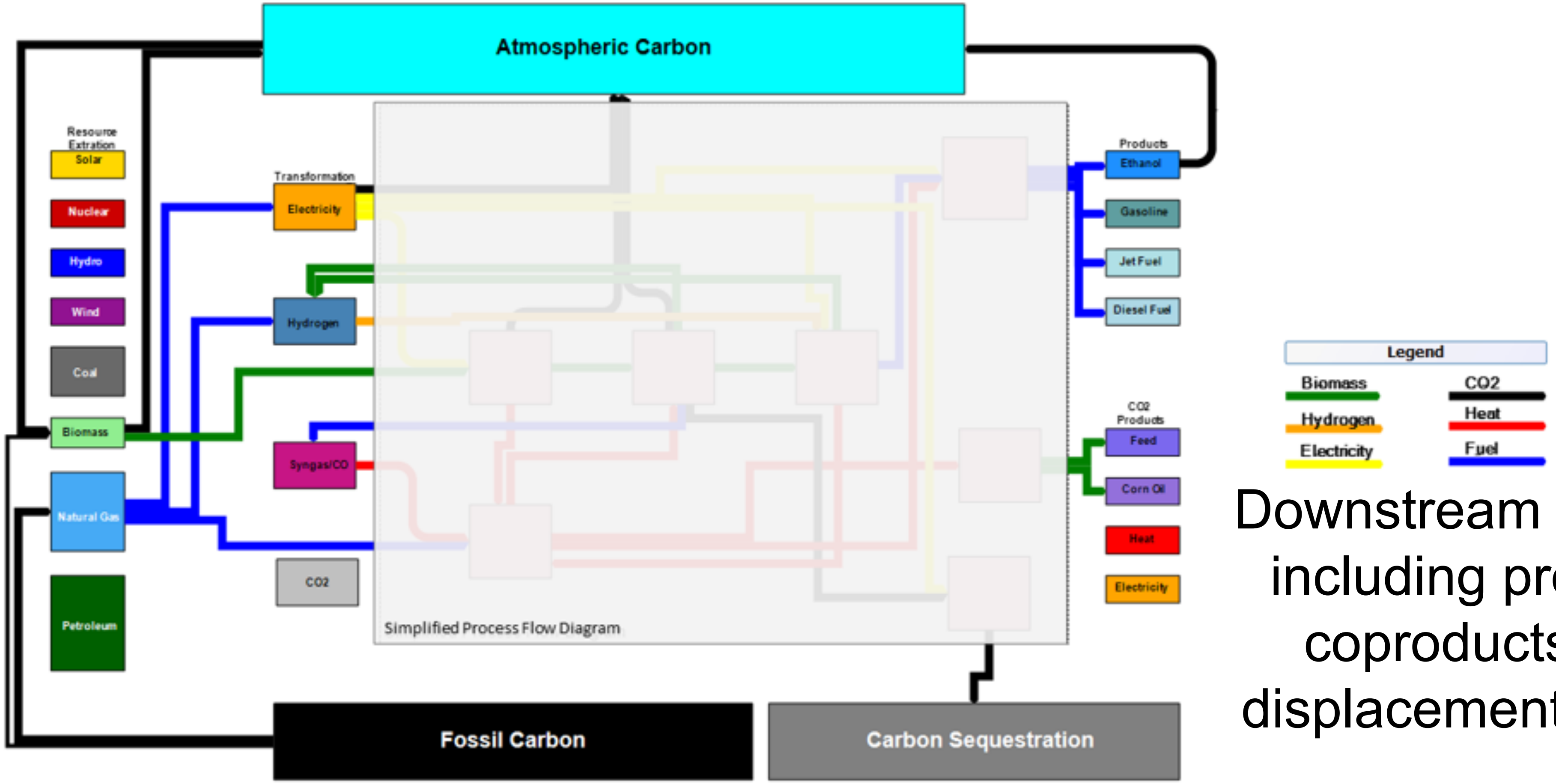
	Conventional Scenario	Renewable Scenario
Electricity	U.S. grid mix (2020) 440 gCO_2e/kWh	Renewable electricity 0 gCO_2e/kWh
H_2	NG SMR (off-site, 50 miles) 79 gCO_2e/MJ Compare to electrolysis with grid electricity 170 gCO_2e/MJ (on-site)	Electrolysis with renewable electricity 0 gCO_2e/MJ (on-site) 0.5 gCO_2e/MJ (off-site, 50 miles)
NG	Fossil NG 69 gCO_2e/MJ	Renewable natural gas from landfill gas 11 gCO_2e/MJ
Ammonia	Conventional ammonia 2,636 gCO_2e/kg	Green ammonia 293 gCO_2e/kg

CCS Parameter	Value
Electricity use for CO_2 compression	112 kWh/tonne CO_2

1. Approach

Analyze varying connectivity flows between resources, intermediates, process configuration, and products.

Upstream conversions, logistics, and process inputs considered.



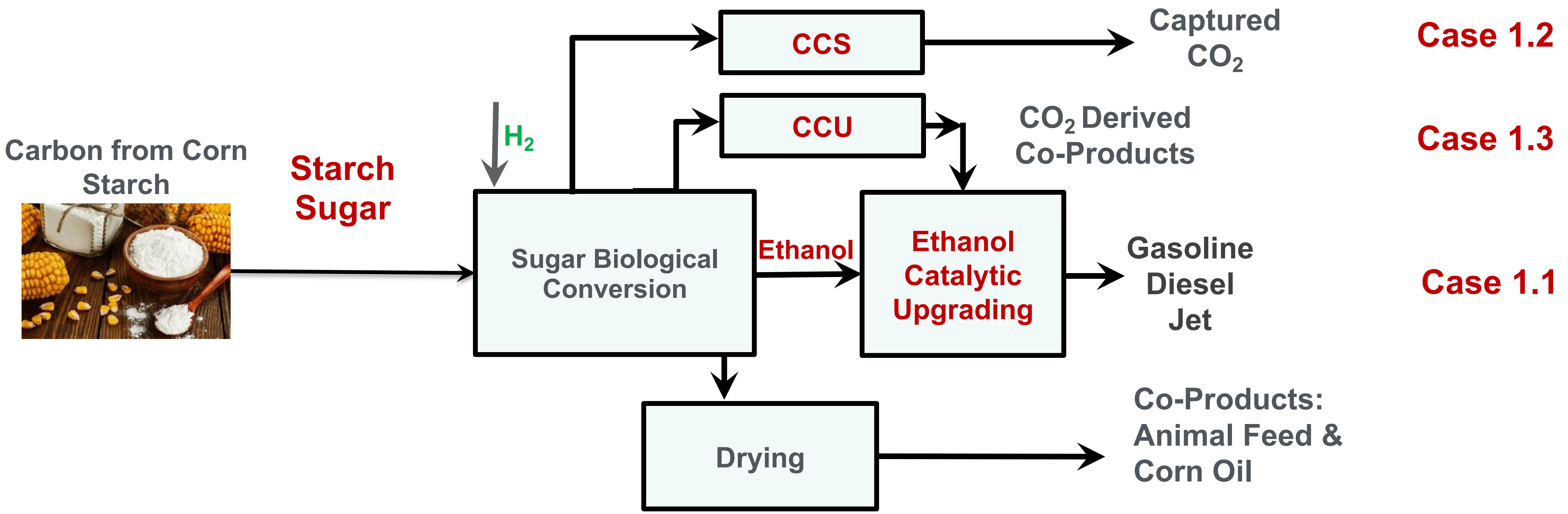
Downstream process, including products, coproducts, and displacement credits.

2. Progress and Outcomes: Comprehensive Pathway Considerations

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Year	Case #	Pathway	Feedstock	Intermediate	Conversion Technology	Product	Decarbonization strategies
Year 1	Case 1	Ethanol from corn	Corn	-	Fermentation	Ethanol	RE, RNG, Green NH3, CCS
	Case 2	HC fuel blendstocks from algae	Algae	HTL biocrude	HTL + Hydrotreating	Gasoline, Diesel and SAF Blendstocks	RE, RNG, RH2
	Case 3.1	Ethanol from woody biomass	Woody Biomass	Syngas	Gasification + Syngas Fermentation	Ethanol	RE, RNG, RH2
	Case 3.2	Ethanol from CO2	CO2	Syngas	Electrification + Syngas Fermentation	Ethanol	RE, RNG, RH2
	Case 4.1	Methanol from woody biomass	Woody Biomass	Syngas	Gasification + Methanol Synthesis	Methanol	RE, RH2, CCU
	Case 4.2	Methanol from CO2	CO2	Syngas	Electrification + Methanol Synthesis	Methanol	RE, RNG, RH2
	Case 4.3	Methanol from CO2	CO2	CO	Electrification + Methanol Synthesis	Methanol	RE, RNG, RH2
	Case 4.4	High octane gasoline from woody biomass	Woody Biomass	Syngas and Methanol	Gasification + Methanol Synthesis + MeOH Conversion	High Octane Gasoline	RE, RH2, CCU
Year 2	Case 1	SAF from corn ethanol	Corn	Ethanol	Fermentation + Ethanol Upgrading	SAF	RE, RH2, Green NH3, CCS, CCU
	Case 2	SAF from cellulosic ethanol	Corn Stover	Ethanol	Fermentation + Ethanol Upgrading	SAF	RE, RH2, Green NH3, CCS, CCU
	Case 3	HC fuel blendstocks from woody biomass	Woody Biomass	Syngas	Gasification + Fischer Tropsch Synthesis	Gasoline, Diesel and SAF Blendstocks	RE, RH2, RNG, CCS, CCU
	Case 4	HC fuel blendstocks from wet waste	Sludge from WWT	HTL Biocrude	HTL + Hydrotreating	Gasoline, Diesel and SAF Blendstocks	RE, RNG, RH2
	Case 5	SAF from DAC CO2	DAC CO2	Syngas	DAC + Electrification + Fischer Tropsch Synthesis	Gasoline, Diesel and SAF Blendstocks	RE, RNG, RH2, CCS

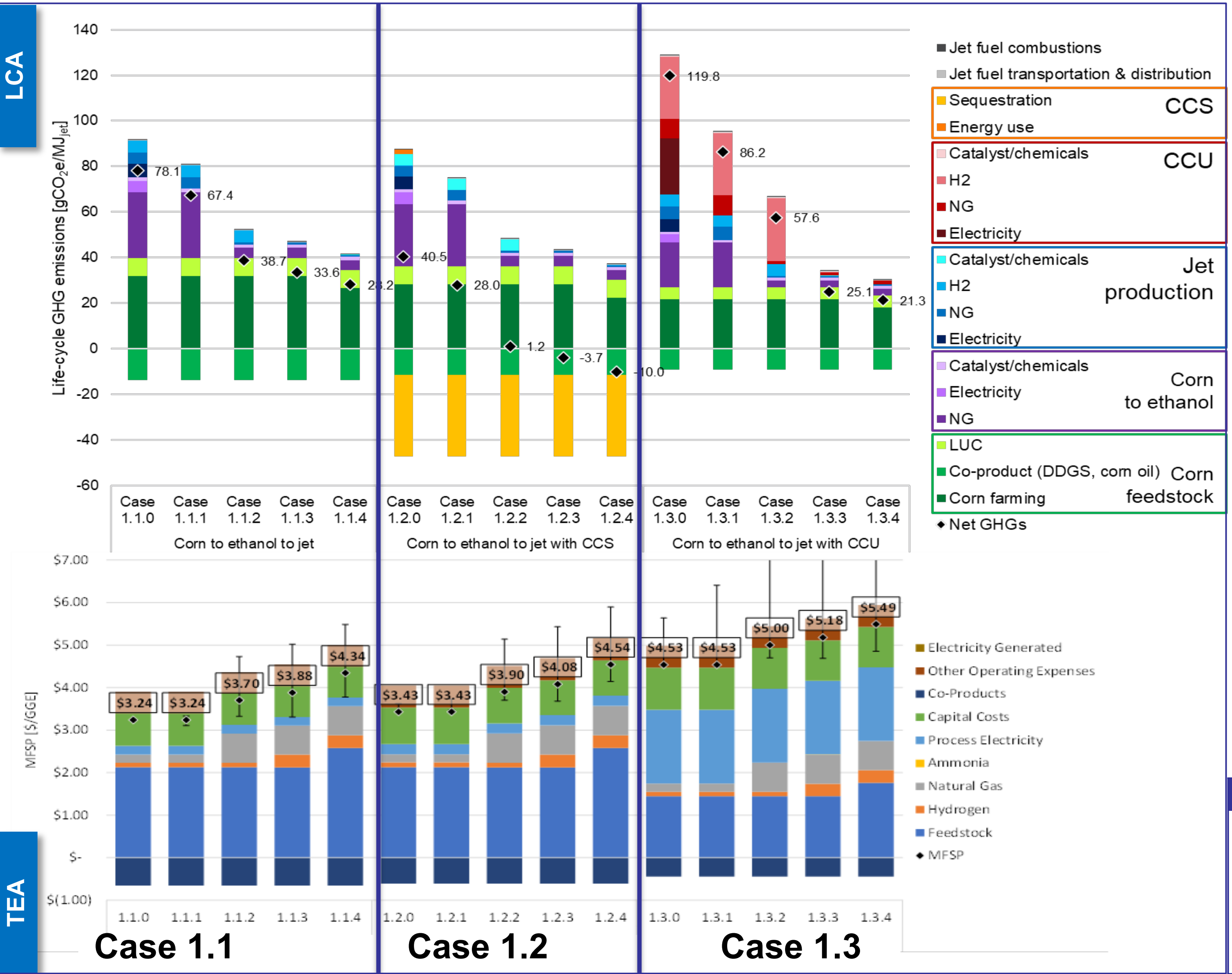
2. Progress and Outcomes: Year 2 Case 1 Starch Ethanol (Example)



- Extent corn ethanol to ethanol to jet.
- Consider renewable sources of H_2 and process heat.
- Include both CCS and CCU options as emission reduction strategies.

Case
1.1 – Starch EtOH with catalytic upgrading to Jet
1.2 – Starch EtOH with catalytic upgrading to Jet & CCS
1.3 – Starch EtOH with catalytic upgrading to Jet & CCU

2. Progress and Outcomes: TEA/LCA Results



- Corn ethanol and ethanol to SAF reduces carbon intensity (CI) by 7% when compared with fossil baseline.
- Renewable energy sources can substantially reduce the CI.
- CCS can make the fuels to be carbon negative with marginal increase in cost.
- CCU provides additional fuel production utilizing waste carbon; however, depending on the input energy sources, CIs may increase.

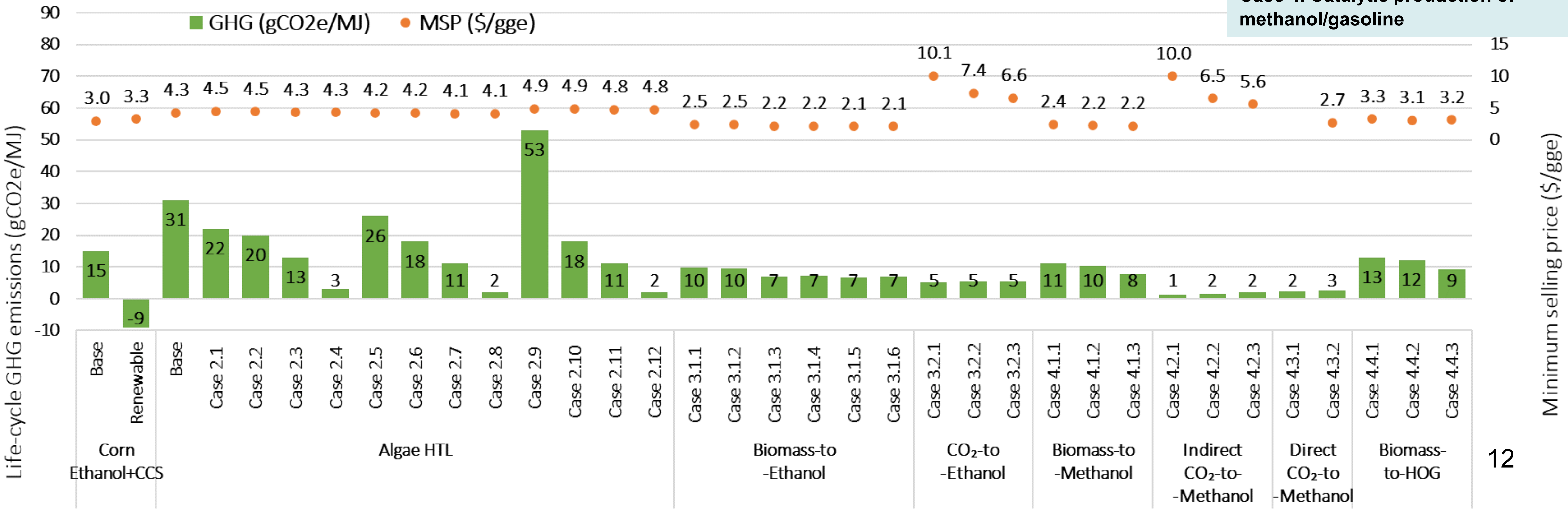
Case	Electricity	NG	H_2	Ammonia
1.X.0	US mix	fossil	SMR	conventional
1.X.1	renewable	fossil	SMR	conventional
1.X.2	renewable	landfill	SMR	conventional
1.X.3	renewable	landfill	Renewable	conventional
1.X.4	renewable	landfill	Renewable	green

2. Progress and Outcomes: Year 1 Results of All Pathways

- Evaluated four low-carbon fuel production pathways evaluated, which presents economic and environmental tradeoffs.
- Found significant low-carbon fuel production potential through incorporation of renewable energy and CCU/CCS options with biofuel production and CO_2 utilization pathways of various TRL conditions.

This chart just shows a high-level summary; details can be found in [the USDRIVE report](#)

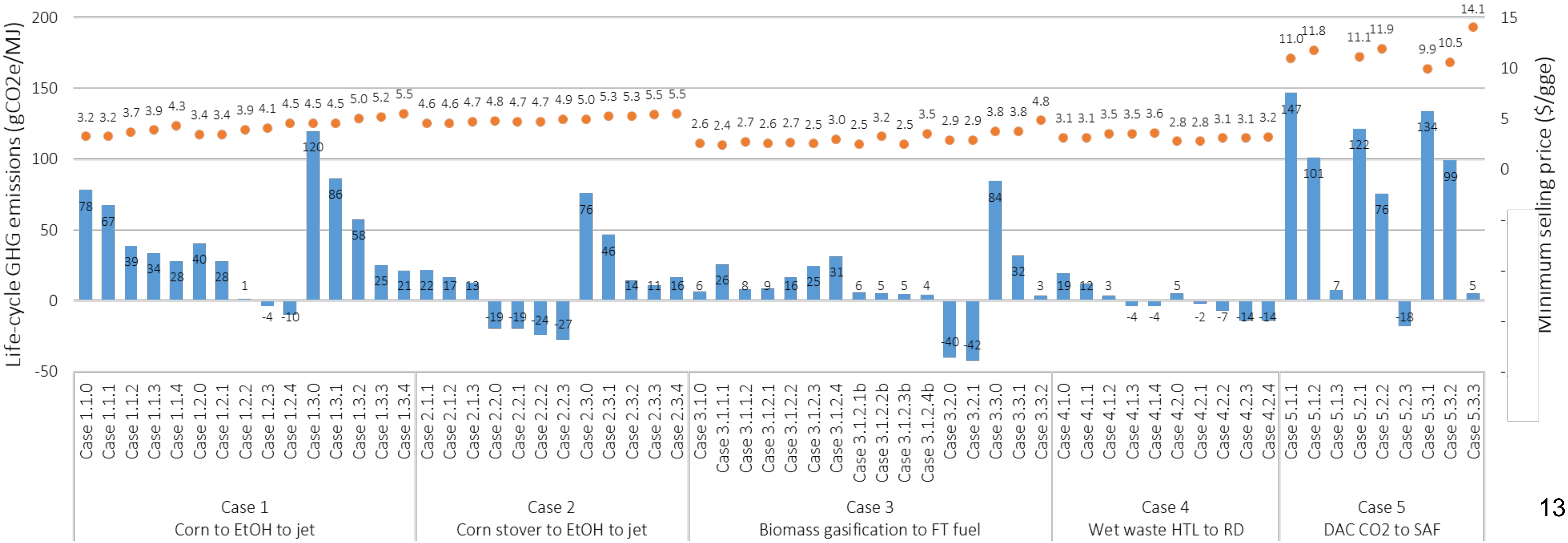
Case 1. Conventional ethanol with CCS
Case 2. Drop-in fuels from HTL of algae
Case 3. Ethanol production from syngas fermentation
Case 4. Catalytic production of methanol/gasoline



2. Progress and Outcomes: Year 2 — Results of All Pathways

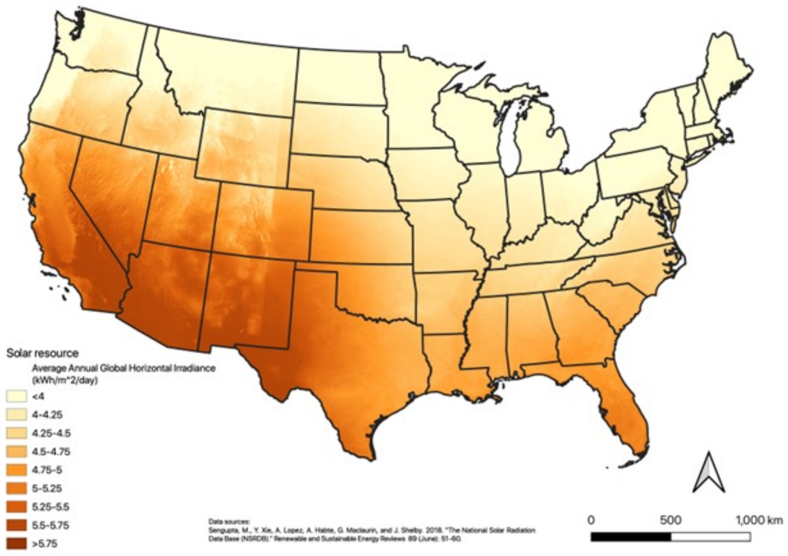
- Evaluated five additional low-carbon fuel production pathways.
- Most pathways require both technical maturation of core conversion processes and one or more process inputs (e.g., feedstock, electricity, process heat) to be substantially decarbonized to deliver a net-zero product.

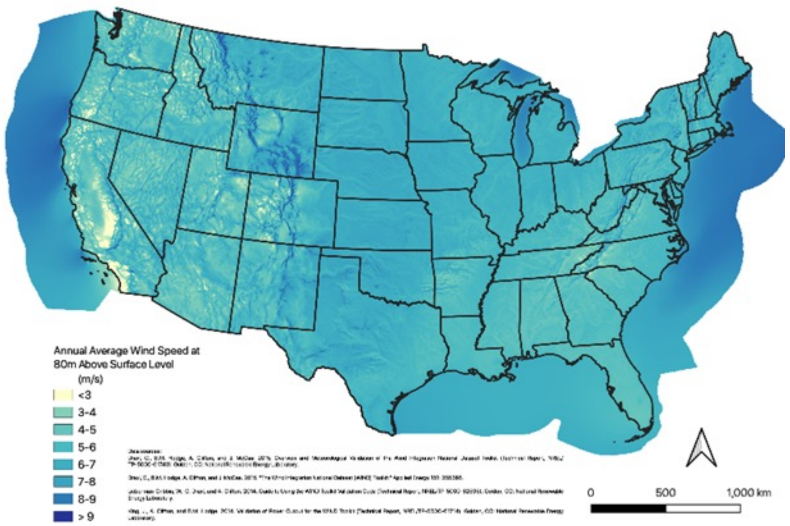
This chart just shows a high-level summary; the report will be released through BETO/EERE.



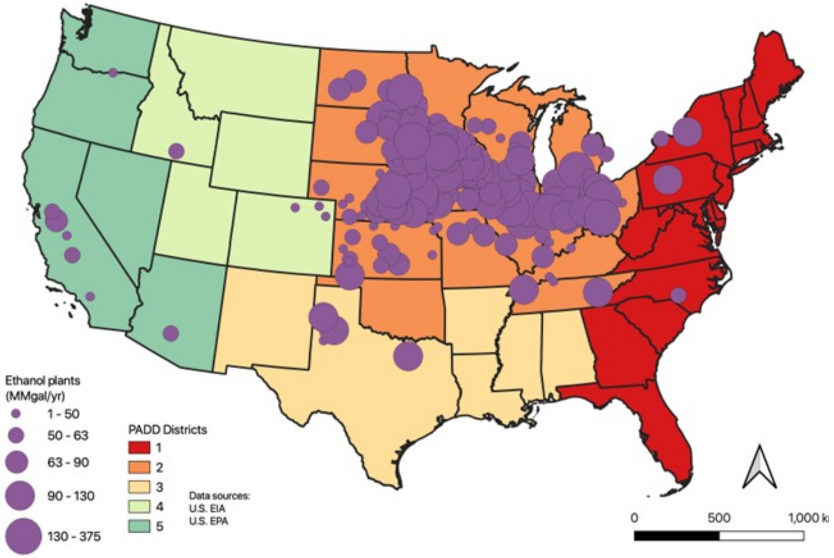
2. Progress and Outcomes: Regional Analysis

Renewable Energy Sources

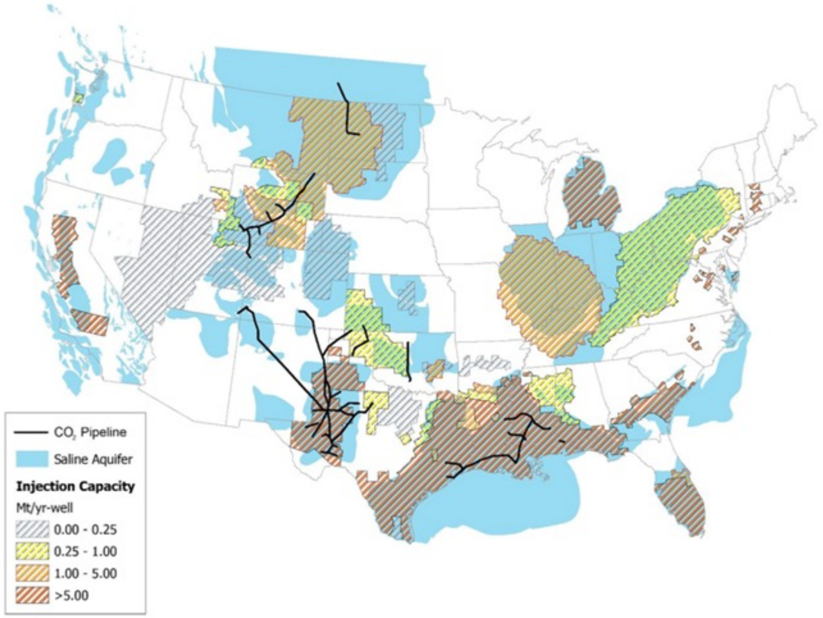




Bioethanol Plants



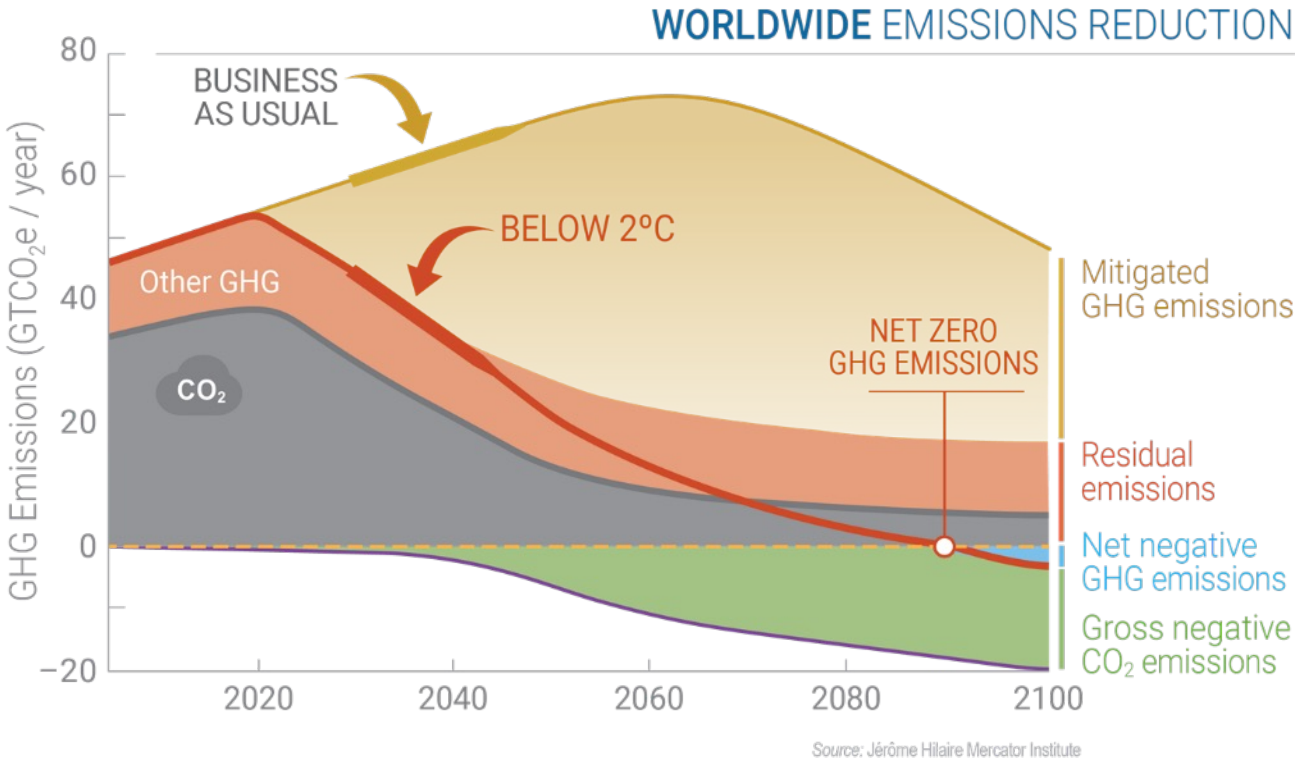
CO_2 Storage and Pipelines



- Impact analysis with consideration of CCS/CCU, geographical relevant resources (or supply chain).
- Renewable electricity and renewable hydrogen.
- Carbon transportation and sequestration.

3. **Impact:** Align with BETO's Goals

- BETO Goal (1): Develop low-cost, reliable feedstock supply from the entire range of biomass waste.
- BETO Goal (2): Develop carbon management strategies including soil carbon storage and carbon drawdown.
- BETO Goal (3): Develop waste management and environmental remediation strategies.



3. Impact: Synergize with BETO, EERE and Industry

Toward achieving U.S. DRIVE Mission. We maintain **synergies with BETO project portfolio, other EERE Offices and industry stakeholders** by:

- Monthly discussion and exchanging data with USDRIVE NZTT team.
- Validate our analysis works by collaborations and exchange of data/learnings with industrial sectors (Tech team advisor).

Federal Government Partner

Office of Energy Efficiency and Renewable Energy. (Energy Efficiency Office, Renewable Energy Office, Sustainable Transportation Office).

Fuels Industry Partner

BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, Shell Oil Products US.

Net-Zero Carbon Liquid Fuels Technical Team

Argonne National Laboratory; NREL National Renewable Energy Laboratory; Lawrence Livermore National Laboratory; Pacific Northwest National Laboratory

USDRIVE – Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability

Electric Utility Industry Partner

American Electric Power, DTE Energy Company, Duke Energy, Southern California Edison Company, and the Electric Power Research Institute.

Automobile Industry Partner

U.S. Council for Automotive Research LLC (USCAR, the cooperative research organization for Ford Motor Company, General Motors Company, and Stellantis).

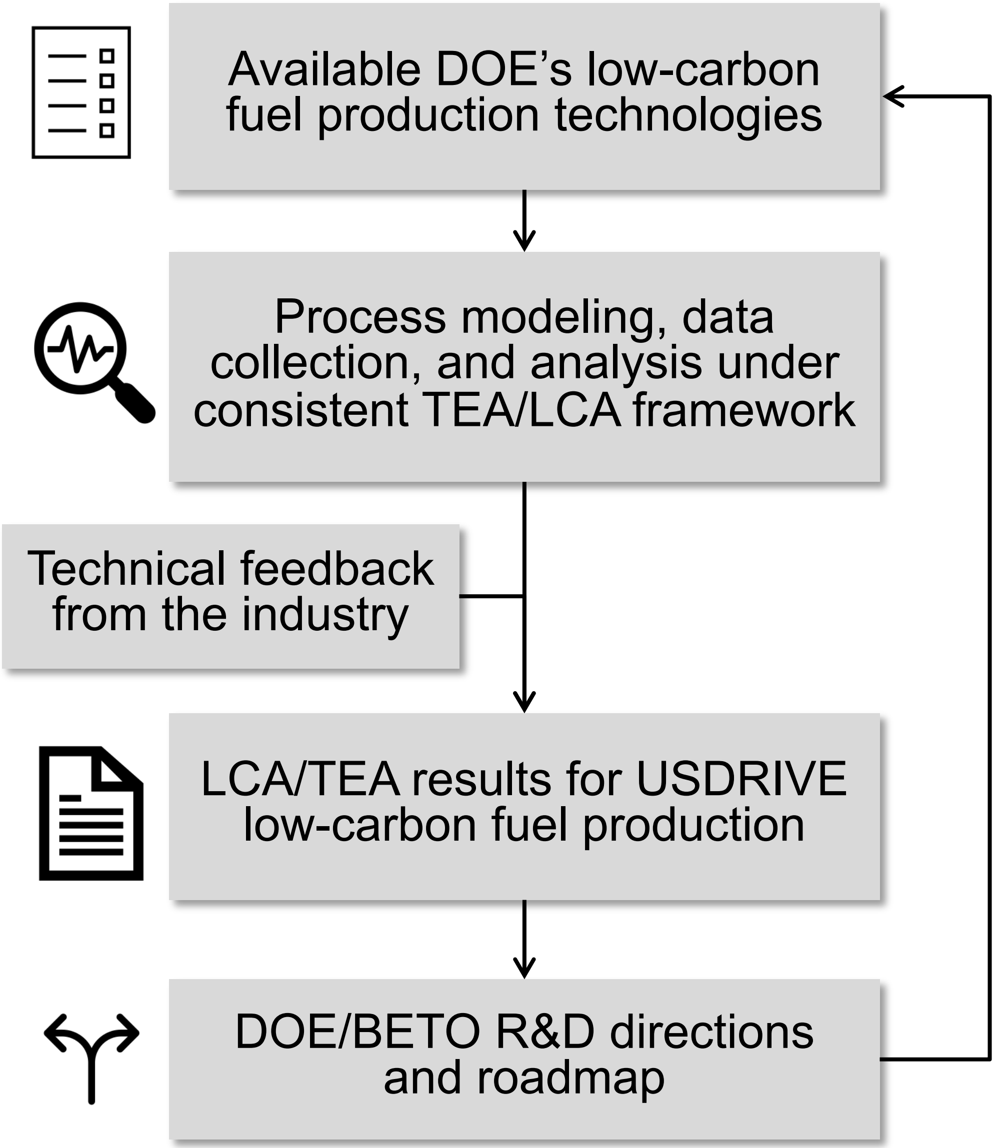
3. **Impact:** Support BETO's Mission on SAF Grand Challenge

- More than 400 biorefineries and 1 billion tons of biomass and/or gaseous feedstock will be needed to produce 35 billion gal/yr by 2050.

- Provide decarbonization options for to achieve SAF Grand Challenge's goal for the aviation sector to achieve net-zero emissions by 2050.

3. **Impact:** Provide Low Carbon Options for DOE and BETO

- The analyses provide comprehensive list of available low-carbon fuel production pathways and their economic and environmental tradeoffs and implications.
- TEA and LCA have been conducted with consistent datasets and system boundary, which enables comparing the results of various pathways.
- The analyses help DOE/BETO identify opportunities/challenges and set up the R&D directions and portfolio, which supports meeting decarbonization goals.



3. Impact

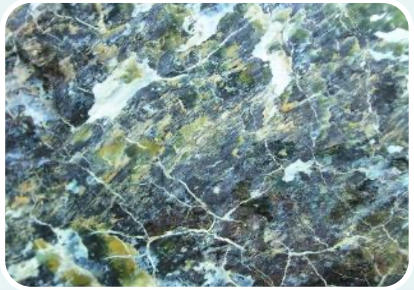
Carbon neutrality is achievable but needs the entire breadth of strategies

Coastal Blue Carbon

Terrestrial Carbon Removal and Sequestration

Biomass Energy with Carbon Capture & Sequestration

Direct Air Capture



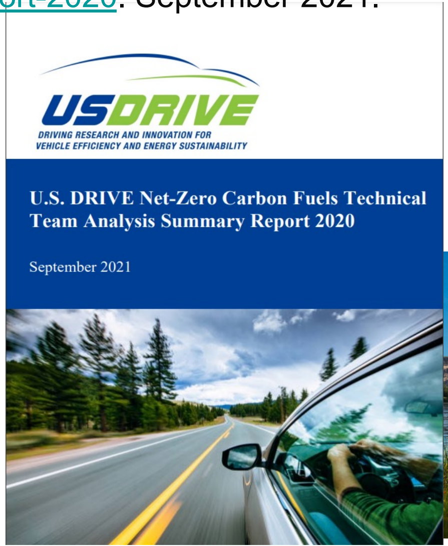
Carbon Mineralization of CO_2

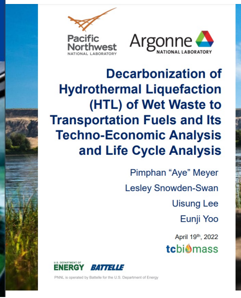
Bioeconomy Pathways are a Critical Component of the Negative Emissions Technology Portfolio

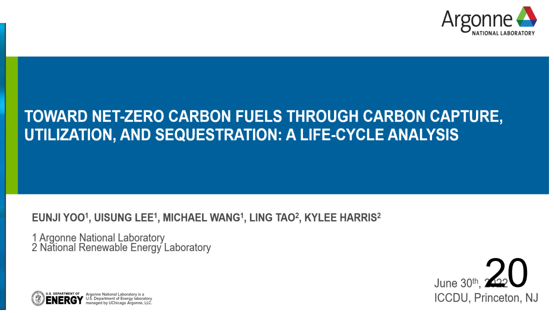
Figure source: Negative Emissions Technologies and Reliable Sequestration – A Research Agenda (National Academies Press, 2019)

3. Impact: Publications and Presentations

1. U.S. DRIVE Net-Zero Carbon Fuels Technical Team Analysis 2021 Summary Report. Pending for publication approval from EERE.
2. Tao, Ling; Lee, Uisung; Meyer, Pimphan Aye; Wenqin Li and Ian Rowe, Net Zero Carbon Fuel Pathways, SAE WCX, invited panel presentation, April 18-20, 2023
3. Tao, Ling; Lee, Uisung; Meyer, Pimphan Aye; Wenqin Li and Ian Rowe, USDRIVE Net Zero Carbon Fuel Team (NZTT), Coordinating Research Council Sustainable Mobility Committee (CRC SMC), invited presentation, December 13-15, 2022
4. Meyer, Pimphan Aye; Snowden-Swan, Lesley; Lee, Uisung; Yoo, Eunji. Decarbonization of Hydrothermal Liquefaction (HTL) of Wet Waste to Transportation Fuels and Its Techno-Economic Analysis and Life Cycle Analysis. TCbiomass 2022 Conference. April 19th, 2022. Denver, Colorado. https://www.gti.energy/wp-content/uploads/2022/05/06-tcbiomass2022-Presentation-Aye-Meyer.pdf
5. Tao, Ling; Harris, Kylee; Lee, Uisung; and Yoo, Eunji. Techno-Economic Evaluation of Strategies to Approach Net-Zero Carbon Sustainable Aviation Fuel via Woody Biomass Gasification and Fischer-Tropsch Synthesis. United States: TCbiomass 2022 Conference. April 20th, 2022. Denver, Colorado. https://www.osti.gov/servlets/purl/1865606.
6. Yoo, Eunji; Lee, Uisung. Toward Net-Zero Carbon Fuels Through Carbon Capture, Utilization, and Sequestration: A Life-Cycle Analysis. 19th International Conference on Carbon Dioxide Utilization (ICCDU) 2022. Princeton University, New Jersey. June 26-30. 2022.
7. Harris, Kylee, Grim, R. Gary, and Tao, Ling. A Comparative Techno-Economic Analysis of Renewable Methanol Synthesis Pathways from Biomass and CO2: Preprint. United States: N. p., 2021. https://www.osti.gov/biblio/1823019
8. Harris, Kylee, Grim, R. Gary, and Tao, Ling, A comparative techno-economic analysis of renewable methanol synthesis from biomass and CO2: Opportunities and barriers to commercialization, Applied Energy, Volume 303, 2021, 117637, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2021.117637. 2021
9. Harris, Kylee, Grim, R. Gary, and Tao, Ling. A Comparative Techno-Economic Analysis of Renewable Methanol Synthesis Pathways from Biomass and CO2. Presented at 12th International Conference on Applied Energy https://www.nrel.gov/docs/fy21osti/78547.pdf Dec 1. ,2020
10. U.S. DRIVE Net-Zero Carbon Fuels Technical Team Analysis 2020 Summary Report. https://www.energy.gov/eere/vehicles/articles/us-drive-net-zero-carbon-fuels-technical-team-analysis-summary-report-2020. September 2021.







Summary

❑ Approach:

- Integrate TEA/LCA to analyze a diverse set of decarbonization options for net-zero-carbon fuels.
- Routine communications with NZTT team, industrial collaborations/advisors.
- Lay the groundwork for continual assessment of net-zero-carbon fuel production options as this landscape evolves.

❑ Progress and Outcomes:

- Analyzed various carbon conversion pathways, covering a wide range of feedstocks, process inputs, products, environmental impacts, and technology with diverse TRLs.
- Identified numerous net-zero-carbon fuel strategies.
- Presented and published decarbonization strategies and shared key learnings to public.

❑ Impact:

- Directly support BETO's mission, SAF grand challenges and emission reduction goals.
- Collaborate with industry via USDRIVE NZTT platform.
- Net-zero-carbon fuel pathways are a critical component of the national and global negative emissions technology portfolio.

Quad Chart Overview

Timeline

- *2020*
- *2023*

	FY22 Costed	Total Award
DOE Funding	*$400,000*	*$1,200,000*
Project Cost Share *		

TRL at Project Start: 1-9
TRL at Project End: 1-9

Project Partners*

- USDRVE NZTT team
- DOE SA
- DOE VTO

Project Goal

- *Investigate options for generating liquid carbon-based fuels with a reduced carbon intensity (CI) such that, from a life cycle carbon accounting standpoint, they have a net carbon emissions profile approaching zero.*
- *Perform integrated TEA and LCA to assessing potential renewable fuel pathways.*
- *Optimize pathway technology to reduce carbon intensity and to assess cost trade-offs and provide solutions sets to USDRVE and DOE/BETO for a given technology solution set.*

End of Project Milestone

Continue to explore additional pathways (the combinations of feedstocks, conversion technologies, and products) to expand the coverage of net-zero-carbon fuel production pathways, as well as to perform expanded analysis on the cases reported here to include logistic, system-level, regional-level, and technical considerations. Summarize analysis findings in the year 3 report and present analysis key takeaways to USDRIVE NZTT, BETO, as well as other relevant stakeholders.

Additional Slides

Acronym List

ANL	Argonne National Laboratory
BETO	Bioenergy Technology Office
CCS	Carbon Capture Sequestration/Storage
CCU	Carbon Capture Utilization
CCUS	Carbon Capture Sequestration/Storage and Utilization
CI	Carbon Intensity
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
LCA	Life Cycle Assessment
LLNL	Lawrence Livermore National Laboratory
NREL	National Renewable Energy Laboratory
NZTT	Net Zero Technical Team
PNNL	Pacific Northwest National Laboratory
RE	Renewable Energy
RH2	Renewable Hydrogen
RNG	Renewable Natural Gas
SAF	Sustainable Aviation Fuel
TEA	Techno-Economic Analysis
TRL	Technology Readiness Leve
USCAR	U.S. Council for Automotive Research
USDRIVE	U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability

1. Approach

Metric	Definition	Unit
Cost	Minimum fuel selling price	\$/GGE
Carbon efficiency	$\frac{Carbon\ in\ product\ (methanol)}{Total\ carbon\ in\ (biomass\ \frac{and}{or}\ CO2)}$	%
Energy efficiency	$\frac{Product\ LHV\,(methanol)}{Total\ energy\ in\ (biomass, H_2, process\ electricity\ and\ heat)}$	%
Life-cycle GHG emissions	equivalent grams of CO_2 per MJ fuel	gCO_2e/MJ
Technology Readiness Level (TRL)	U.S. Department of Energy (DOE) TRL Guide 2011	Scale 1-9

Key Metrics

- Derived from TEA to produce cross-comparison
- Selected to harmonize economic and environmental factors
- Considered “time-to-deployment” as a key indicator

2. Progress and Outcomes—Year 1 Cases

Case	Feedstock	Tech.	Product	Description	
Case 1	Corn	CCS	Ethanol	Case 1.0 Base case-corn ethanol with CCS	
				Case 1.1	Case 1.0 + RNG
				Case 1.2	Case 1.0+ ReElec
				Case 1.3	Case 1.0 + green ammonia
Case 2	Algae	HTL	Renewable diesel	Case 2.0 Base case algae HTL	
				Case 2.1	Case 2.0 + RNG
				Case 2.2	Case 2.1 + ReElec. for conversion
				Case 2.3	Case 2.2 + ReElec. for algae farm
				Case 2.4	Case 2.3 + ReElec. for CO_2
				Case 2.5	Off-gas for H_2 production
				Case 2.6	Case 2.5 + ReElec. for conversion+ Electrolysis for H_2 (U.S. mix electricity)
				Case 2.7	Case 2.6 + ReElec. for algae farm
				Case 2.8	Case 2.7 + ReElec. for CO_2
				Case 2.9	Electrolysis for H_2
				Case 2.10	Case 2.9 + ReElec. for conversion (U.S. mix electricity)
				Case 2.11	Case 2.10 + ReElec. for algae farm
				Case 2.12	Case 2.11 + ReElec. for CO_2
Case 3	Woody biomass	Gas fermentation	Ethanol	Case 3.1.1	Benchmark, no external energy inputs
				Case 3.1.2	NG import
				Case 3.1.3	Import H_2
				Case 3.1.4	Import H_2 and NG
				Case 3.1.5	Import H_2 and electricity
				Case 3.1.6	Import H_2, NG, and electricity
	CO_2	Gas fermentation	Ethanol	Case 3.2.1	H_2:CO_2:CO = 3:1:0
				Case 3.2.2	H_2:CO_2:CO = 2:0:1
				Case 3.2.3	H_2:CO_2:CO = 5:0:3
Case 4	Woody biomass	Methanol synthesis	Methanol	Case 4.1.1	Benchmark, no external energy inputs
				Case 4.1.2	Import electricity
				Case 4.1.3	Import H_2/CO_2 utilization
	CO_2	Indirect methanol synthesis	Methanol	Case 4.2.1	H_2:CO = 1
				Case 4.2.2	H_2:CO = 1.61
				Case 4.2.3	H_2:CO = 2
		Direct methanol synthesis	Methanol	Case 4.3.1	SOT
				Case 4.3.2	Future
	Woody biomass	HOG production	HOG	Case 4.4.1	Benchmark, no external energy inputs
				Case 4.4.2	Import electricity
				Case 4.4.3	Import H_2/CO_2 utilization

Detailed Data can be found from the FY20 Report : https://www.energy.gov/eere/vehicles/articles/us-drive-net-zero-carbon-fuels-technical-team-analysis-summary-report-2020

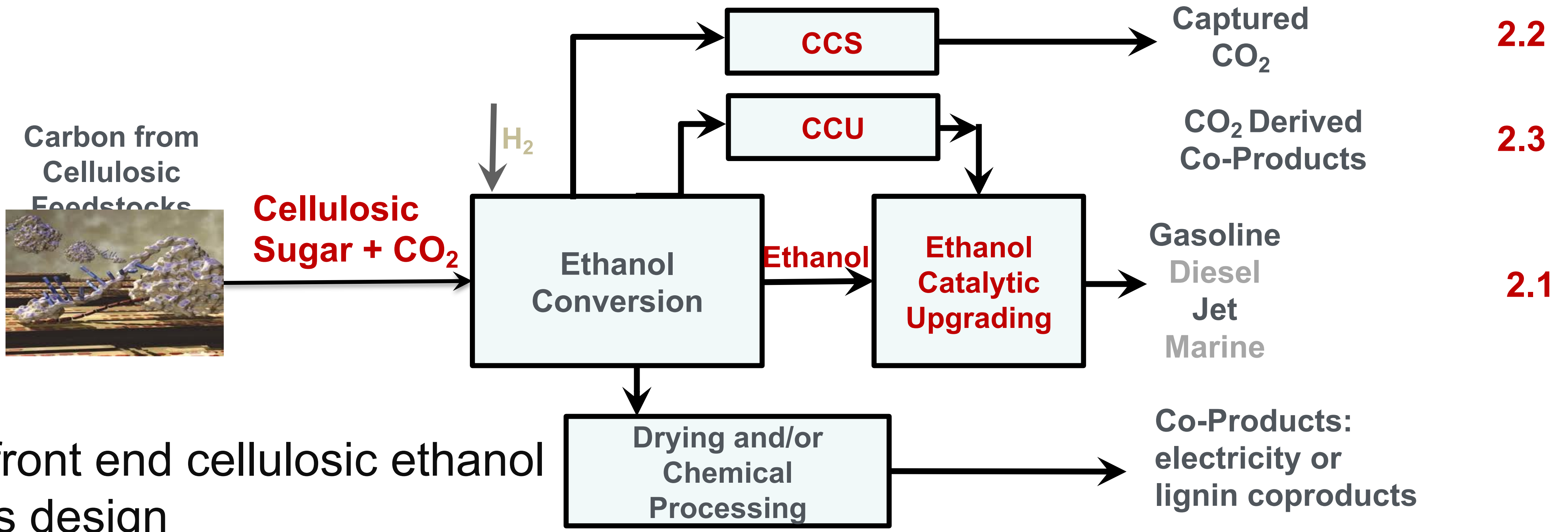
2. Progress and Outcomes—Year 2 Cases

Case		Description	Intervention of renewable resources	Feedstock	Product
Case 1 Corn to EtOH to SAF	Case 1.1.0	Benchmark	-	Corn	SAF
	Case 1.1.1		RE	Corn	SAF
	Case 1.1.2		RE & RNG	Corn	SAF
	Case 1.1.3		RE & RNG & renew. H_2	Corn	SAF
	Case 1.1.4		RE & RNG & renew. H_2 & GA	Corn	SAF
	Case 1.2.0	With additional CC	-	Corn	SAF w/ CCS
	Case 1.2.1		RE	Corn	SAF w/ CCS
	Case 1.2.2		RE & RNG	Corn	SAF w/ CCS
	Case 1.2.3		RE & RNG & renew. H_2	Corn	SAF w/ CCS
	Case 1.2.4		RE & RNG & renew. H_2 & GA	Corn	SAF w/ CCS
	Case 1.3.0	With additional CCU	-	Corn + CO_2	SAF
	Case 1.3.1		RE	Corn + CO_2	SAF
	Case 1.3.2		RE & RNG	Corn + CO_2	SAF
	Case 1.3.3		RE & RNG & renew. H_2	Corn + CO_2	SAF
	Case 1.3.4		RE & RNG & renew. H_2 & GA	Corn + CO_2	SAF
Case 2 Corn stover to EtOH to SAF	Case 2.1.0	Benchmark	-	Corn stover	SAF
	Case 2.1.1		RE	Corn stover	SAF
	Case 2.1.2		RE & renew. H_2	Corn stover	SAF
	Case 2.1.3		RE & renew. H_2 & GA	Corn stover	SAF
	Case 2.1.4		RE & GA	Corn stover	SAF
	Case 2.2.0	With additional CCS	-	Corn stover	SAF w/ CCS
	Case 2.2.1		RE	Corn stover	SAF w/ CCS
	Case 2.2.2		RE & renew. H_2	Corn stover	SAF w/ CCS
	Case 2.2.3		RE & renew. H_2 & GA	Corn stover	SAF w/ CCS
	Case 2.2.4		RE & GA	Corn stover	SAF w/ CCS
	Case 2.3.0	With additional CCU	-	Corn stover + CO_2	SAF
	Case 2.3.1		RE	Corn stover + CO_2	SAF
	Case 2.3.2		RE & renew. H_2	Corn stover + CO_2	SAF
	Case 2.3.3		RE & renew. H_2 & GA	Corn stover + CO_2	SAF
	Case 2.3.4		RE & GA	Corn stover + CO_2	SAF

Project report is pending for publication
Detailed analysis data are listed from slides 28-41

Case 3 Biomass gasification to FT fuel	Case 3.1.0	Benchmark, no external energy inputs	-	woody biomass	SAF
	Case 3.1.1.1	Import NG for process fuel	Fossil NG	woody biomass	SAF
	Case 3.1.1.2		RNG	woody biomass	SAF
	Case 3.1.2.1	Import gray H2 for tar reforming (250, 1000, 2000, 3000 lbmol/hr)	NG SMR H_2	woody biomass	SAF
	Case 3.1.2.2		NG SMR H_2	woody biomass	SAF
	Case 3.1.2.3		NG SMR H_2	woody biomass	SAF
	Case 3.1.2.4		NG SMR H_2	woody biomass	SAF
	Case 3.1.2.1b	Import renew. H2 for tar reforming (250, 1000, 2000, 3000 lbmol/hr)	Renew. H_2	woody biomass	SAF
	Case 3.1.2.2b		Renew. H_2	woody biomass	SAF
	Case 3.1.2.3b		Renew. H_2	woody biomass	SAF
	Case 3.1.2.4b		Renew. H_2	woody biomass	SAF
	Case 3.2.0	With additional CCS	-	woody biomass	SAF w/ CCS
	Case 3.2.1		RE	woody biomass	SAF w/ CCS
	Case 3.3.0	With additional CCU	-	woody biomass + CO_2	SAF
	Case 3.3.1		RE	woody biomass + CO_2	SAF
	Case 3.3.2		RE & renew. H_2	woody biomass + CO_2	SAF
Case 4 Wet waste HTL to RD	Case 4.1.0	With ammonia removal	-	Wastewater sludge	RD
	Case 4.1.1		RE	Wastewater sludge	RD
	Case 4.1.2		RNG	Wastewater sludge	RD
	Case 4.1.3		RE & RNG	Wastewater sludge	RD
	Case 4.1.4		RE & RNG & renew. H_2	Wastewater sludge	RD
	Case 4.2.0	Without ammonia removal	-	Wastewater sludge	RD
	Case 4.2.1		RE	Wastewater sludge	RD
	Case 4.2.2		RNG	Wastewater sludge	RD
	Case 4.2.3		RE & RNG	Wastewater sludge	RD
	Case 4.2.4		RE & RNG & renew. H_2	Wastewater sludge	RD
Case 5 DAC CO2 to SAF	Case 5.1.0	Benchmark	-	DAC CO_2	SAF
	Case 5.1.1		RE	DAC CO_2	SAF
	Case 5.1.2		RE & RNG	DAC CO_2	SAF
	Case 5.1.3		RE & RNG & GA	DAC CO_2	SAF
	Case 5.2.0	With additional CCS	-	DAC CO_2	SAF w/ CCS
	Case 5.2.1		RE	DAC CO_2	SAF w/ CCS
	Case 5.2.2		RE & RNG	DAC CO_2	SAF w/ CCS
	Case 5.2.3		RE & RNG & GA	DAC CO_2	SAF w/ CCS
	Case 5.3.0	With additional CCU	-	DAC CO_2 + flue gas CO_2	SAF
	Case 5.3.1		RE	DAC CO_2 + flue gas CO_2	SAF
	Case 5.3.2		RE & RNG	DAC CO_2 + flue gas CO_2	SAF
	Case 5.3.3		RE & RNG & GA	DAC CO_2 + flue gas CO_2	SAF

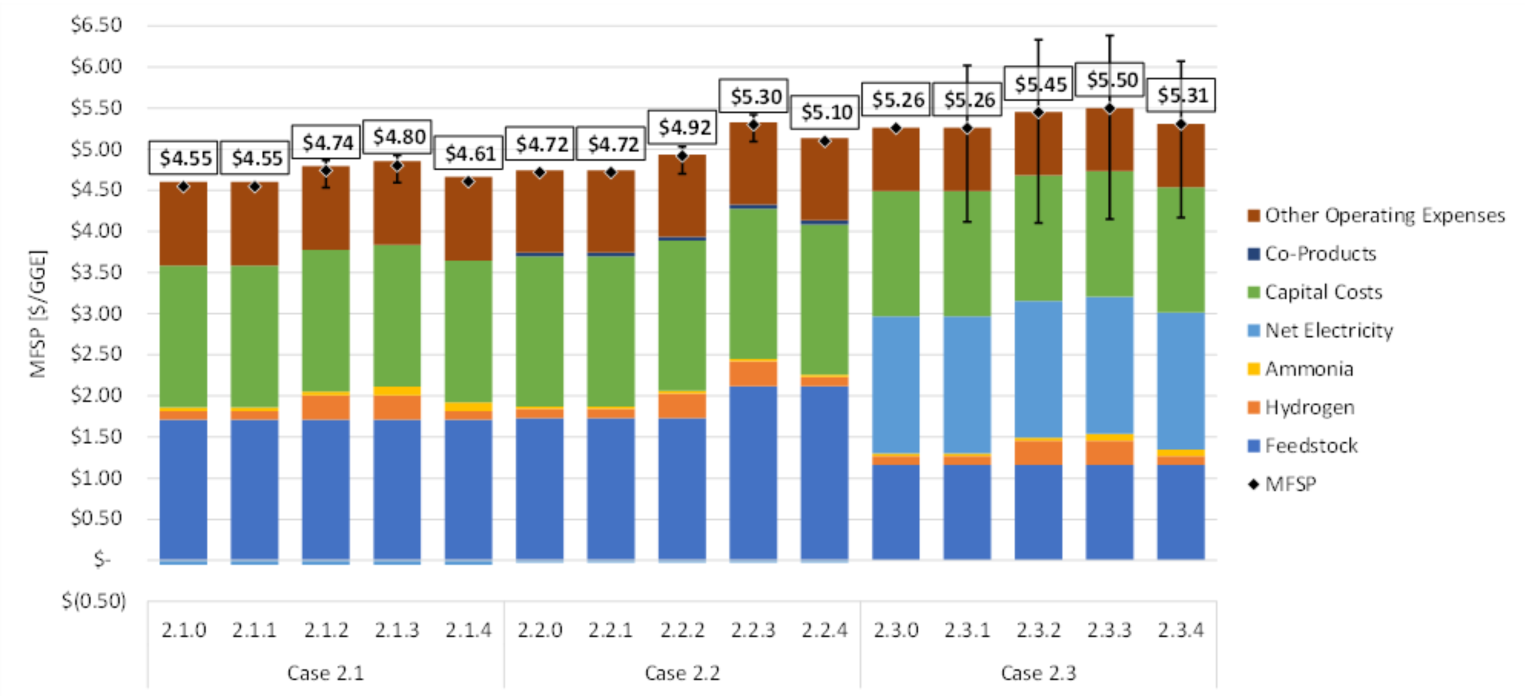
2. Progress and Outcomes: Year 2 Case 2 Cellulosic Ethanol



- Adopt front end cellulosic ethanol process design
- Include both CCS and CCU options
- Consider renewable sources of H_2 and process heat, similar to analysis performed in year 1

Case
2.1 – Cellulosic EtOH with catalytic upgrading to Jet
2.2 – Cellulosic EtOH with catalytic upgrading to Jet & CCS
2.3 – Cellulosic EtOH with catalytic upgrading to Jet & CCU

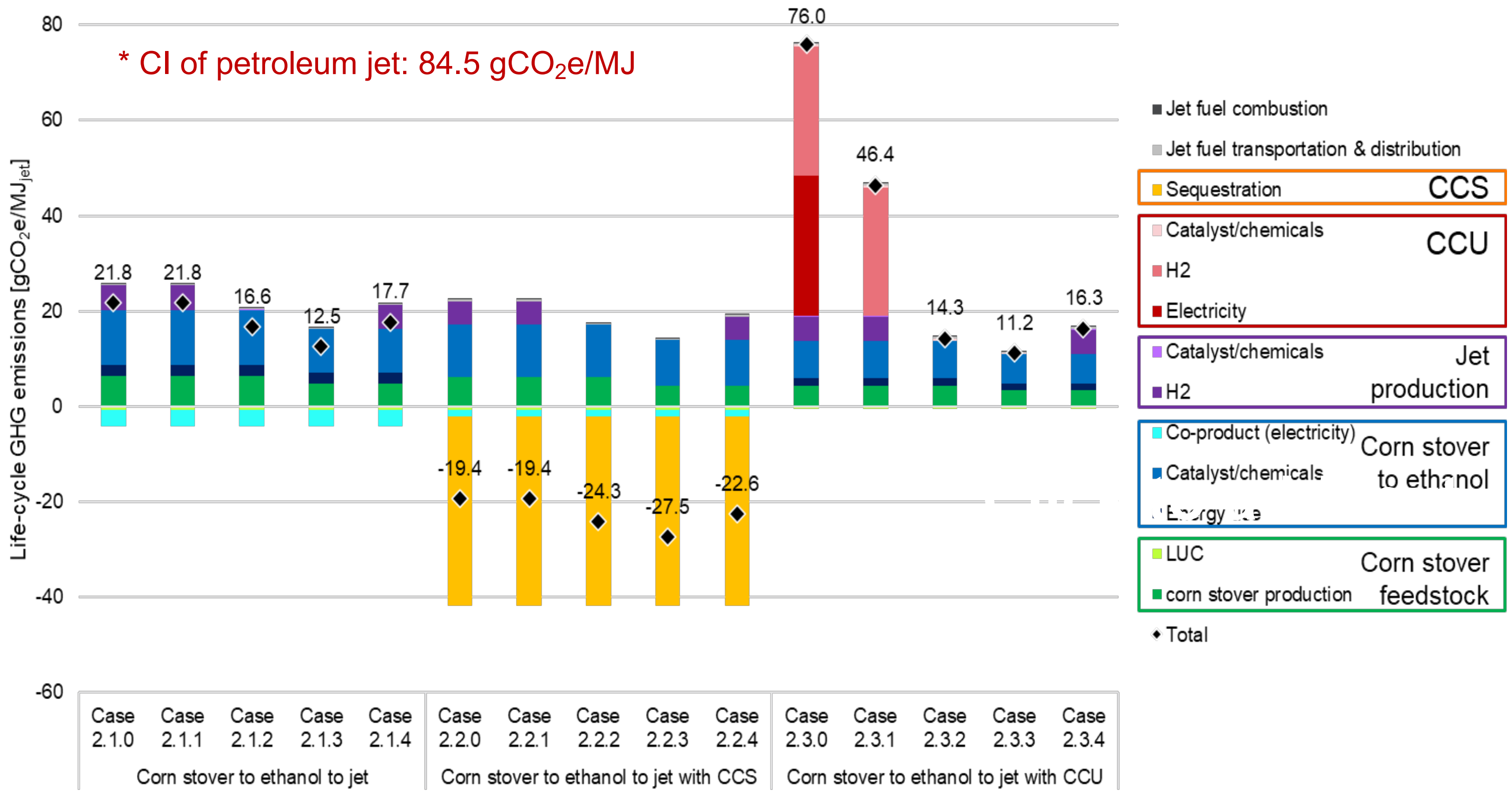
2. Progress and Outcomes: Year 2 Case 2 TEA Results



- The baseline cost of cellulosic ethanol to SAF is $4.55/GGE (Case 2.1.0)
- The $0.19/GGE increase for the substitution of green hydrogen represents a carbon abatement cost of $280/tonne CO2, and the $0.05/GGE increase for the substitution of green ammonia represents a $260/tonne cost of abatement. These interventions cut across all variants in Case 2.1 – Case 2.3

- Cellulosic ethanol to SAF with CCS (Case 2.2.0) results in an increase of the MFSP to $4.72/GGE
- Carbon capture and sequestration, including the $10/tonne disposal cost, costs $36/tonne as evidenced by the results of Cases 2.2.1 – 2.2.3
- The strategy of recycling CO2 into fuels (Cases 2.3.x) raises the baseline MSFP of stover-based SAF from $4.55 to $5.24 because the lower feedstock costs (resulting from an approximate doubling of the carbon efficiency of the process) are offset by the costs of electricity and hydrogen required for CO2 conversion and upgrading

2. Progress and Outcomes: Year 2 Case 2 LCA Results

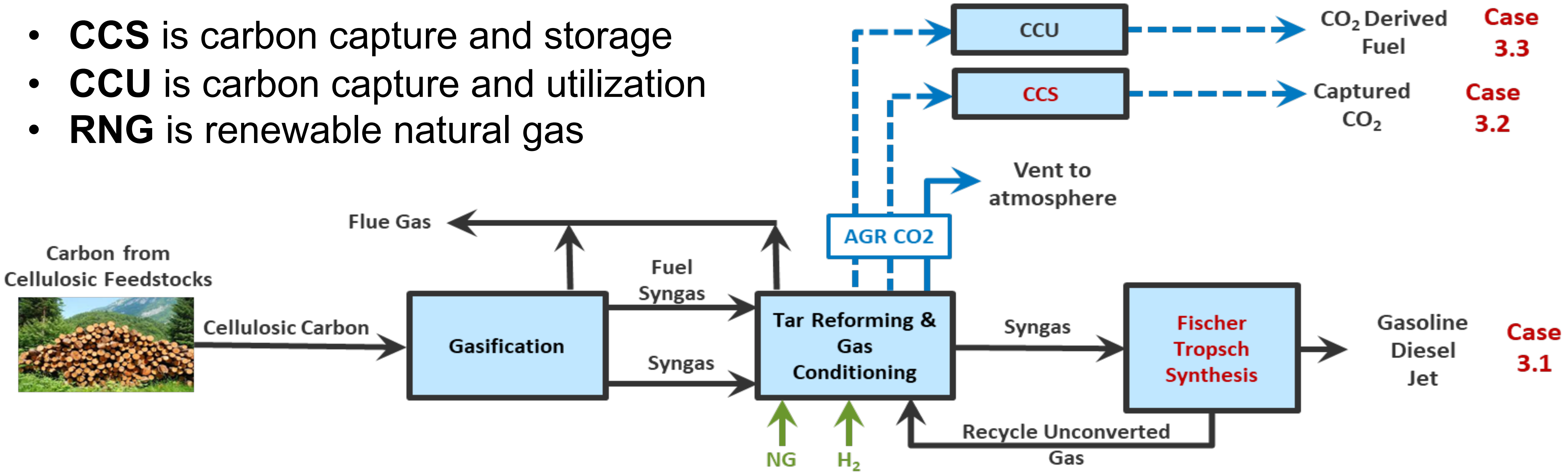


Case	Electricity	H_2	Ammonia
2.X.0	US mix	SMR	conventional
2.X.1	renewable	SMR	conventional
2.X.2	renewable	Renewable	conventional
2.X.3	renewable	Renewable	green
2.X.4	renewable	SMR	green

- In the base case (Case 2.1.0), CI of cellulosic ethanol to SAF is 74% lower than petroleum jet, because the jet production process uses carbon-neutral heat and power and corn stover does not take emissions burdens of corn farming (cf. CI of Case 1.1.0: 78.1 gCO_2e/MJ)
- CCS of fermentation CO_2 does substantially reduce the CI of aviation fuel produced from cellulosic biomass converted to ethanol and subsequently upgraded to SAF (Case 2.2)
- CCU cases (Case 2.3) help generate additional 47% fuels compared to Case 2.1 and Case 2.2 with the same amount of corn stover by maximizing carbon utilization. Renewable interventions help reduce the CI to become as low as 11.2 gCO_2e/MJ

2. Progress and Outcomes: Year 2 Case 3 Biomass Gasification

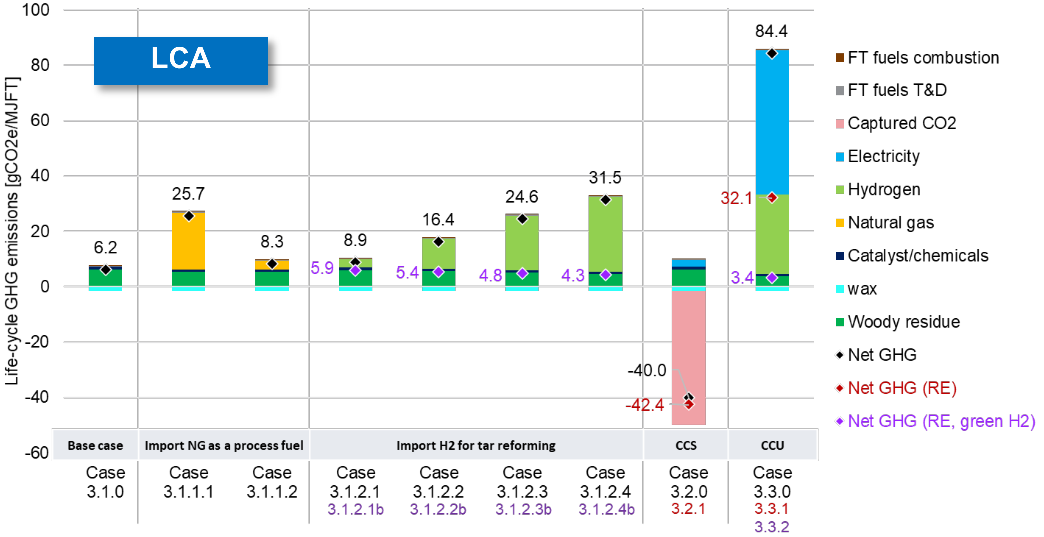
- **CCS** is carbon capture and storage
- **CCU** is carbon capture and utilization
- **RNG** is renewable natural gas

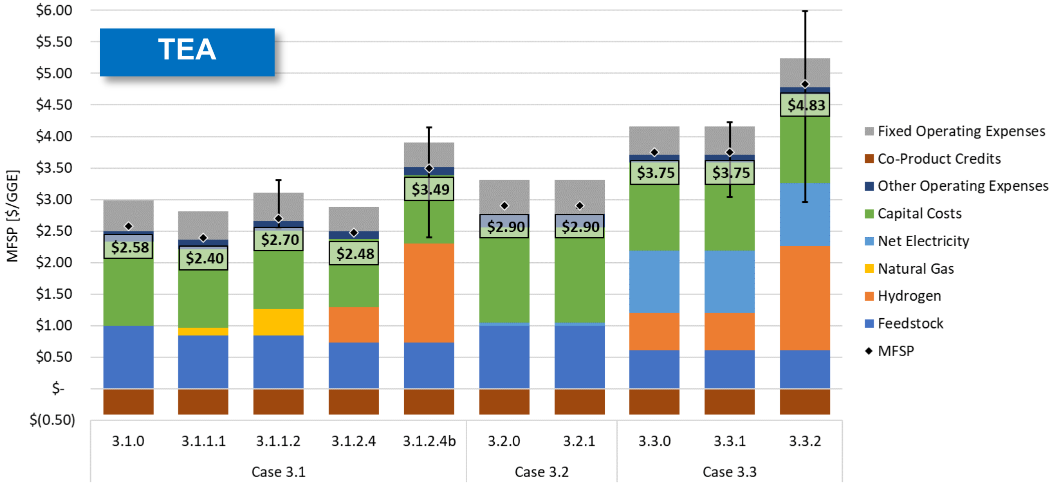


Case	CO_2 capture	Electricity	Heat	H_2
3.1.0	-	Biomass (internal)	Biomass (internal)	-
3.1.1.2	-	Biomass (internal)	Import RNG	-
3.1.2.4	-	Biomass (internal)	Biomass (internal)	Renewable
3.2.1	With CCS	Renewable (for CCS)	Biomass (internal)	-
3.3.2	With CCU	Renewable (for CCU)	Biomass (internal)	Renewable

2. Progress and Outcomes: Year 2 Case 3 TEA/LCA Case Results

LCA and TEA results show the GHG emission and cost contributions, which helps further reduce emissions while minimizing cost increase.

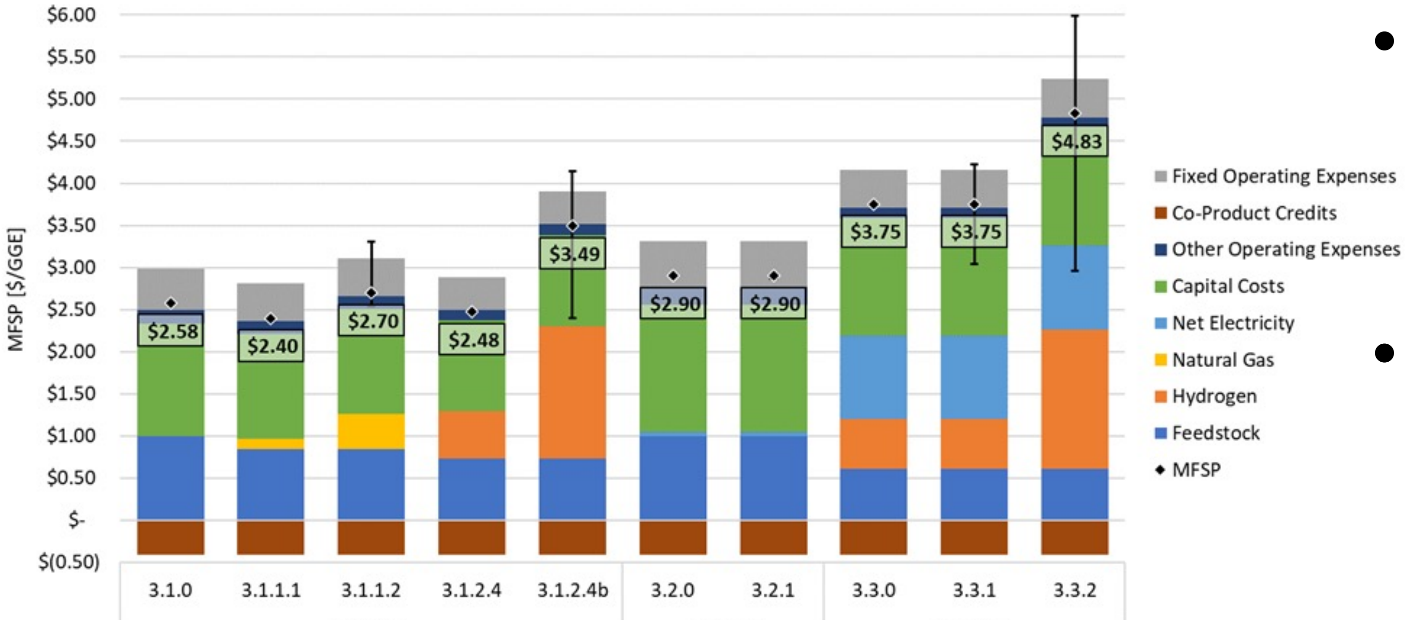


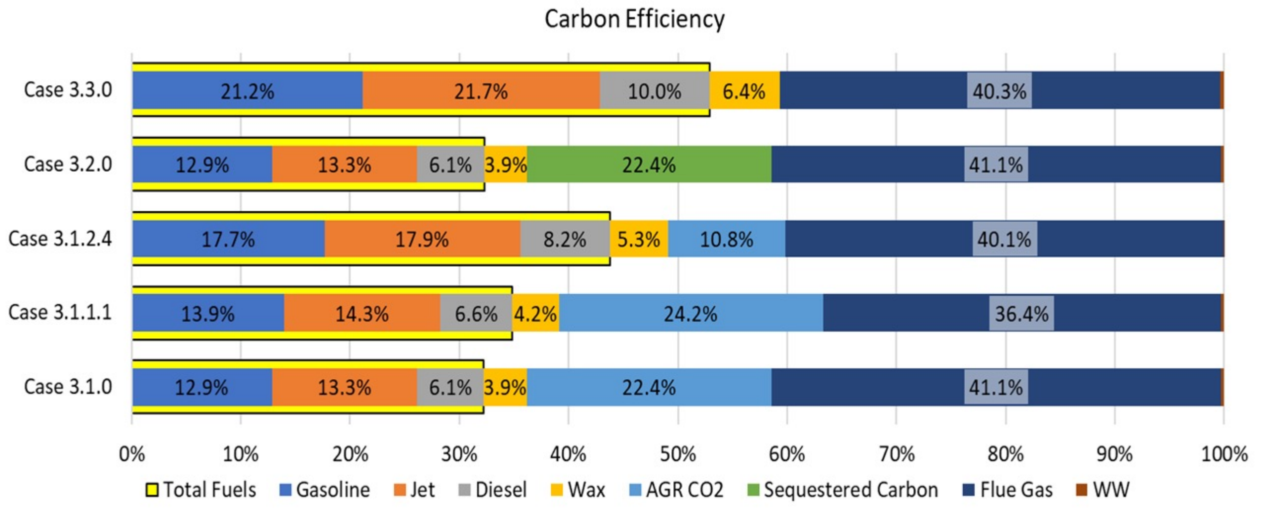


- The CIs of SAF show significant emission reductions compared to the baseline petroleum jet CI.
- CCS can make the fuels to be carbon negative with marginal increase in cost.
- CCU provides additional fuel production utilizing waste carbon; however, depending on the input energy sources, CIs may increase.

Case Number	AGR CO_2	Flue Gas CO_2	Electricity	Fuel	Hydrogen
Case 3.1.0	Vented	Vented	N/A	Syngas + Offgases	N/A
Case 3.1.1.1	Vented	Vented	N/A	Offgases + NG	N/A
Case 3.1.1.2	Vented	Vented	N/A	Offgases + RNG	N/A
Case 3.1.2.1	Vented	Vented	N/A	Syngas + Offgases	Fossil H_2
Case 3.1.2.1b	Vented	Vented	N/A	Syngas + Offgases	Renewable H_2
Case 3.1.2.2	Vented	Vented	N/A	Syngas + Offgases	Fossil H_2
Case 3.1.2.2b	Vented	Vented	N/A	Syngas + Offgases	Renewable H_2
Case 3.1.2.3	Vented	Vented	N/A	Syngas + Offgases	Fossil H_2
Case 3.1.2.3b	Vented	Vented	N/A	Syngas + Offgases	Renewable H_2
Case 3.1.2.4	Vented	Vented	N/A	Syngas + Offgases	Fossil H_2
Case 3.1.2.4b	Vented	Vented	N/A	Syngas + Offgases	Renewable H_2
Case 3.2.0	CCS	Vented	US mix	Syngas + Offgases	N/A
Case 3.2.1	CCS	Vented	RE	Syngas + Offgases	N/A
Case 3.3.0	CCU	Vented	US mix	Syngas + Offgases	Fossil H_2
Case 3.3.1	CCU	Vented	RE	Syngas + Offgases	Fossil H_2
Case 3.3.2	CCU	Vented	RE	Syngas + Offgases	Renewable H_2

2. Progress and Outcomes: Year 2 Case 3 Biomass Gasification Preliminary TEA Results





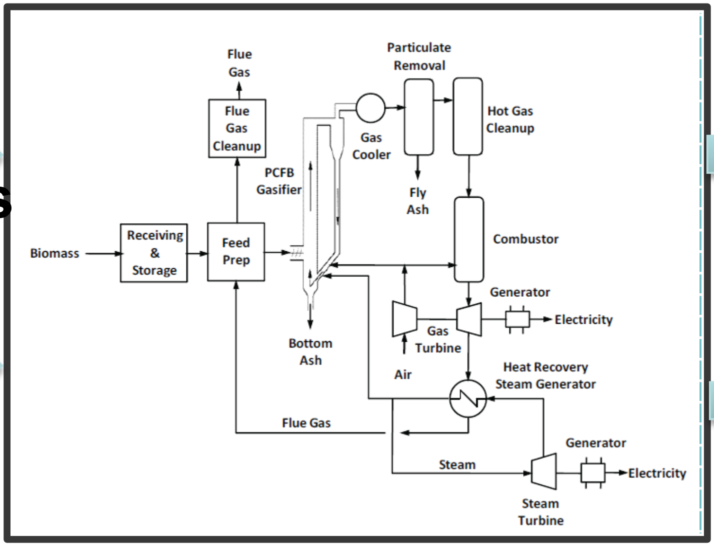
- Gasification and Fischer Tropsch (FT) synthesis technologies present a near-term viable pathway for biomass-derived fuel production.
- CCS is another near-term carbon mitigation strategy with a high TRL which could readily be implemented and remove a large fraction of CO_2 emissions, with a low-cost burden.
- CCU technologies present a strategy for reincorporating CO_2 to fuels. Implementing a CCU system results in the largest increase in carbon efficiency, up to 53%, but should be viewed as a long-term strategy for carbon mitigation and utilization in the biomass-to-fuels via FT pathway.

2. Progress and Outcomes: Year 2 Case 3 Biomass Gasification

Gasification or Conversion Technologies

Woody or Solid Waste Feedstocks

Gas Waste



Methanol

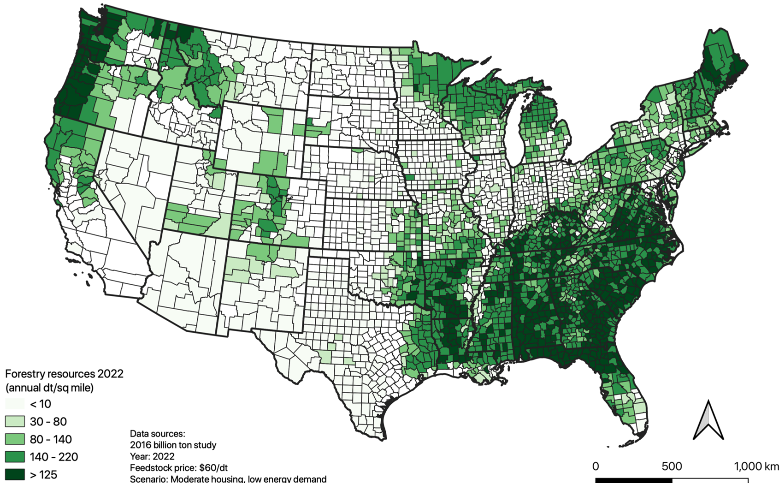
Liquid Biofuel

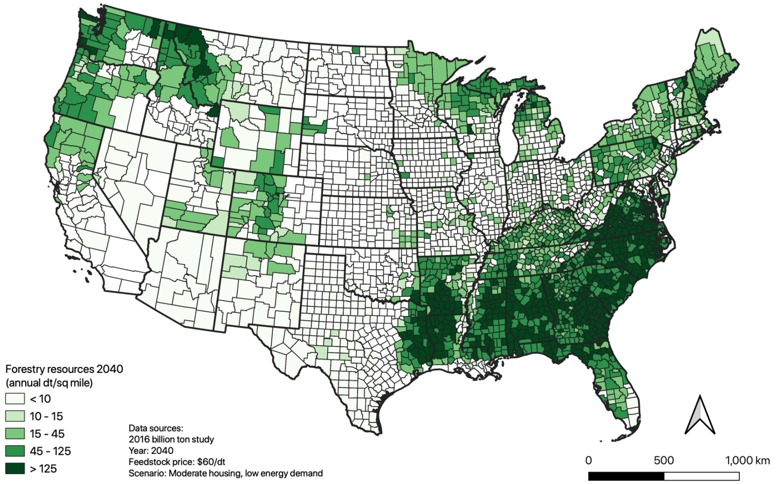
	Feedstock Availability	Renewable Energy Sources	Geological Storage Capacity
West Coast	High	High	Low
East Coast	High	High	Low

- Impact analysis with consideration of CCS/CCU, geographical relevant resources (or supply chain)
- Renewable electricity and renewable hydrogen
- Carbon sequestration

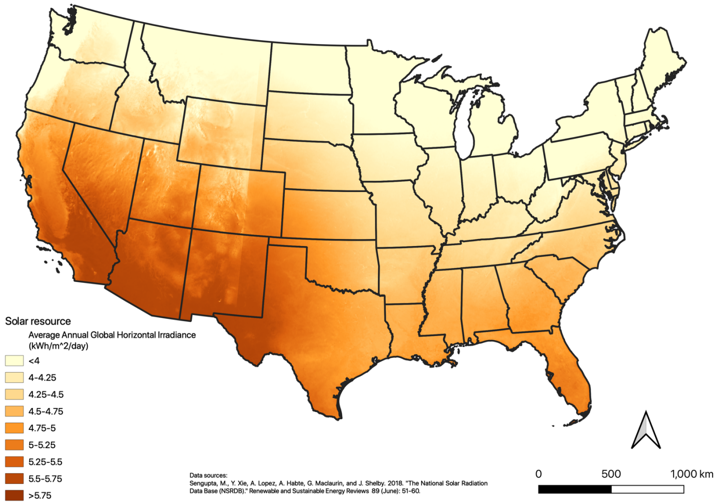
2. Progress and Outcomes: Regional Analysis

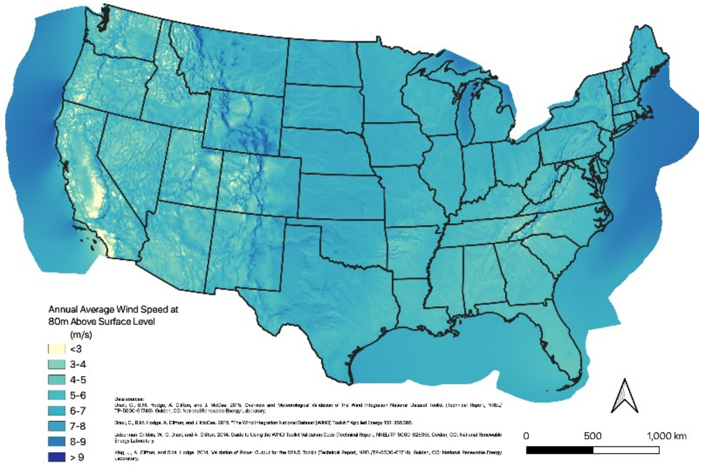
Biomass



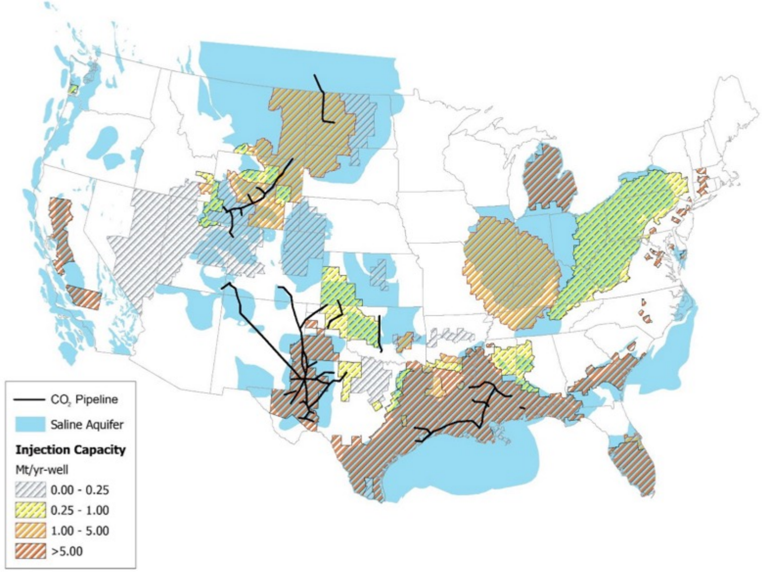


Renewable energy sources





CO_2 storage and pipelines



- Impact analysis with consideration of CCS/CCU, geographical relevant resources (or supply chain)
- Renewable electricity and renewable hydrogen
- Carbon sequestration

Source: https://bioenergykdf.net/billionton2016/overview

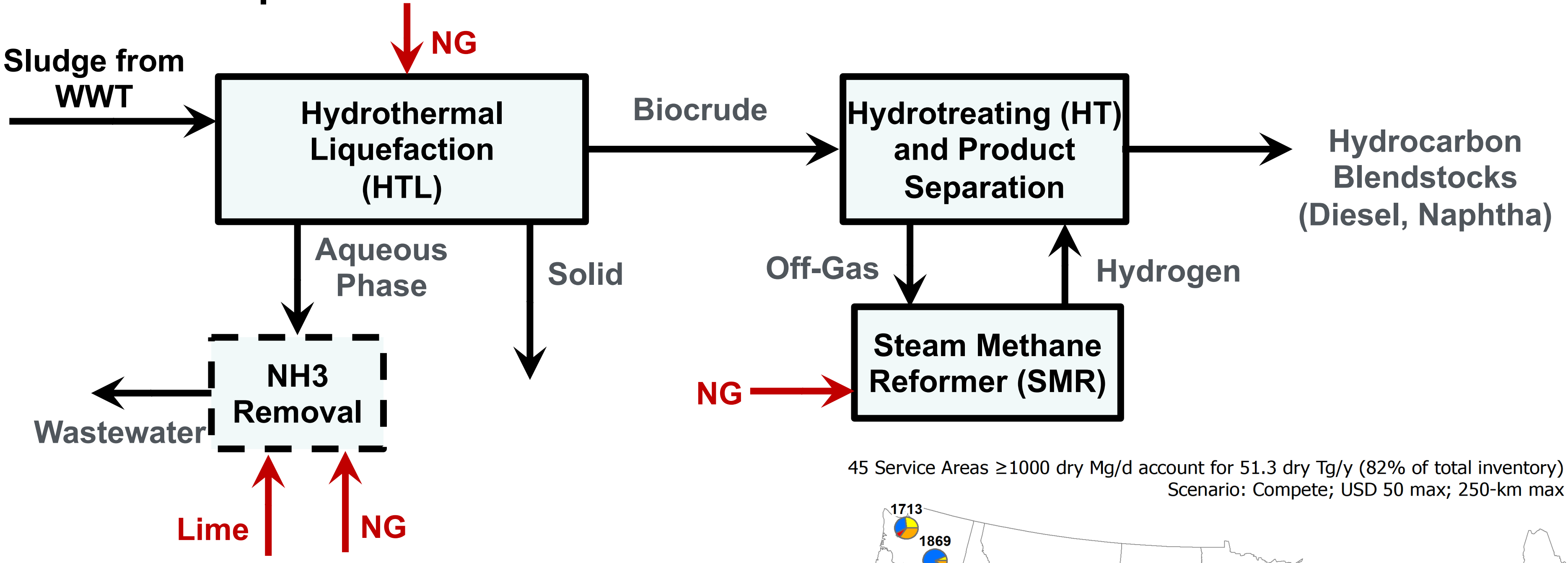
2. Progress and Outcomes: Year 2 Case 4 Hydrothermal Liquefaction of Wet Waste


Wastewater Solids

Fats/Oils/Grease


Food Waste

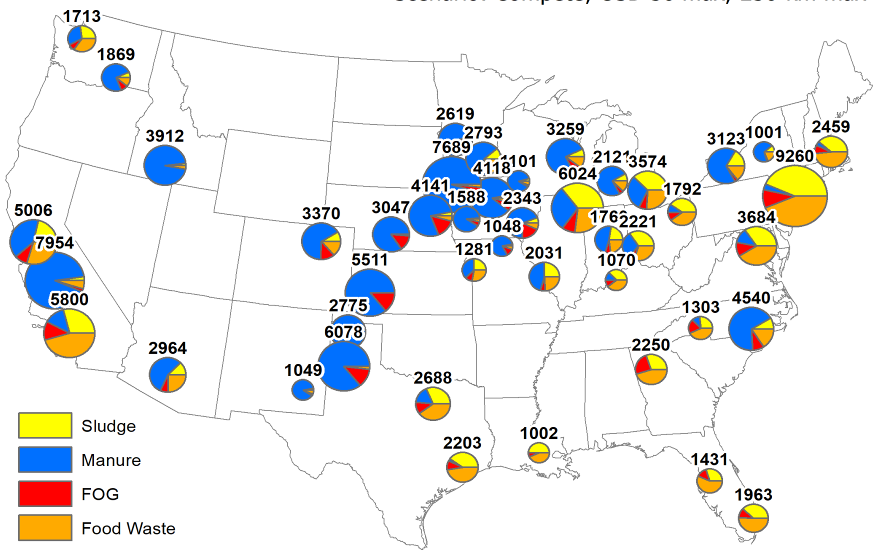

Manures



77 million dry ton/year of **wet waste** is produced in the U.S.

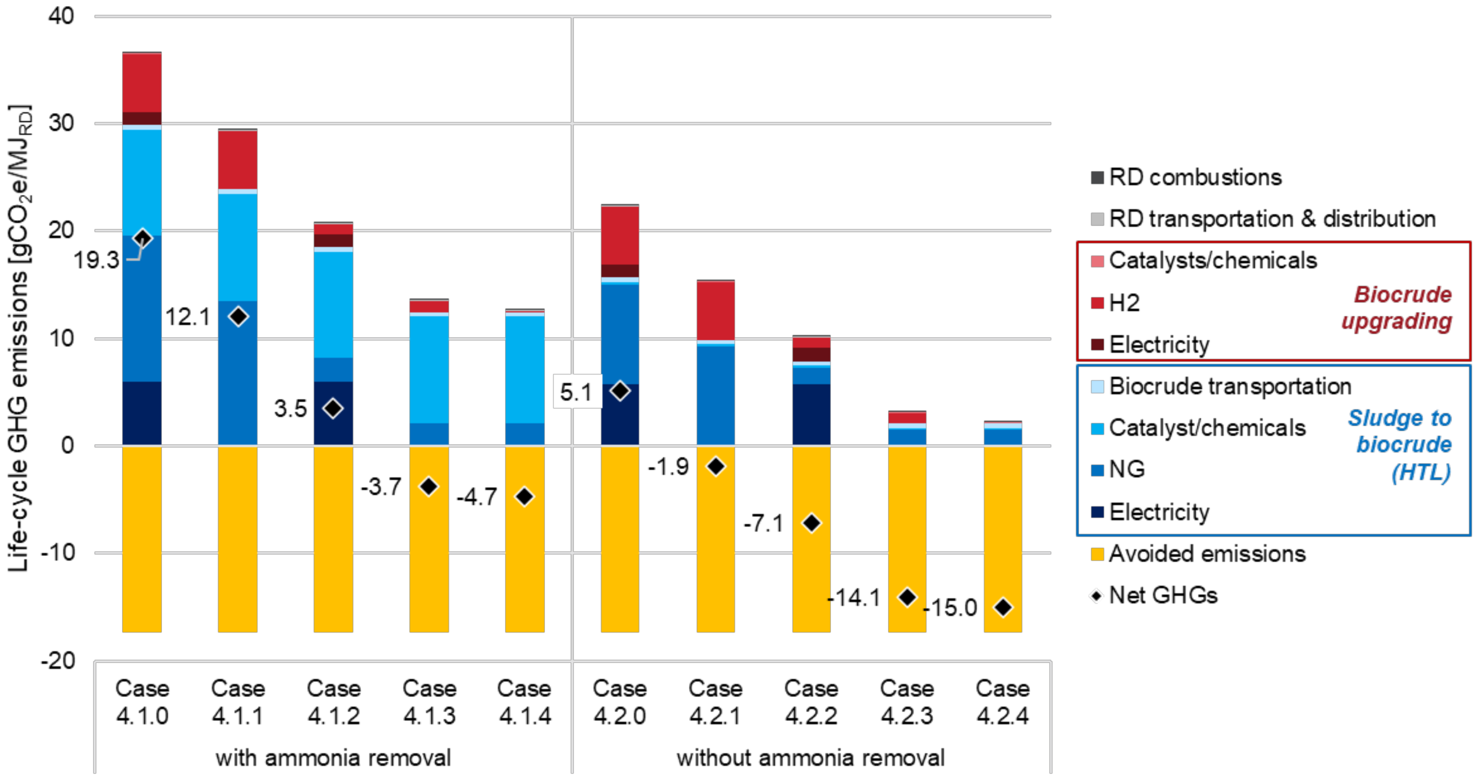
- Using inexpensive and abundant wet waste feedstock to produce gasoline and diesel blendstocks.
- Decarbonizing the fuel production process by using renewable energy and resources.
- Investigating GHG vs economics from different feedstocks; regional blending and hotspot.

45 Service Areas ≥1000 dry Mg/d account for 51.3 dry Tg/y (82% of total inventory)
Scenario: Compete; USD 50 max; 250-km max



Regional collection and blending enables economies of scale

2. Progress and Outcomes: Year 2 Case 4 : Hydrothermal Liquefaction of Wet Waste LCA Results



Case	Electricity	NG	H2
4.X.0	US mix	fossil	On-site SMR
4.X.1	renewable	fossil	On-site SMR
4.X.2	US mix	landfill	On-site SMR
4.X.3	renewable	landfill	On-site SMR
4.X.4	renewable	landfill	On-site SMR + import renewable H_2

* CI of petroleum diesel: 90.5 gCO_2e/MJ

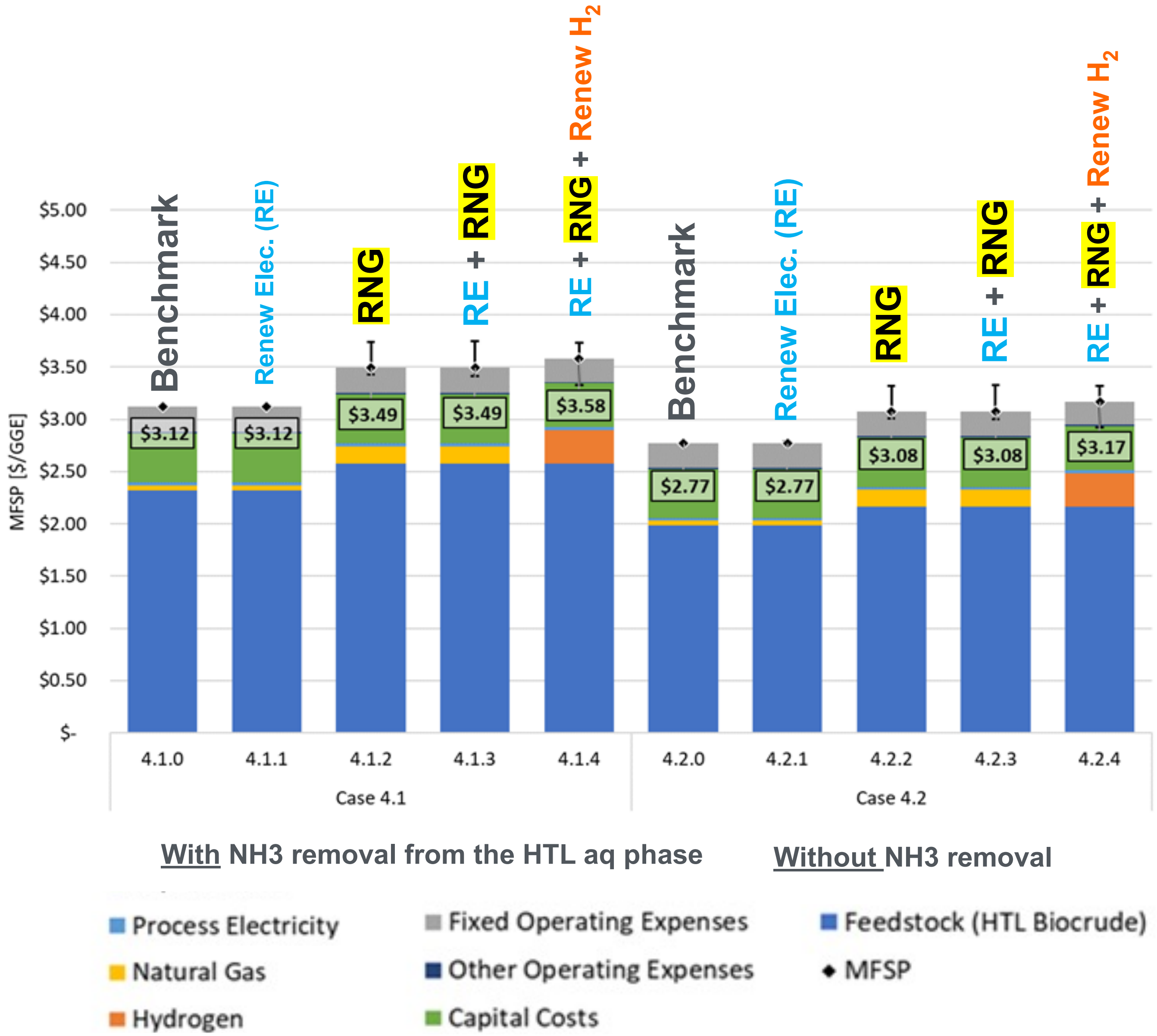
- Using wastewater sludge as a feedstock of RD brings two LCA benefits;

- biogenic carbon emissions are carbon neutral,

- using sludge leads to avoiding GHG emissions (-17 gCO_2e/MJ) from conventional sludge management practices

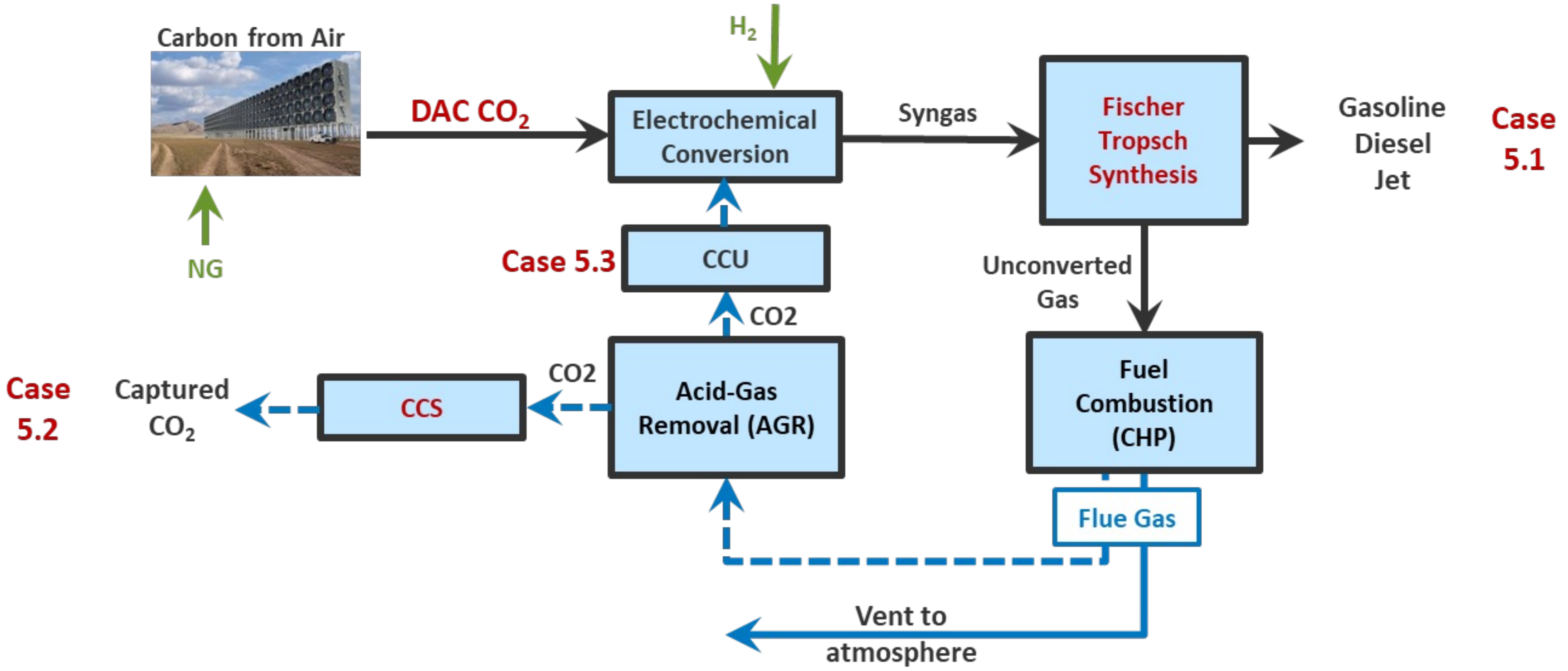
- The base case CI (Case 4.1.0) is 79% lower than conventional diesel, and can be further reduced to -4.7 gCO_2e/MJ with the renewable interventions.
- Quicklime (CaO) for ammonia removal adds 9.7 gCO_2e/MJ in Case 4.1, which may be eliminated in the future (Case 4.2).
- Comparing to the previous algae HTL case, the waste HTL pathway has lower CI mainly due to avoiding emissions related to algae growth (e.g., CO_2 capture and transportation and energy inputs for algae growth) and additional GHG emission credits from the conventional sludge management practices.

2. Progress and Outcomes: Year 2 Case 4 Hydrothermal Liquefaction of Wet Waste - TEA Results



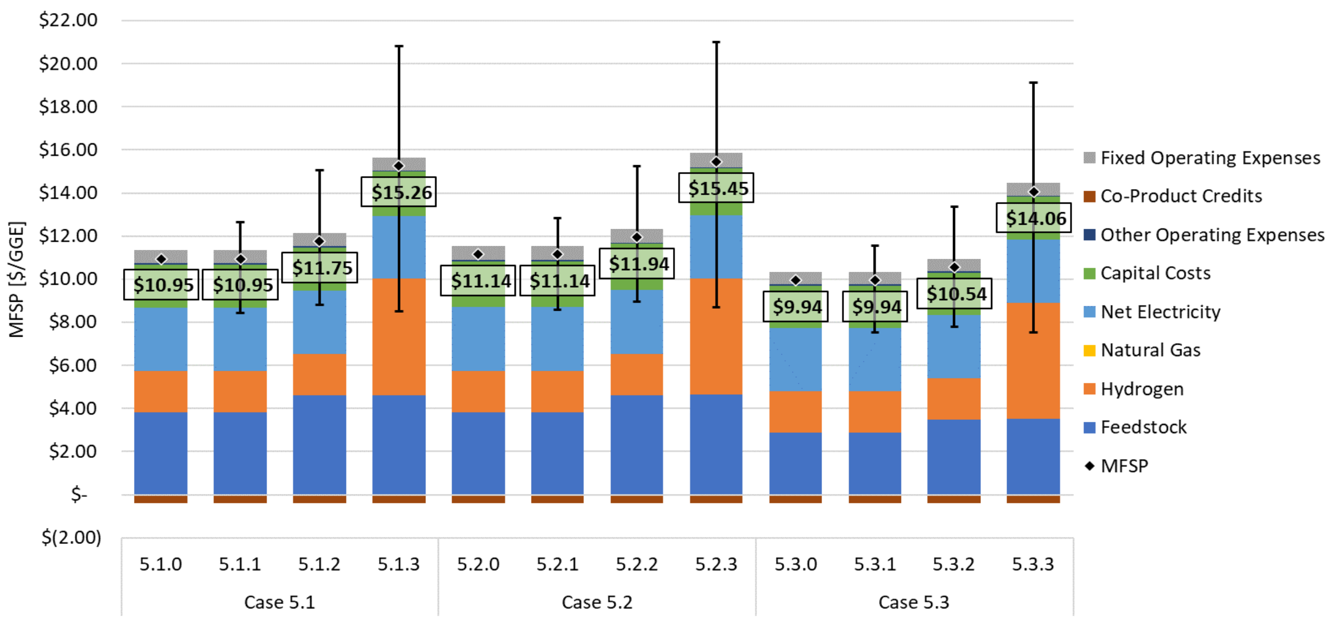
- For the range of electricity cost studied, process economics are not significantly impacted. This is because electricity cost and electricity consumption are not major cost contributors for the HTL process.
- Natural gas cost is one of the largest operating costs in the wet waste HTL and biocrude upgrading pathway. Using renewable natural gas could increase the biocrude production cost by 20-50 cents per gge biocrude (for the cases including HTL aqueous phase ammonia removal). Moreover, the most expensive cost of RNG (at $29.44/MM BTU) could increase the final product fuel cost by at least 10 cents per gge.
- Renewable hydrogen could increase the MFSP by 10 cents per GGE.

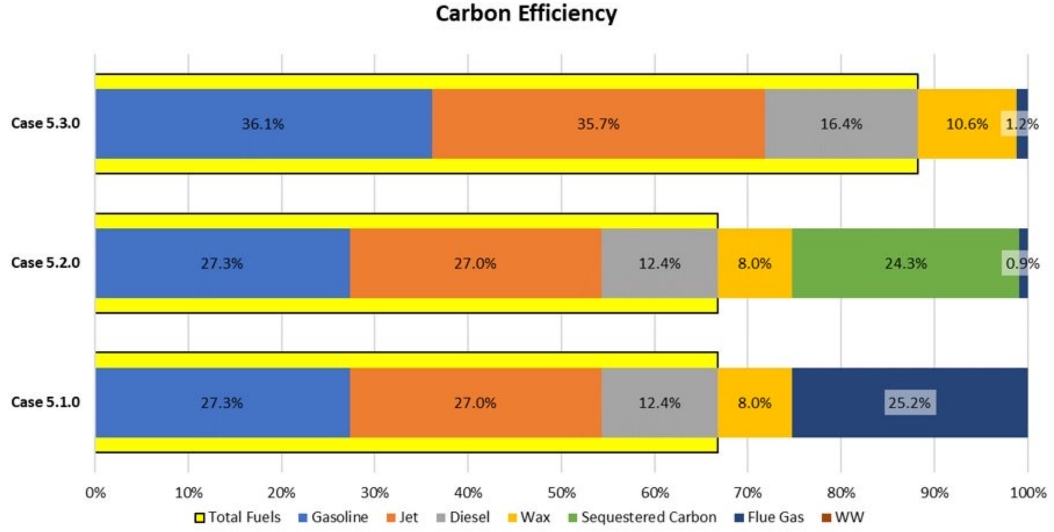
2. Progress and Outcomes: Year 2 Case 5 DAC CO2 FTS



- Include DAC CO2 plus traditional rWGS followed by FT to fuel as a process alternative
- Consider CO2 point sources and their impacts on carbon intensity

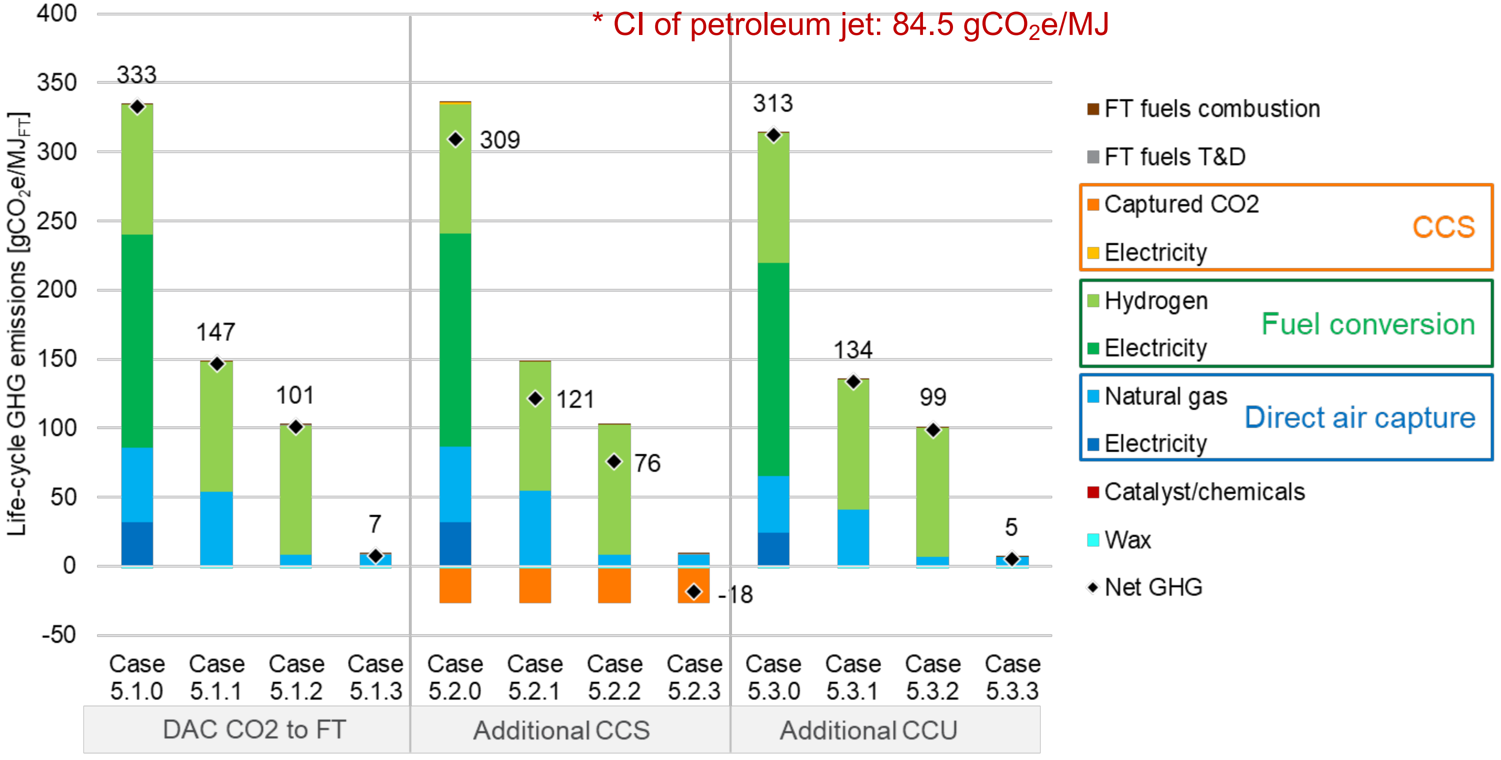
2. Progress and Outcomes: Year 2 Case 5 TEA Results





- Both DAC and CO_2-to-CO electrolysis are low TRL technologies, require significant R&D efforts. Coupling with the established FT technology shows potential for the development of a novel pathway with high carbon efficiency in the baseline design (66.8%).
- CCS technologies has key environmental benefits, but this strategy does not recover the costs of expensive DAC CO_2 and does not improve carbon or energy efficiency to fuels.
- CCU strategy requires only the addition of an amine flue-gas scrubbing system and can utilize the existing CO_2-to-CO framework to improve both carbon and energy efficiency to fuels.
- Due to low TRL and high near-term costs, the DAC CO_2-to-SAF pathway should be considered a long-term option for SAF and other fuels production.

2. Progress and Outcomes: Year 2 Case 5 LCA Results



Case	Electricity	NG	H_2
5.X.0	US mix	fossil	SMR
5.X.1	renewable	fossil	SMR
5.X.2	renewable	landfill	SMR
5.X.3	renewable	landfill	Renewable

- DAC CO_2 to FT fuel is an energy intensive technology that requires 1.2 MJ of H_2, 0.4 MJ of NG, and 0.5 MJ of electricity.
- Without using renewable energy, the DAC CO_2 FT process does not provide CI reduction benefits, but shifting to renewable energy sources significantly reduces the CIs of FT fuels.
- With additional 0.02 MJ of electricity for CCS, CI is decreased by 25.5 gCO_2e/MJ.
- Implementation of CCU can reduce the CI of SAF by 2–20 gCO_2e/MJ compared to Case 5.1, because energy use of CO_2 capture from the flue gas is lower than energy use of DAC
- Once renewable energy sources are used, the CIs of CCS (Case 5.2.3) and CCU (Case 5.3.3) become -18 and 5 gCO_2e/MJ, respectively.