DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

TRIFTS Catalytic Conversion of Biogas to Drop-in Renewable Diesel Fuel

WBS 3.5.1.201

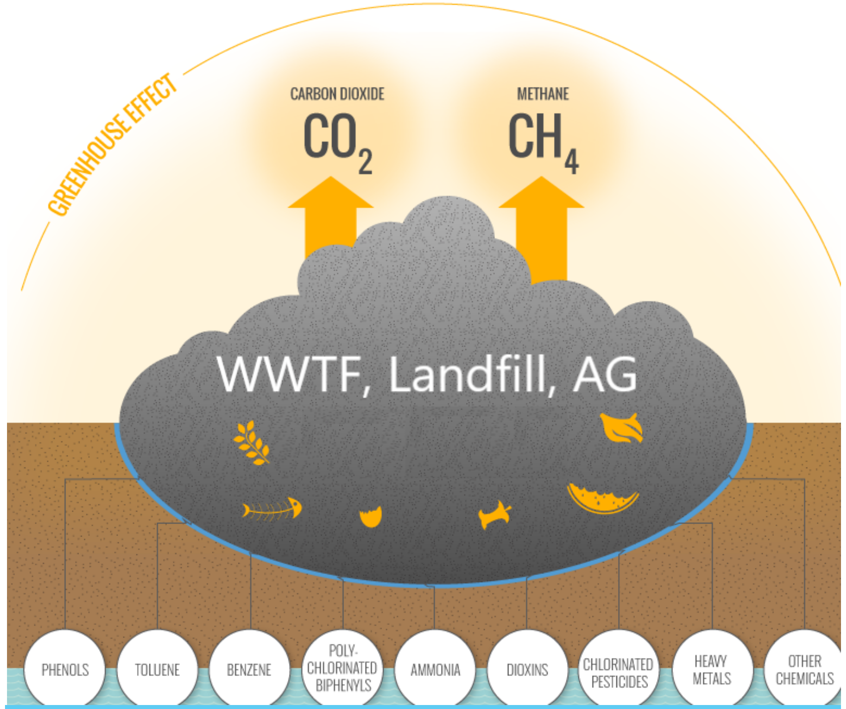
April 3, 2023

Systems Development and Integration Session B

Principal Investigator: Devin Walker
Organization: T2C-Energy

Project Overview

GREENHOUSE GAS PROTOCOL

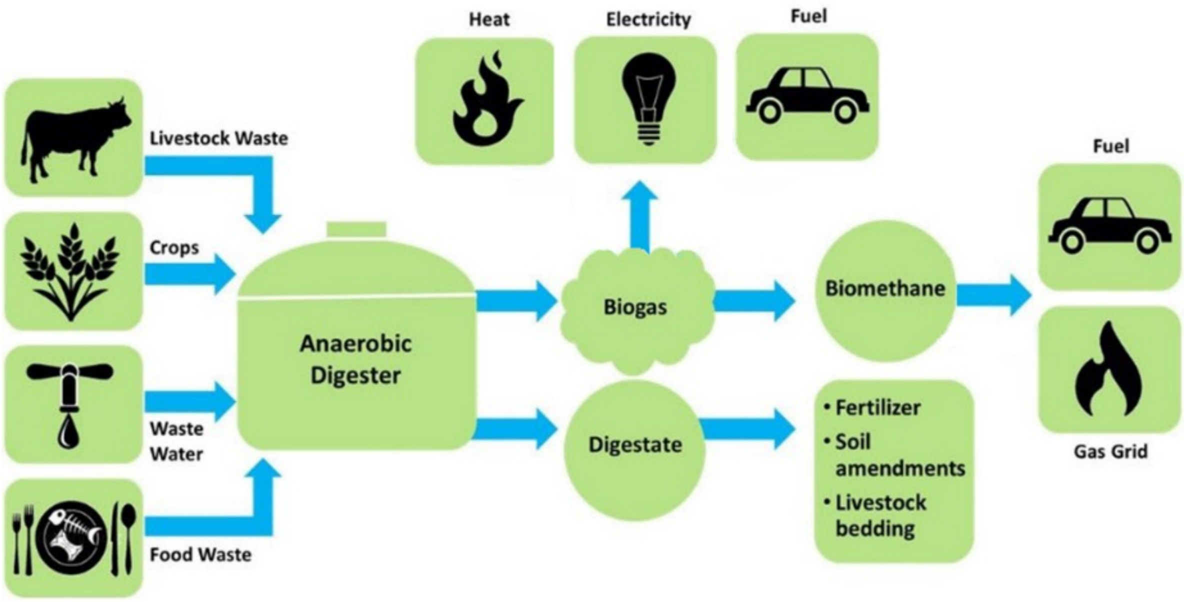


US: Biogas ~ 800,000 SCFM

Global: Biogas ~3,800,000 SCFM

- Avg Size AD in US Produces ~210 SCFM Biogas
- Avg Size Landfill in US Produces ~1,380 SCFM Biogas
- Avg Natural Gas Processing Plant ~ 88,000 SCFM Biogas

What's the best use of this energy resource?



Key Factors

Economics

Location

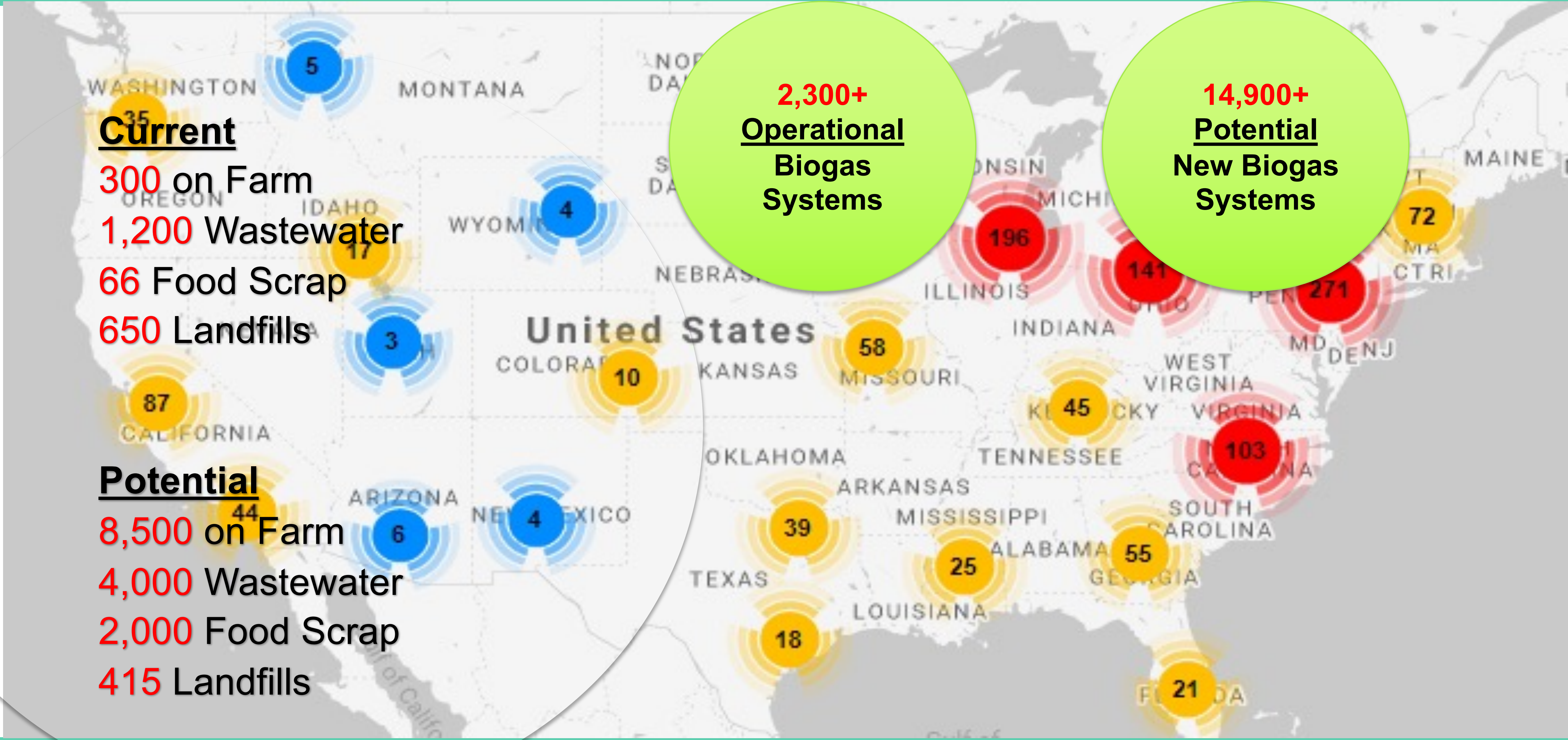
Infrastructure

Efficiency

Policy

Project Overview

T2C-ENERGY



<u>Current</u>

300 on Farm

1,200 Wastewater

66 Food Scrap

650 Landfills

<u>Potential</u>

8,500 on Farm

4,000 Wastewater

2,000 Food Scrap

415 Landfills

2,300+
<u>Operational</u>
Biogas Systems

14,900+
<u>Potential</u>
New Biogas Systems

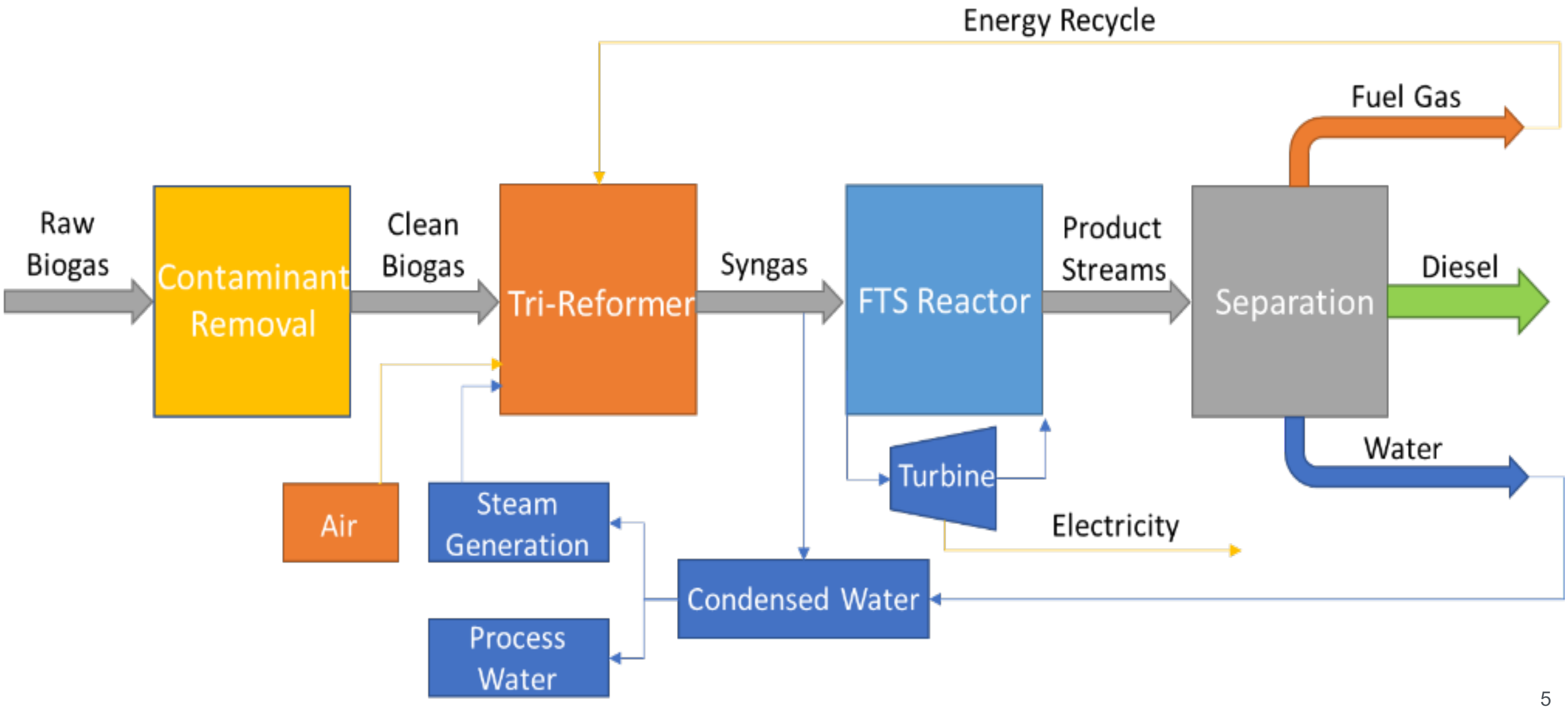
Project Overview

Goals

- Rigorously test pilot over broad range of biogas
- Optimize process design
- Produce drop-in cellulosic diesel meeting ASTM D975 spec
- De-risk technology at engineering scale (3rd party verification)
- Fuel pathway verification and carbon intensity (g CO_2e/MJ Fuel)
- Detailed design and technoeconomic analysis of commercial scale plant

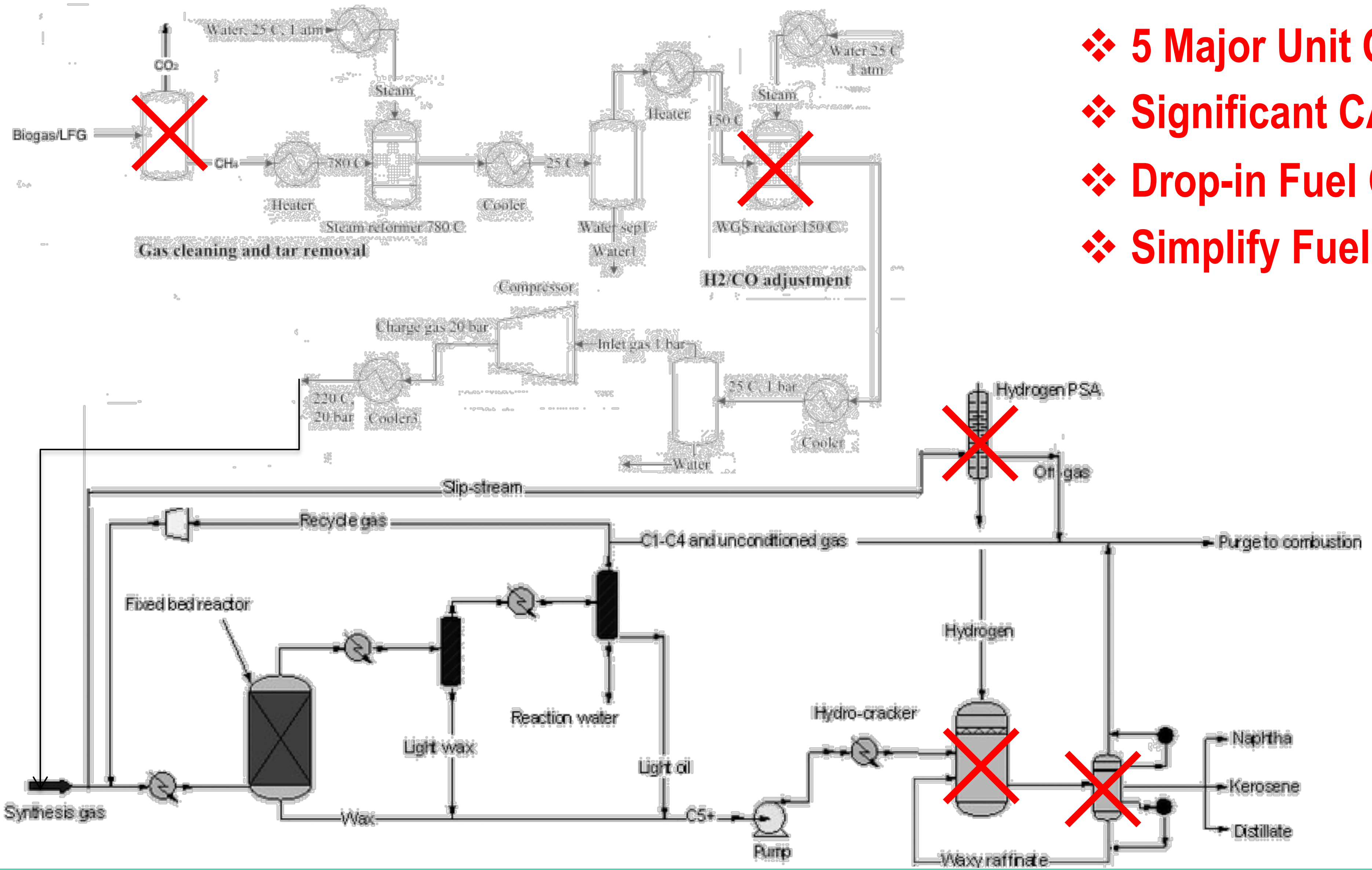
https://youtube.com/watch?v=GbioqF6G9Ow

Approach



Energy Recycle
Fuel Gas
Raw Biogas
Contaminant Removal
Clean Biogas
Tri-Reformer
Syngas
FTS Reactor
Product Streams
Separation
Diesel
Water
Turbine
Electricity
Air
Steam Generation
Condensed Water
Process Water

Approach

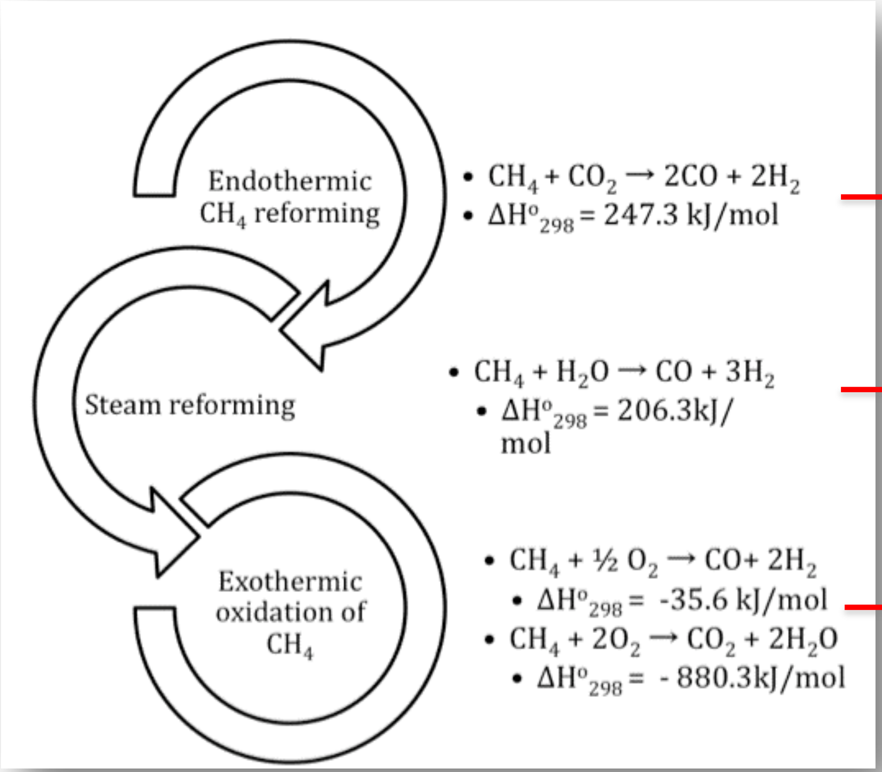


- 5 Major Unit Operations Removed
- Significant CAPEX/OPEX Reduction
- Drop-in Fuel Out of FTS
- Simplify Fuel Distribution and Logistics

Approach

Tri-reforming:

- Minimize cleanup and pretreatment process (**No CO_2 removal**)
- Less energy consumption
- Produce high quality syngas (H_2:CO ~ 2)



Utilize 100% of Biogas as Feedstock

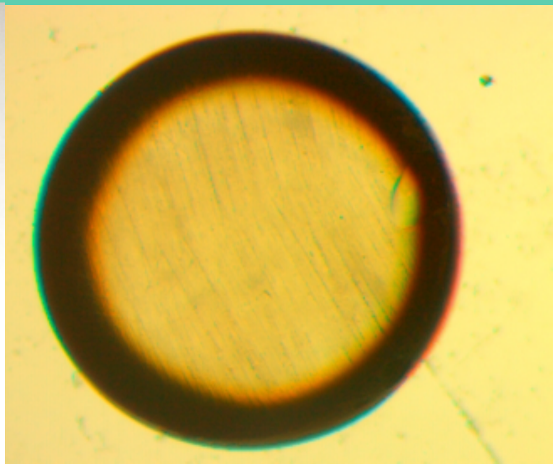
Control H2 and CO Selectivity

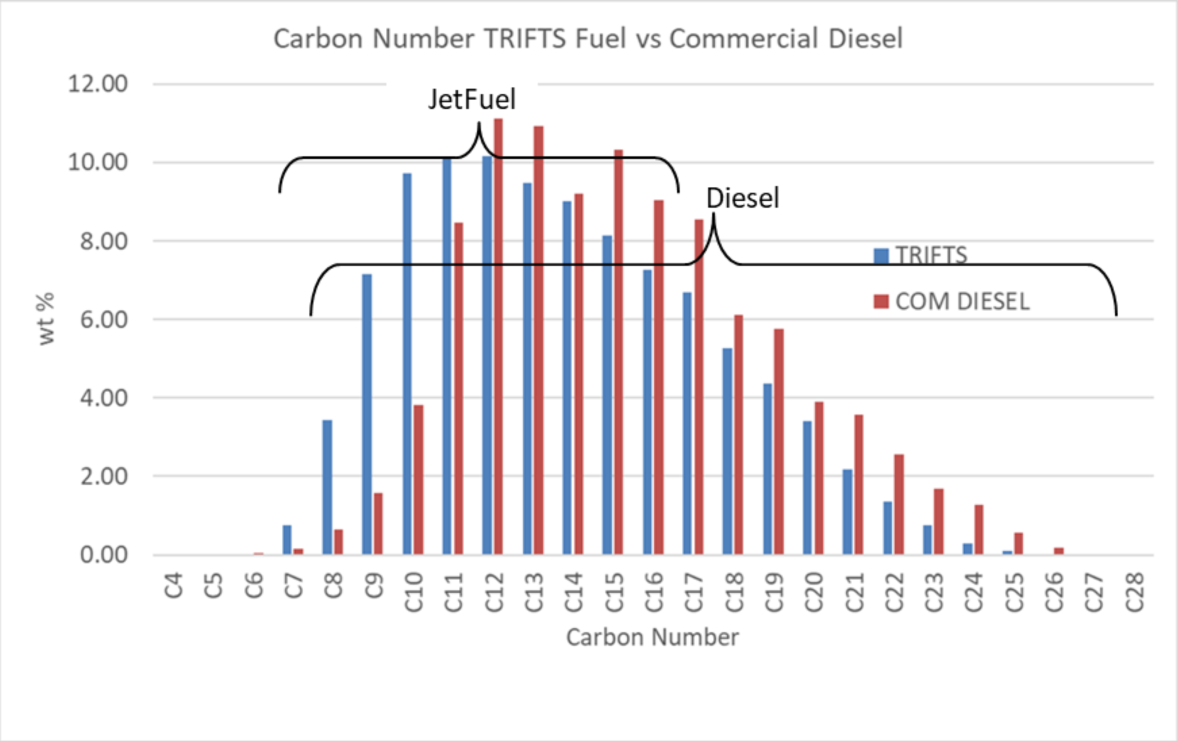
Generate Heat In-situ

Approach

FTS Eggshell Catalyst

- Overcome heat and mass transfer limitations
- Tight temperature control throughout reactor
- Selective product distribution in middle distillate region
- Fuel product tunability
- Avoid wax production





Approach

- Maximize Biogas Feedstock Potential (CO_2 Utilization)
- Reduction of GTL Unit Operations
- Compatible with Current Infrastructure (Relevant Scale)
- Waste Derived Drop-In Diesel (Decarbonize Transport)
- Self Sufficient Process
- Produce D3/D7 RIN and LCFS credits
- Attractive Economics and Profitability

Approach

Challenges

- MYP Barriers ADO-D & ADO-F
- Cost Effective at Waste Industry Scales (Achieve MFSP of < \$3.00/GGE)
  MYP Goal G20AD22
- Consistent production of in-spec diesel regardless of biogas source and over industrial relevant time periods
- Maintain high CO2 conversions while producing desired syngas quality and avoiding coke formation
- Achieve catalyst lifetimes > 6 months and On Stream Factor > 92%.

Approach

Period	Go/No-Go Decision Point and Milestones
Period 1	**Go/No-Go Decision Point:** Initial DOE Verification (Completed March 2020)
Period 2	**Go/No-Go Decision Point**: Demonstrate Ability to Produce Drop-in Diesel Meeting ASTM D975 Fuel Specifications **Milestone:** Conduct pilot demo on-site biogas production facility **Milestone:** Produce diesel fuel for ASTM testing. **Milestone:** Recycle TRIFTS product water during pilot operations with no decrease (<1%) in conversions, product qualities, and efficiencies. **Milestone:** Verify heating and utility requirements are met by process outputs for self-sufficiency at steady state for full scale design. **Milestone:** Prove ability to produce drop-in fuels (per ASTM D975) without use of additional hydrocracking and/or hydrotreatment operations.
Period 3	**Go/No-Go Decision Point**: Achieve Over 100 hr Continuous Time On Stream and Produce Over 100 Gallons of Certifiable Diesel From Raw Biogas **Milestone:** Complete LCA and verification of GHG reduction. **Milestone:** Complete techno-economic analysis for both full scale facility and modular farm scale facility and prove MFSP of less than $3.00/GGE. **Milestone:** Obtain RIN credit approval.

Approach

Parameter/Performance	Description	Units	Benchmark	Intermediate Target	Final Target
Technology Readiness Level (TRL)	*Use TRL definitions provided in the TRL tab to describe the state of the proposed unit operation*	*TRL*	*6*	*7*	*7*
Scale for operations	*Raw Biogas Feed Rate to TRIFTS Pilot Plant*	*Biogas SCFM*	*9*	*12*	*14*
Contaminant Removal	*Removal of H2S below 10 ppm*	*ppm*	*3*	*0*	*0*
Residence Time	*Reformer*	*GHSV*	*12000 h-1*	*13000 h-1*	*13000 h-1*
Residence Time	*FTS*	*GHSV*	*2910 h-1*	*2910 h-1*	*2910 h-1*
Reformer Efficiency	*CH4 and CO2 conversion*	*mol conversions*	*CH4>81.6%, CO2>32.4%*	*CH4>90%, CO2>40%*	*CH4>90%, CO2>40%*
FTS Efficiency	*H2 and CO conversion*	*mol conversions*	*H2>64.95%, CO>57.02%*	*H2>70%, CO>60%*	*H2>70%, CO>60%*
H2:CO Rati	*Syngas molar ratio (H2:CO)*	*mol*	*1.7-2.4*	*1.7-2.4*	*1.7-2.4*
Catalyst Lifetime	*Estimated or actual lifetime*	*hours*	*>2688 h*	*>4320 h*	*>4320 h*
Stability	*Hours on stream between regenerations*	*hours*	*336 h*	*672 h*	*672 h*
Overall Liquid Yield	*Mass of liquidproduct/Mass of Feed*	*wt. %*	8.24%	10.41%	11.00%

- Contaminant removal < 10ppm
- Optimize regeneration cycles of media and catalyst
- Optimize ratio control of oxidants to achieve H_2:CO~1.7-2.4 and CO_2 conversions above 40%
- In-situ separations without distillation column (desired boiling points directly from process)
- Emulsion free liquid fuel product directly from process
- Fuel spec testing (ASTM D975)
- Recycle product water to process and measure effects
- Verify energy content of product gas exceed energy requirements of reformer and steam production (self sufficiency)

- Ability to generate sufficient electricity to power equipment & controls
- EPA fuel certification
- Complete GREET LCA model (AD and Landfill)
- Long term demo (>1000 hr)
- Verify commercial relevant catalyst lifetimes (>6 months)
- Independent 3rd party engineering assessment (verify nameplate and efficiencies)
- Finalize technoeconomic analysis (MFSP < $3.00/GGE)
- 3rd party diesel engine testing (secure fuel market / offtake)
- Fuel pathway approval for RIN and LCFS
- Design full scale facility

Approach

Project Risk & Mitigation

Meet Process Performance Goals

- Gaps Identified During Demo
- Remedial Measures Made
- Strategies Developed, Modeled, & Tested
- Significant Design or Equipment Changes Reviewed (Cost/benefit justification)
- Process Design Improvements Modeled (COMSOL & HYSIS)

Operations & Safety

- Robust Standard Operating Procedures
- Environmental Management Control and Compliance
- Site Specific Safety Plans & Hazard Assessment
- Process Hazard Reviews

Process & Catalyst Longevity

- Long-term, Continuous Pilot Testing

Fuel Marketability

- Fuel Pathway Verification & Registration Assistance
- Fuel Policy & Price Reviews
- Long-term Off Take Agreements & Guaranteed Price

Process Economics & Funding

- Equipment Specs and Detailed Design
- Achieve MFSP < $3.00/GGE
- Stakeholder Engagement

Diversity, Equity, and Inclusion Plan

- Project Development within underserved rural communities
  - Index of Deep Disadvantaged Communities
  - STEM learning at elementary and high school levels
  - Public tours and presentations
- Inclusion of underrepresented groups as employees, researchers, and interns
  - Woman, Hispanic, and Veteran Staff
  - Support University of South Florida URM/REU/RET programs for underrepresented minorities
- Thoughtful and deliberate integration of diversity into everyday practice
- Implicit bias training for existing and new staff
- Utilize minority, woman, and veteran owned businesses as vendors and contractors
  - URM > 25%
- Local disadvantaged businesses utilized during construction and operational phases
- Collaboration with American Indian Tribes (waste to energy strategy development)

Progress and Outcomes

Initial Verification (Completed March 2020)

Milestone 1 (Completed June 2020): Conduct pilot demo on-site at landfill facility.

Milestone 2 (Completed October 2021): Conduct pilot demo on-site at biogas production Wastewater AD facility.

Milestone 3 (Completed May 2020): Produce diesel fuel for ASTM testing.

Milestone 4 (Completed May 2020): Successfully recycle TRIFTS product water during pilot operations with little to no impact to product quality and efficiencies.

Milestone 5 (Completed Jun 2021): Verify heating and utility requirements are met by process outputs for self-sufficiency during steady state for full-scale design.

Milestone 6/7 (Completed May 2020): Produce drop-in fuels (per ASTM D975) without hydrotreatment and/or hydrocracking operations.

Milestone 8 (Completed October 2021): Intermediate DOE verification of project.

Milestone 9 (Completed March 2022): Complete Life Cycle Analysis model and verification of Green House Gas reduction.

Milestone 10 (Completed March 2022): Complete techno-economic analysis for Farm/AD/Landfill full scale facilities and prove MFSP of less than $3.00/Gasoline Gallon Equivalent.

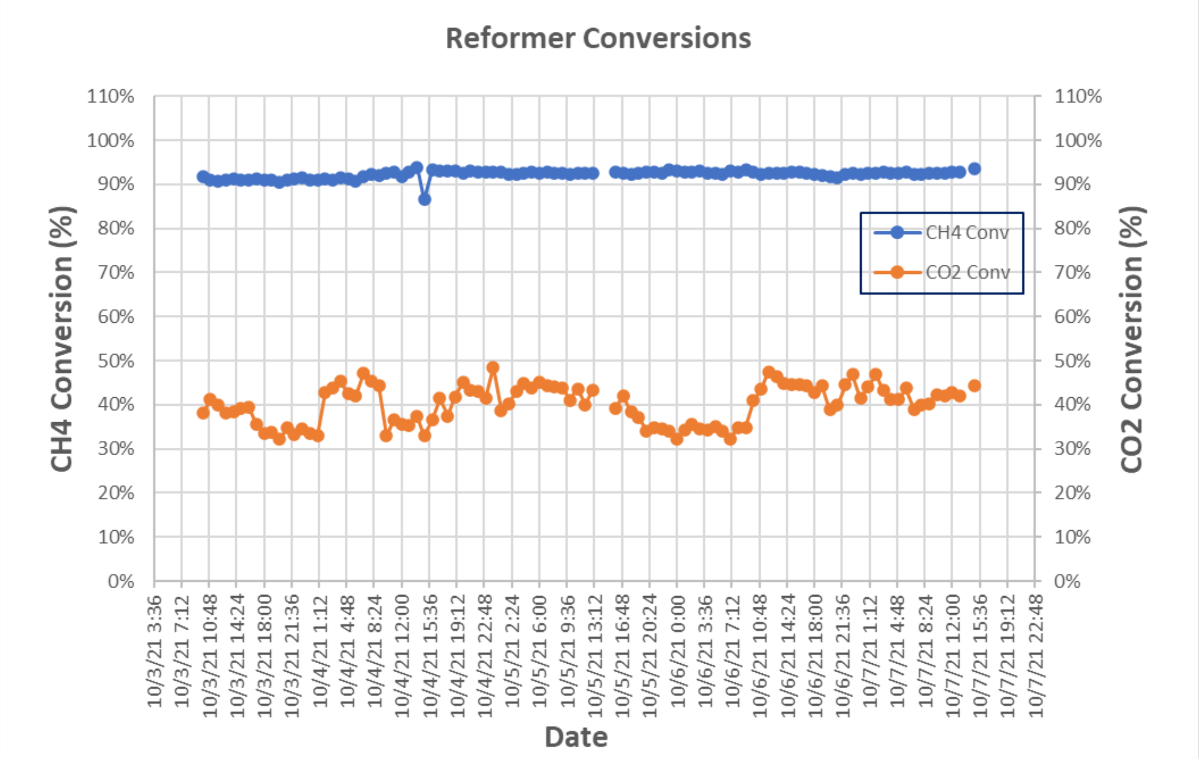
Milestone 11 (Ongoing expected completion date June 2023): Fuel pathway approval.

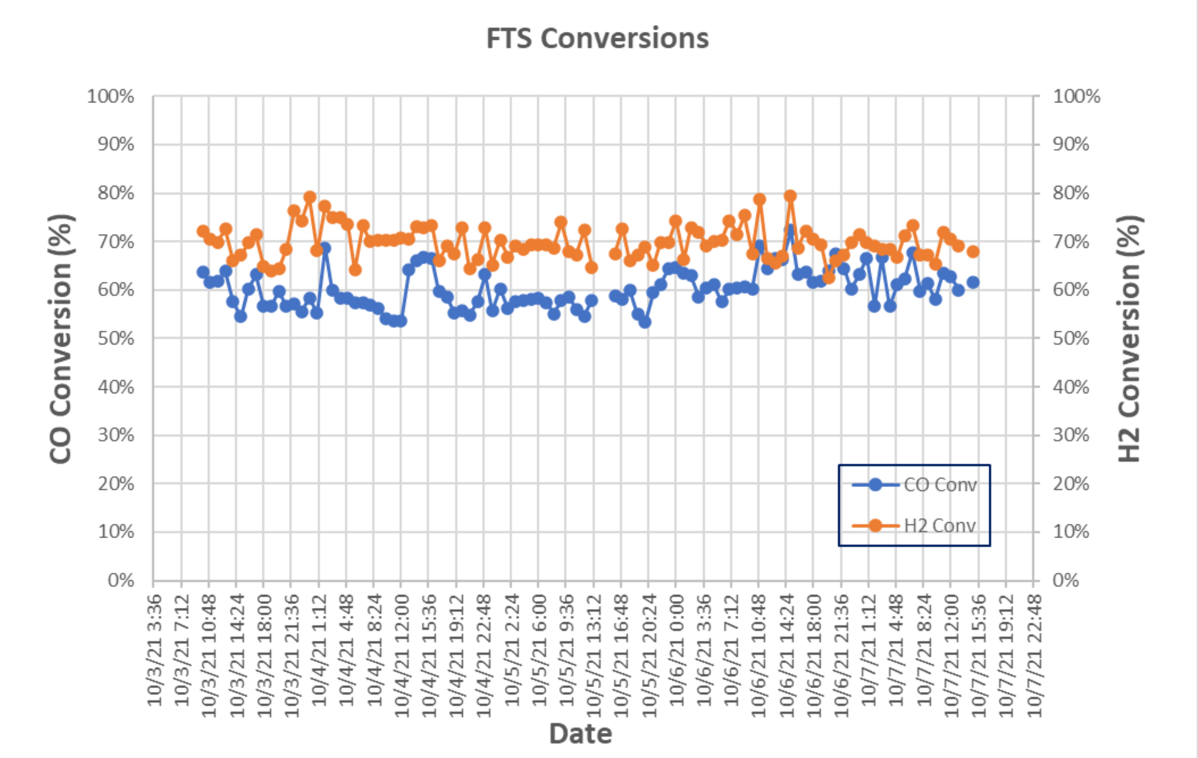
Milestone 12 (Completed 06/30/20): Achieve over 100 hour of continuous time on stream to produce over 100 gallons of certifiable drop-in TRIFTS diesel fuel from raw (directly from waste facility biogas supply) biogas.

Milestone 13 (Expected completion date June 2023): Final verification of project.

Progress and Outcomes

KPP Metrics	REFORMER UNIT			FTS UNIT		
	CH4 Conv (%)	CO2 Conv (%)	H2:CO	CO Conv (%)	H2 Conv (%)	Mass Liquid product/Mass Feed
Verification Averages	92.23	40.02	2.32	59.68	69.82	22.7%
Targets Intermediate	90%	40%	1.7-2.4	60%	70%	10.4%
Targets Full Scale	90%	40%	1.7-2.4	60%	70%	21.0%





Steam & Air ratio control allows for consistent syngas/fuel quality under varying biogas compositions

Progress and Outcomes

ASTM Method	EN Method	Lab Number	49673	TRIFTS DIESEL	Blend 27/73	Blend 27/73	ASTM D975		EN 590	
		Sample Code	Units	100% (neat)	Dairy/Com Diesel	Landfill/Com Diesel	min	max	min	max
D130 Fuels	EN ISO 2160	Copper		1A	1A	1A	-	No. 3	Class 1	Class 1
D2500	EN 23015	CloudPt	Deg C	-1	3	3	-	-	-	-
D2624	-	EConduct	pS/m	0	290	321	25	-	-	-
D2709	ISO 12937	TtlSmpl	Vol% (mg/kg)	< 0.005 (<50)	< 0.005 (<50)	< 0.005 (<50)	-	0.05	-	200 mg/kg
D4052	ISO 3675	Dens@15C	g/ml	0.7626	0.8245	0.8249	-	-	0.820	0.845
D445 40c	ISO 3104	Viscosty	cSt	1.792	2.321	2.347	1.9	4.1	2	4.5
D482	SO 6245	Ash	mass %	<0.001	<0.002	<0.003	-	0.01	-	0.01
D5186		TtlArom	Mass%	0.3	18.8	18.8	-	35	-	-
		MonoArom	Mass%	0.2	15.9	15.8	-	-	-	-
	EN 12916	PolyArom	Mass%	0.1	3.0	3.0	-	-	-	11
D524_10%	ISO 10370	RamsBott	wt%	0.04	0.05	0.06		0.35	-	0.3
D5453	ISO 20846	Sulfur	ppm	<0.5	5.96	5.89	-	15	-	10
D6079	ISO 12156-1	ASTM WSD	micron	340	330	340	-	520	-	460
D613	ISO 5165	CetaneNo		>75.3	55.6	53.6	40	-	51	-
D6217	EN12662	Ttl_Cont	mg/L (mg/kg)	1.2 (1.57)	1.6 (1.94)	1.9 (2.30)	-	-	-	24 mg/kg
D6371	EN 116	CFPP	Deg C	-4	-3	-3	-	-	-	0 (Grade B)
D6468_180	ISO 12205	Avg%Refl	%	100	99	99	80	-	-	25 g/m3
D86	ISO 3405	PCorrIBP	degF (°C)	316.9 (158.3)	318.9 (159.4)	328.6 (164.8)	-	-	-	-
		PCorrFBP	degF (°C)	616.1 (324.5)	670 (354.4)	669.2 (354)	-	-	-	-
		PCorrD10	degF (°C)	359.2 (181.8)	389.6 (198.7)	392.4 (200.2)	-	-	-	-
		PCorrD50	degF (°C)	455.9 (235.5)	491.9 (255.5)	493.9 (256.6)	-	-	-	-
		PCorrD60	degF (°C)	486.2 (252.3)	521.6 (272)	522.8 (272.7)		-	-	<65% @ 250C
		PCorrD90	degF (°C)	585.2 (307.3)	616.6 (324.8)	616.8 (324.9)	540 (282)	640 (338)	-	-
		PCorrD95	degF (°C)	605.7 (318.7)	645.8 (341)	647 (341.7)	-	-	-	680 (360)
D93	ISO 2719	FlashP-C	degC	59	57	63	-	-	> 55 C	-
D976	ISO 4264	CetanInd		73.4	53.3	53.4	40	-	46	-
	EN 14078	FAME	volume %	0.6	1.4	1.4		-	-	7

- 3rd Party Fuels Testing
- Landfill, Wastewater, Dairy Waste Derived Fuels
- Meet US and European Standards
- Cleaner Burning (Reduced SOx, NOx, and Particulates)
- Flexibility in Use and Distribution

Impacts

T2C-ENERGY

Conversion Efficiencies of TRIFTS vs. RNG Processes

Biogas Composition			LFG to RNG		TRIFTS	
Component	mol %	wt %	RNG Conv Effeciency	Biofuel wt%	TRIFTS Conv Effeciency	Biofuel wt%
Methane	56%	32.5%	90.0%	29.3%	90.0%	29.3%
Carbon Dioxide	42%	66.0%	0.0%	0.0%	40.0%	26.4%
			Overall Effeciency	**29.3%**	**Overall Effeciency**	**55.7%**

Financial Comparison of TRIFTS vs RNG at 1,300 scfm Biogas Capacity

LFG to RNG		LFG to TRIFTS Diesel	
CAPEX	$14.0MM	**CAPEX**	$12.1MM
OPEX	$1.72MM/yr	**OPEX**	$1.56MM/yr
Annual Revenues		**Annual Revenues**	
RNG wholesale ($2.50/mmbtu)	$ 686,909	Diesel wholesale ($3.45/gal)	$ 3,136,826
D3 RINS ($31.04/mmbtu)	$ 8,528,377	D7 RINS ($5.20/gal)	$ 4,779,788
LCFS ($3.68/mmbtu @ CI=50 gCO2e/MJ)	$ 1,011,130	LCFS ($2.16/gal @ CI=-35 gCO2e/MJ)	$ 1,963,926
IRR Env. Attributes Included	65.1%	**IRR Env. Attributes Included**	59.9%
IRR Env. Attributes Excluded	**-69.8%**	**IRR Env. Attributes Excluded**	**8.00%**

Impact

<u>Private and Municipal Engagement</u>

- Dairy Farm AD Demo (Trenton, FL)
- Citrus County Landfill Demo (Lecanto, FL)
- Pinellas County Water Reclamation Facility Demo (St. Petersburg, FL)
- Fuel Offtake Partners at Local and National Level
- Environmental Attribute Consultants
- Heavy Duty Engine Testing Facilities
- Specialty Chemical Manufactures
- Maritime Industry
- Waste Operators & Biogas Producers
- Renewable Energy Developers
- DEP & EPA (Permitting & Fuel Registration)
- EPC Firms

Citrus County Chronicle: Landfill Partners for First in Florida Innovative Research

Pinellas County: Florida Wastewater to Clean Diesel

Impact

- Maximize Biogas Potential (Conversion of CO_2 to Fuel)
  - 70% Increase in Convertible Portion of Biogas vs Current State of Art
- Waste feedstock (Waste Volume Reduction Pathway)
- Waste derived-cellulosic renewable diesel (energy dense fuel to decarbonize transport sector)
  - Only 55,892 D7 RIN generated in 2020
  - 459.7 MM D3 RIN generated in 2020
  - Unlocks 1.9 Billion D7 RIN Potential (Meet the liquid fuel gap!)
- Affordable Gas to Liquids Technology at Waste Industry Scale
- Dissemination of Results
  - Demonstrations Private & Municipal Level (Summary/Feasiblity Reports Distributed)
  - Five Patents Issued (5 more patents pending)
  - Peer Review Papers
  - Graduate & Undergraduate Research Engagement at USF

Summary

- Production of drop-in renewable fuel and fertilizer
- Compatible with current waste industry scales
- Creation of circular economies at the rural and metropolitan levels
- Maximize the conversion of carbon within biogas (90% improvement in conversion efficiency vs current state of art)
- Profitable and competitive in the current market
- Achieved BETO Biofuel Tech & Production Milestone
  - 130% GHG reduction
  - MFSP < $2.91/GGE

Department of Energy's Bioenergy Office Achieves Major Biofuel Technology and Production Milestone | Department of Energy

Quad Chart Overview

Timeline
- *October 1st, 2019*
- *June 30th, 2023*

	FY22 Costed	Total Award
DOE Funding	*$925,805*	*$2,177,758*
Project Cost Share *	$87,574	$651,953

Project Goal
The goal of this project is to rigorously test T2C-Energy's mobile TRIFTS pilot plant to optimize catalytic parameters, process conditions, control schemes, mass and heat integration, economics, and environmental impact to design a universal gas to liquids platform capable of processing a broad range of biogas compositions into drop-in diesel fuel while remaining profitable at waste industry scales.

End of Project Milestone
Achieve over 100 hr of continuous time on stream to produce over 100 gallons of certifiable drop-in TRIFTS diesel fuel from raw biogas.

Funding Mechanism
DE-FOA-0002029
FY19 BETO Multi-Topic
Systems Research of Hydrocarbon Biofuel Technologies (AOI 4)

Project Partners
- University of South Florida
- ARGONNE National Lab

Let's Connect

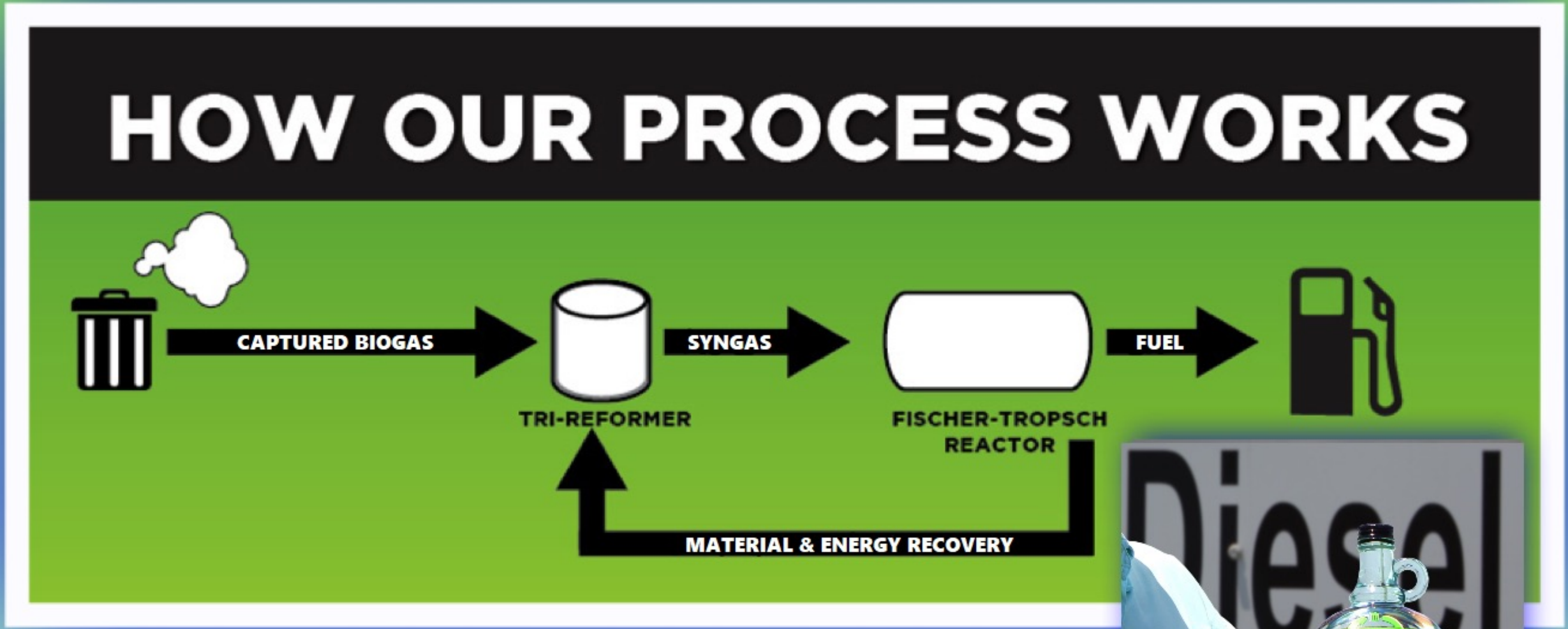
Sustainable Energy Solutions for The Waste Industry

Contact Info

Email: dwalker@t2cenergy.com

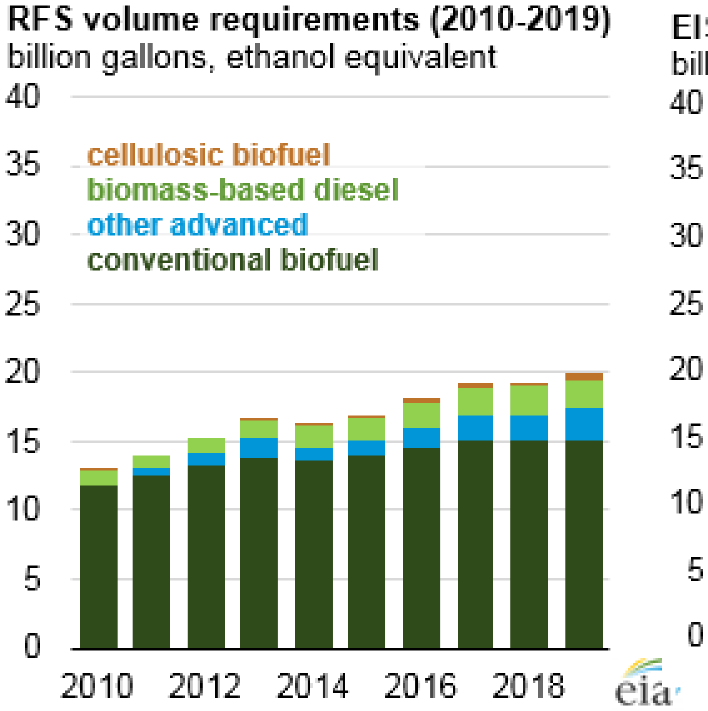
Ph: 813-334-7332

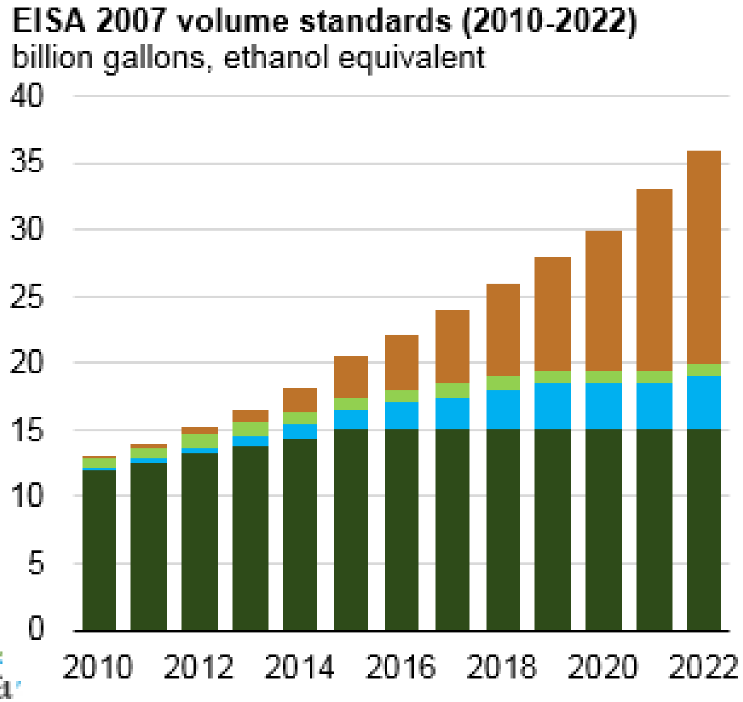
Profitable Gas to Liquids Technology at Waste Industry Scales



The U.S. Renewable Fuel Standard (RFS2)

- Enacted in 2005 / revised in 2007 as an energy security policy
- RINs are generated by renewable fuel producers
- Blenders generally purchase Renewable Fuel and blend it into diesel
  - Blender can now sell two commodities both physical fuel and separated RIN
- Obligated Parties must satisfy their Renewable Volume Obligations using/purchasing RINs





The U.S. Renewable Fuel Standard (RFS2)

- Each of the four Renewable Fuel Mandates has its own lifecycle GHG reduction criteria (established under EISA)
  - Cellulosic Biofuel: ***[Represented by D codes 3, 7]***
    - Must achieve 60% reduction vs. gasoline or diesel baseline
    - Cellulosic RIN production increasing due to new plants and biogas/CNG reclassification
  - Biomass-Based Diesel: ***[D codes 4, 7]***
    - Must achieve 50% reduction vs. diesel baseline
    - Includes Biodiesel and Renewable Diesel
  - Advanced Biofuel: ***[D code 5]***
    - Must achieve 50% reduction vs. gasoline or diesel baseline
    - Includes cellulosic, BBD, sugarcane ethanol and any other qualifying renewable fuel other than corn starch ethanol
  - Total Renewable Fuel: ***[D code 6]***
    - Must achieve 20% reduction vs. gasoline or diesel baseline; except:
      Existing (2007) facilities are "grandfathered", i.e., exempt to its 2007 baseline
    - Includes corn ethanol primarily
- Lifecycle emissions are evaluated by EPA as part of a "well to wheels" analysis, which supports various fuel pathways

The U.S. Renewable Fuel Standard (RFS2)

Renewable Fuels produced from these feedstocks using an approved technology can generate "Cellulosic Biofuel" D3 or D7 RINs

- Agricultural Residues
- Switchgrass
- Miscanthus
- Separated Yard Waste
- Separated Food Waste
- Biogenic separated MSW
- Annual Covercrops
- Forest Product Residues
- Forest Thinnings
- Slash
- Arundo Donax
- Pennisetum purpureum

- Biogas from municipal wastewater treatment facility digesters
- Biogas from agricultural digesters
- Biogas from separated MSW digesters
- Biogas from the cellulosic components of biomass processed in other waste digesters
- Arundo Donax
- Energy Cane
- Bagasse
- Bagasse Straw

Cellulosic feedstocks are evaluated based on their cellulosic content

TRIFTS Renewable Diesel Value Components

- **LCFS credits stack on top of RIN, Physical fuel value, and Blenders tax credit**
- **Renewable Diesel – August 2022 ($/gal)**
  - Physical fuel + CAR = $3.45
  - D3 RIN = $5.20 (1.7 EV x 3.06)
  - LCFS = $2.16 (TRIFTS has **-36** gCO2e/MJ CI score)
  - Blenders Credit = $1.00
  - **Total = $11.81 / gal**

CAR = Cap-At-The-Rack is a premium paid for conventional diesel under the California Cap and Trade program, LCFS and RIN value is NOT passed through to rack under this arrangment

Carbon Intensity Based Standards

Diesel Carbon Intensity (CI) standard = 94.17 $gCO2_e/MJ$ (2019)

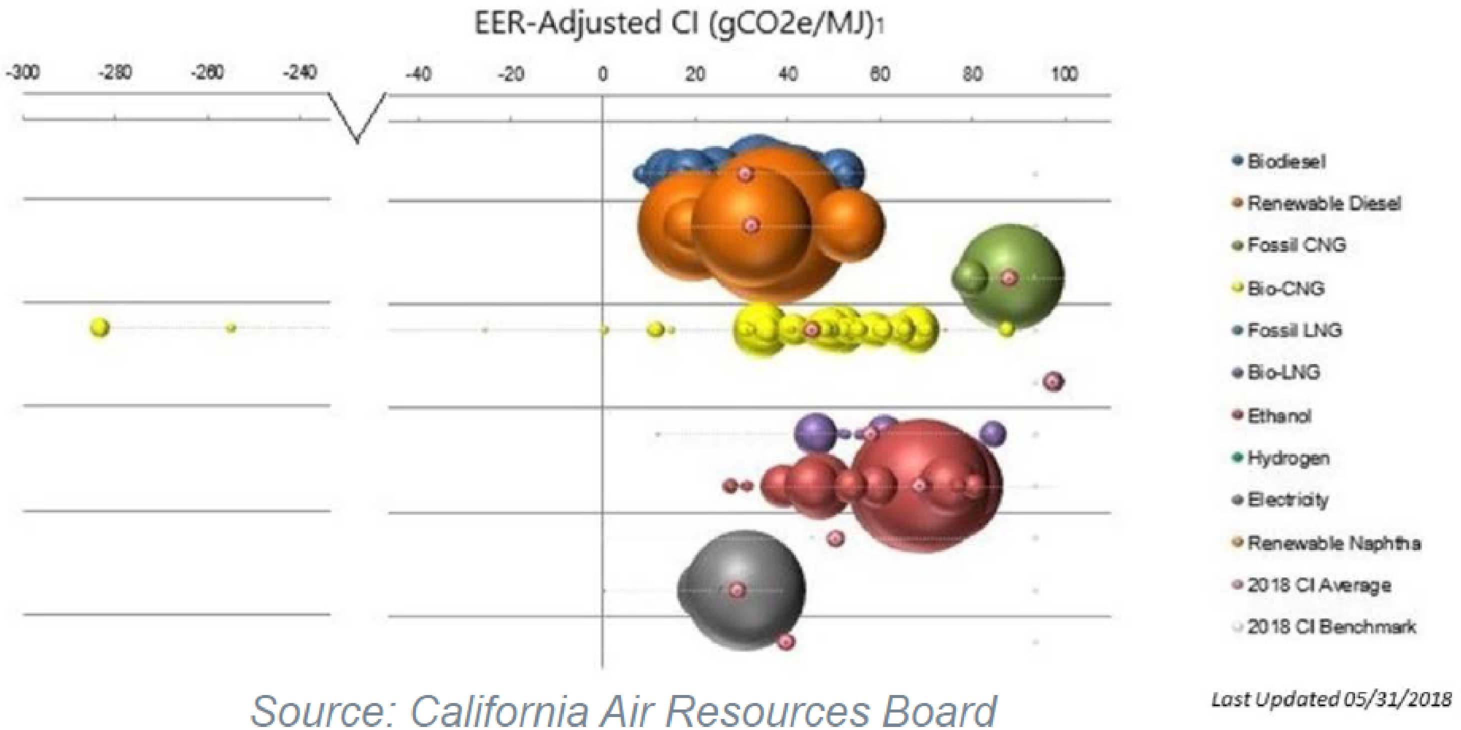
- *Diesel has an energy density of 134.47 MJ/gal*

Credits generated are proportional to the difference between the low carbon fuel and the standard

- *i.e. against a standard of 94, an LFG facility with CI of 54 gCO_2/MJ generates half the credits of a facility with a CI of 14 gCO_2/MJ*

Facilities can have a negative CI when including avoided non-CO_2 GHG emissions (i.e. methane)

2018 Volume-weighted Average Carbon Intensity by Fuel Type



Source: California Air Resources Board