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Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities

California Air Resources Board

Bioresource Economy Summit

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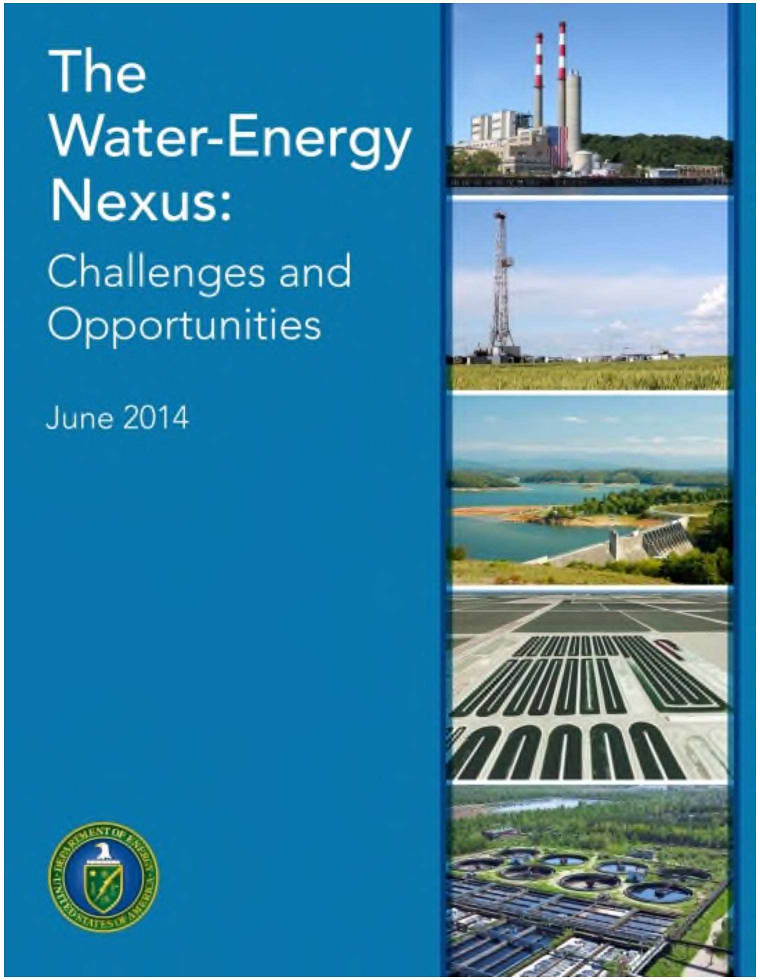
Water-Energy Nexus: 2014 DOE Report

- Congress had been pushing the DOE to do more about Water-Energy Nexus for some time.
- DOE first produced a comprehensive report in June, 2014
- Significant turning point for DOE-wide interest in these issues
- Energy for and from water was a key technology focus



Download the full report at energy.gov

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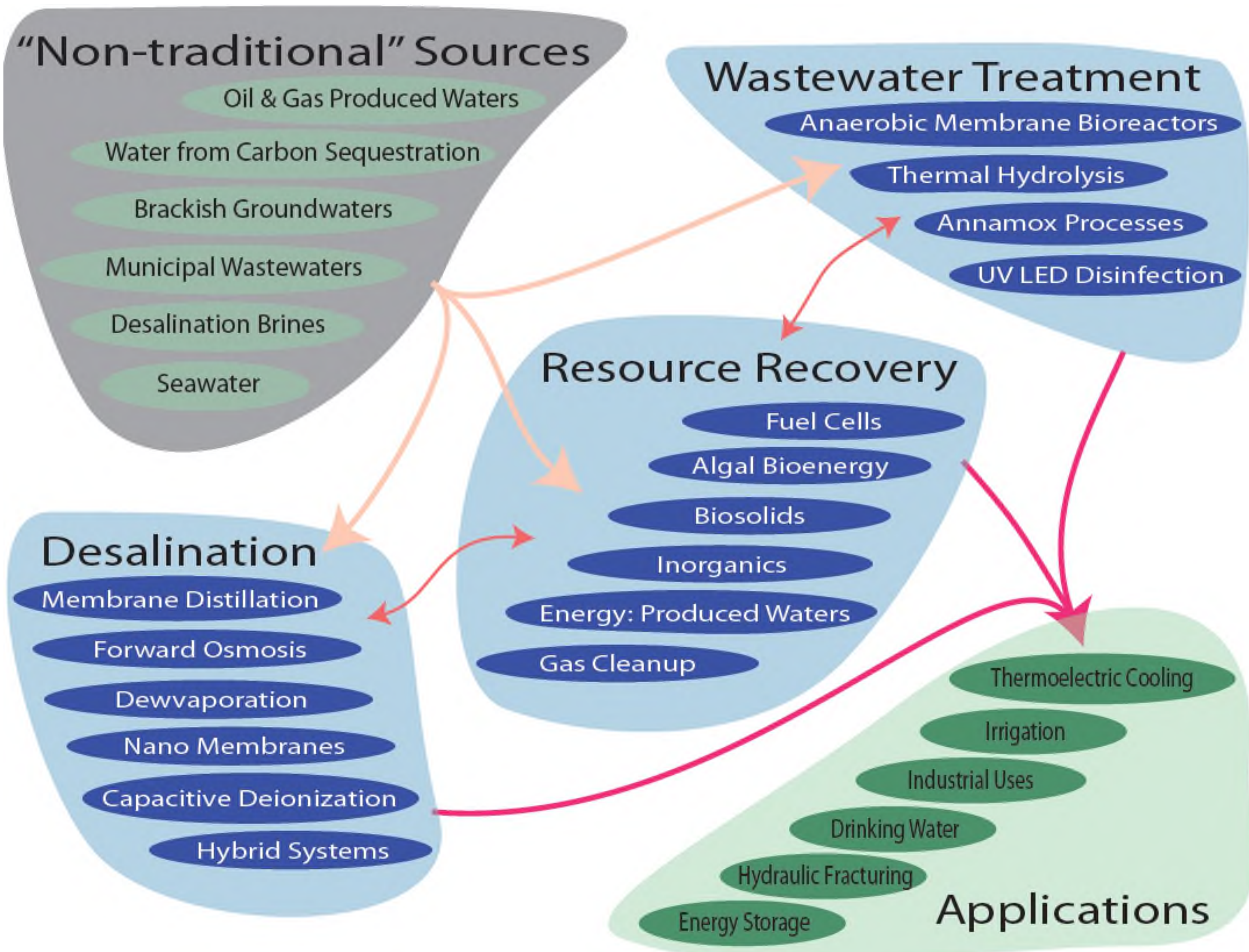
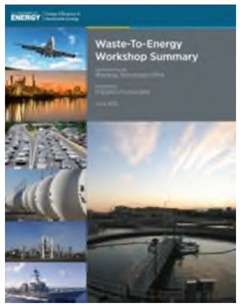
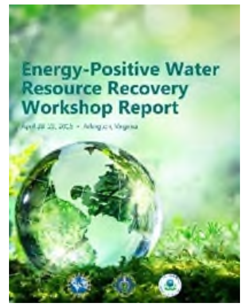
Technology RDD&D: Energy for and from Water



Biofuels and Bioproducts from Wet and Gaseous Waste Streams

Building off of series of four workshops and other recent interagency collaborations.





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Wet and Gaseous Feedstocks: Resource Assessment

Feedstocks	Annual Resource Generation Estimated Annual Resources	Inherent Energy Content (Trillion Btu)	Fuel Equivalent (MM GGE)[1]
Wet Feedstocks	77.17 MM Dry Tons	1,078.6	9,290.8
Wastewater Residuals	14.82	237.6	2,046.6
Animal Waste	41.00	547.1	4,713.0
Food Waste[2]	15.30	79.6	685.3
Fats, Oils, and Greases	6.05	214.3	1,845.9
Gaseous Feedstocks		733.6	6,319.8
Biogas[3]	420 BCF	430.5	3,708.6
CO_2 Streams	3,142 MM Tons	-	-
Associated Natural Gas	289 BCF	303.1	2,611.2
Other Waste Feedstocks		526.1	4,531.6
Glycerol	0.6 MM Tons	8.7	75.1
Black Liquor	44 MM Tons	517.4	4,456.5
DDGS[4]	44 MM Tons	n/a	n/a
Total		**2,338.3**	**20,142.2**

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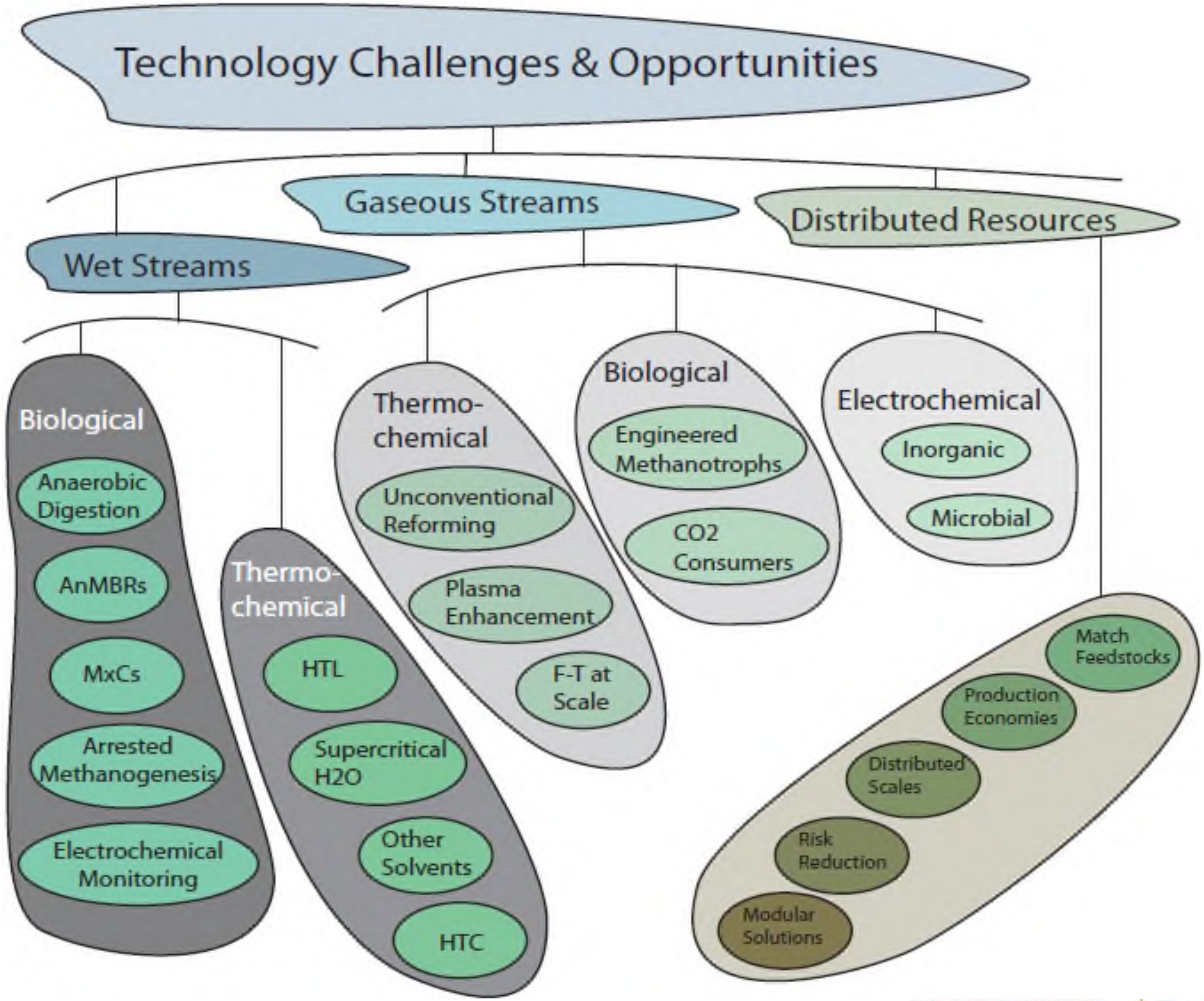
Potential Areas for Technology RDD&D



Estimated Production of HTL Bio-Crude from Waste Streams is Equivalent to 147 MM BBL (26.0%) of 2015 Jet Fuel Consumption in the U.S.

		2015 Consumption[2]	
Feedstocks	Estimated Annual HTL Bio-Crude[1]	Jet Fuel	Diesel
Manure	63.33 MM BBL	11.21%	4.34%
Fattened Cattle Manure	17.62	3.12%	1.21%
Dairy Cow Manure	23.78	4.21%	1.63%
Swine Manure	21.93	3.88%	1.50%
Publicly Owned Treatment Works (POTW)	33.55 MM BBL	5.94%	2.30%
POTW (Primary + Secondary Sludge)	33.55	5.94%	2.30%
Food Waste	22.38 MM BBL	3.96%	1.54%
Food Waste	22.38	3.96%	1.54%
Fats, Oils, and Greases (FOG)	27.61 MM BBL	4.89%	1.89%
Animal Fats (Livestock + Poultry)	14.79	2.62%	1.01%
Brown Grease	7.71	1.37%	0.53%
Yellow Grease	5.11	0.90%	0.35%
Total	**146.87 MM BBL**	**26.00%**	**10.07%**

Jet Fuel Consumption (2015):

565 MM BBL

Estimated Annual HTL Bio-Crude Production:

147 MM BBL

(26% of 2015 Jet and Diesel Consumption)

[1] Estimated annual bio-crude production assessment for each waste feedstock in the conterminous United States. Values from "Waste-to-Energy Biofuel Production Potential for Selected Feedstocks in the Conterminous U.S." by Skaggs, Richard L., et al.

[2] Jet Fuel and Diesel total from Table 3.5 of EIA Monthly Energy Review. Diesel consumption is taken from Distillate Oil consumption which consists of fuel oil and diesel fuel.

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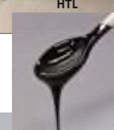
Hydrothermal Liquefaction

Diesel Fuel is made from waste water sludges and is high performing in diesel engine testing

HTL is a process that uses heat and pressure to convert biological materials to biocrude oil in about 15 minutes, using the same principles that nature transforms biological materials to crude oil over centuries

Wet biological material
(waste water, algae, wood)



Stable biocrude oil
(up to 60% yield)

Hydrocarbon fuels
(95%+ yield)

HTL Run Conditions
temperature: 330-350°C
pressure: 2890-2925 psig
Slurry feed rate: 1.5 L/h (LHSV=2.1 L/L/h)

Hydrotreating Run Conditions
temperature: 400°C
pressure: 1500 psig H_2
(typical refinery conditions)

The crude oil from waste water is rich in diesel-range and has high cetane

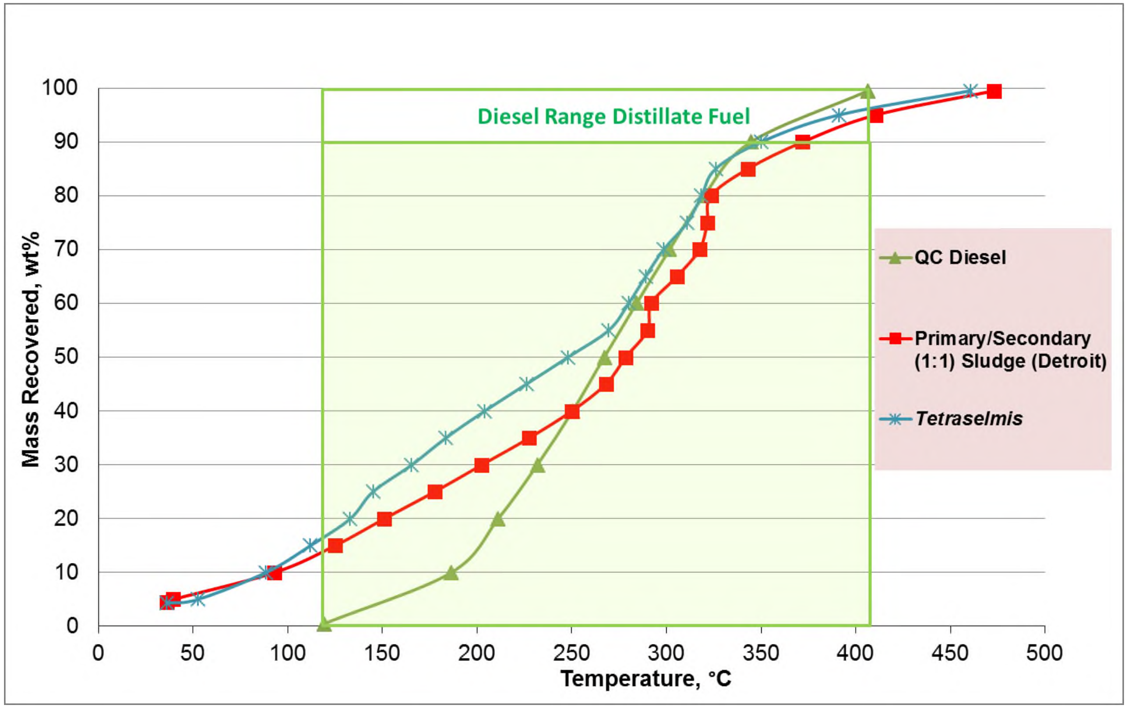
- Fuel has been evaluated by Colorado State University in engine tests using 5% blends and has no negative impact on engine performance and emissions
- The cetane of the sludge-derived diesel is 70 (very high)

- We have worked with Algenol, Metro Vancouver, Detroit Greater Lakes Water Authority, Central Contra Costa County Sanitary District
- The process validated by the Water Environment Research Foundation
- The yield on a carbon basis is the highest of all the processes we have examined

Hydrothermal Liquefaction

Methodology – Biocrude Upgrading

Upgraded Product Boiling Point Distribution



- Over 70% of hydrotreated product from HTL sludge biocrude is in the distillate fuel range.
- Distillate fuel fraction of upgraded biocrude has high cetane of 70 (diesel is ~40).

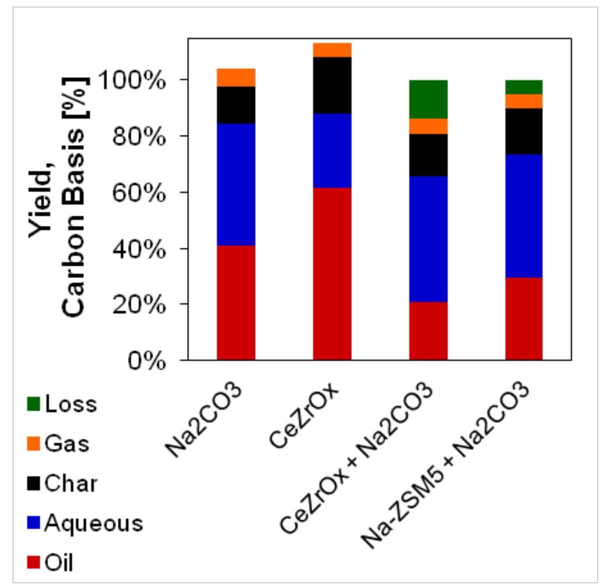
HTL of Food Waste: SBIR Phase I Results

- Het Cat is stable under hydrothermal conditions for at least 165 hrs
- Het Cat ketonized propionic acid to 3-pentanone at 15-20% yield
- Het Cat increased HTL oil yield (from 41% to 61%, Carbon basis) and decreased aqueous organics

[redacted]

Highly Water Soluble

Poorly Water Soluble



HTL Water →Na_2CO_3 Catalyst

HTL Water →Het Catalyst

HTG Water →HTG Catalyst

- **Het Cat reduced aqueous organics 50% compared to Na_2CO_3 (24,200 vs 12,500 ppm TOC)**
- **Catalytic HTG converts 98% of organic carbon to gases (24,200 to 550 ppm TOC)**

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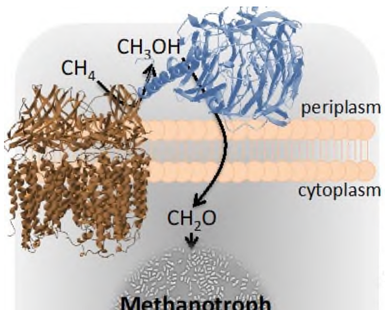
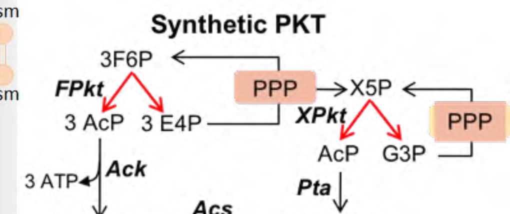
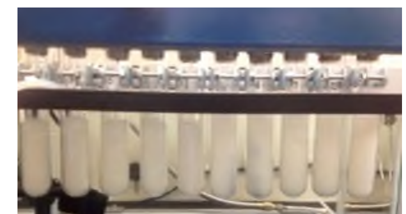
Biological Conversion of Methane

- Biological gas-to-liquid conversion offers a means to bypass conventional chemical and physical conversion strategies.
  - Modular, scalable, highly selective
- Methanotrophic bacteria can use CH_4 as a sole carbon and energy source.





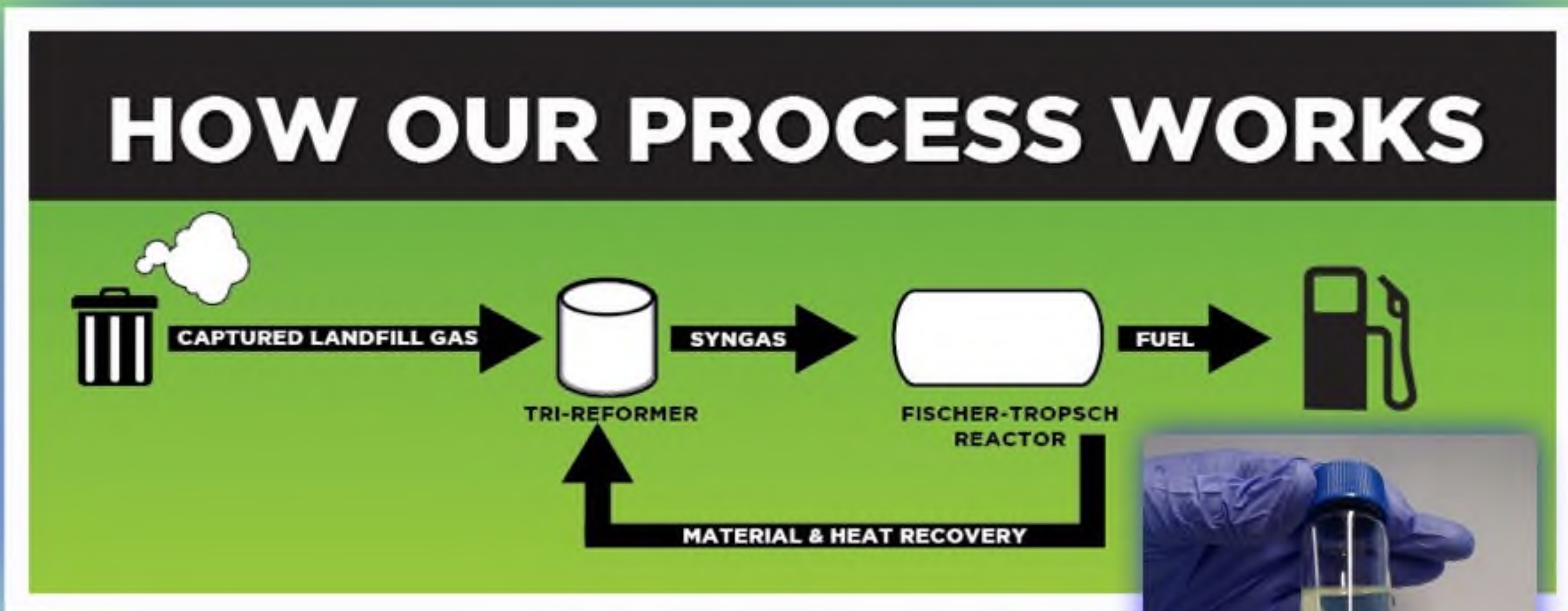


[redacted]

	2016	2017	2018
Titers	0.2g/L (native)	>1g/L	>10g/L
Rate	0.05g/L/hr	0.35g/L/hr	>0.5g/L/hr
Yield	0.25g/g	0.6g/g	0.6g/g

Landfill Gas to Diesel for Trash Collection Fleet - SBIR

Demonstrate small scale GTL in economical and profitable manner



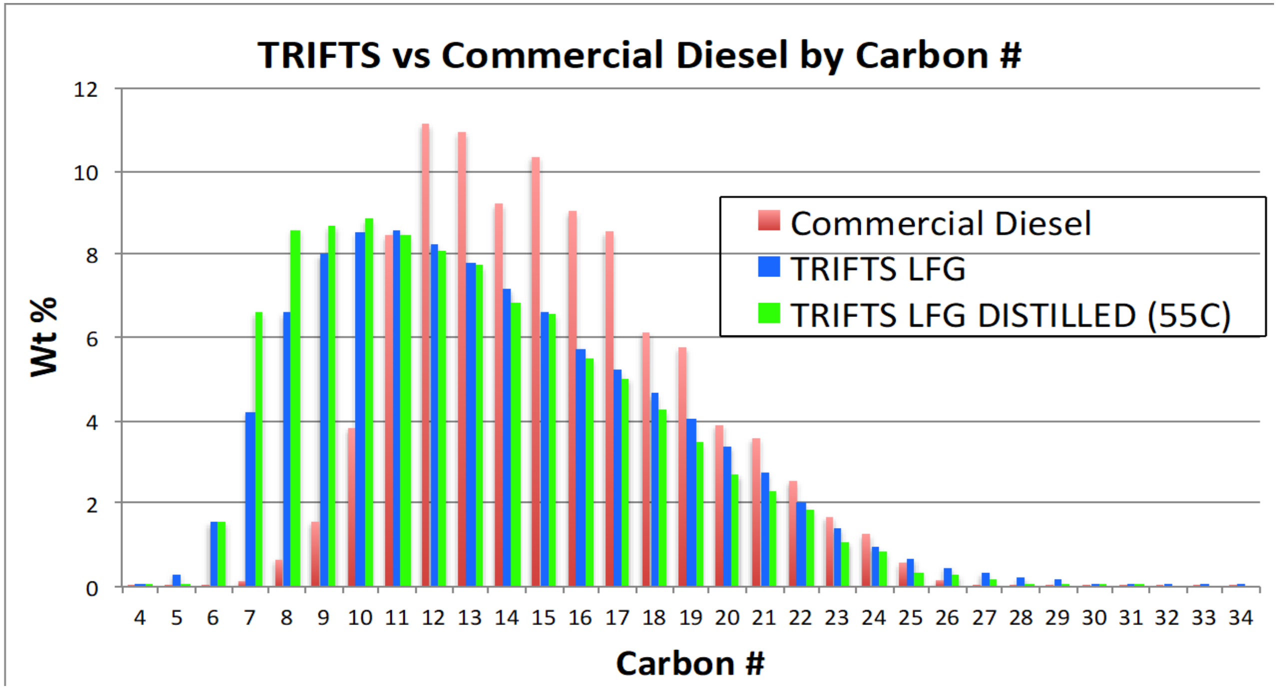
Project Overview – SBIR Phase I & II

Fuel Analysis

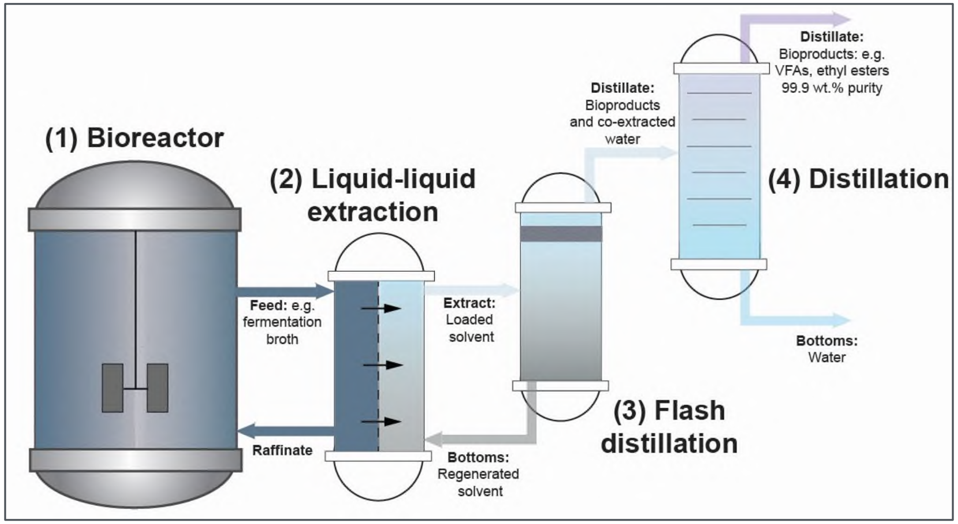
- Low aromatics improve net heat of combustion and reduce soot
- Isomers improve cold temp properties
- Further reduce olefin content w/ addition of catalyst promoters

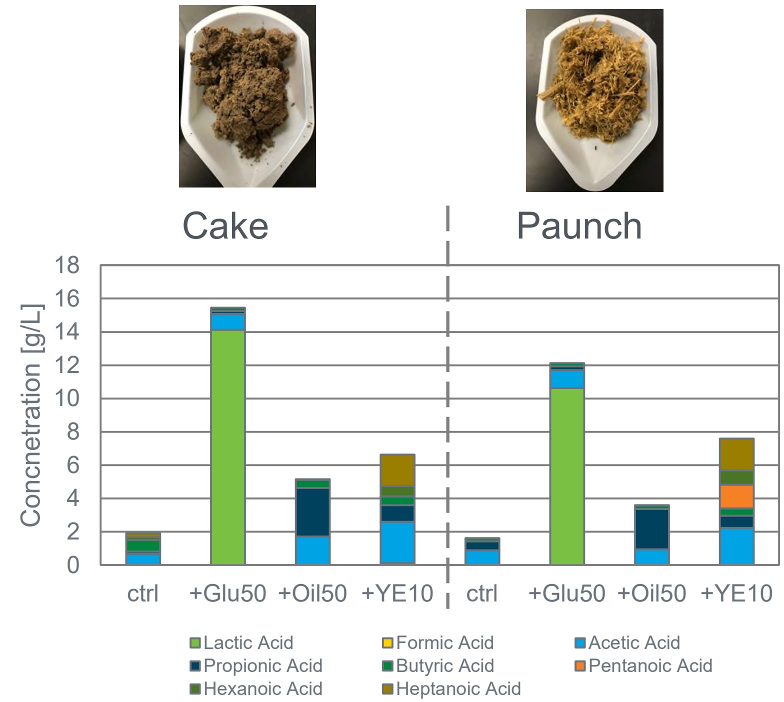
Hydrocarbon Family	T2C-E (H2:CO=1.7)	Commercial Diesel
Paraffins	67.164	19.95
Isomers	28.243	31.6
Olefins	4.323	0.92
Aromatics	0.02	39.48
Cyclics	0.25	8.05

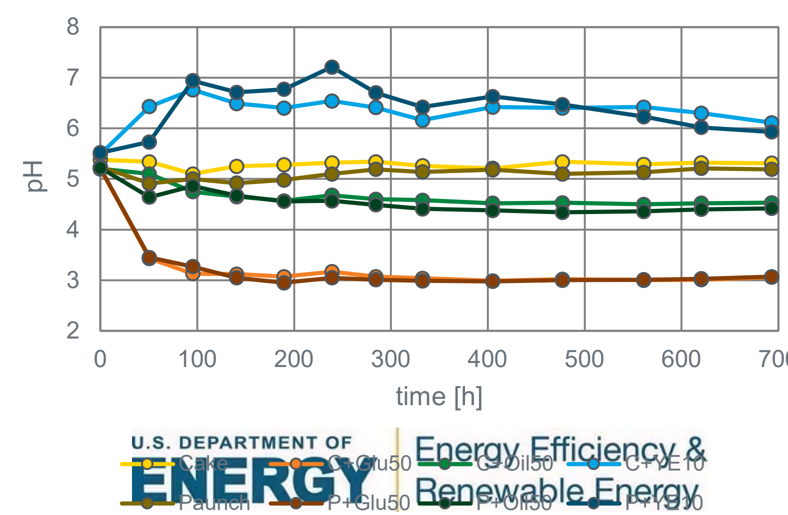
- Excellent middle distillate boiling point distribution
- Control phase separation temp to fractionate light ends
- Final boiling point aligns with commercial diesel



Arresting AD with *in situ* product recovery (ISPR)





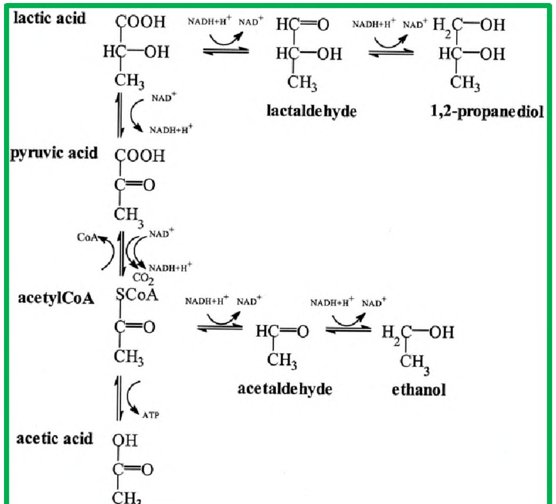


Summary of project

- **Aim:** Produce carboxylic acid platform chemicals from the anaerobic digestion of wet waste feedstocks.
- **Hypothesis:** Removing carboxylic acid with *in situ* separations will effectively arrest methanogenesis.
- **Key results:**
  - Mathematical modeling shows that ISPR is feasible if pH ~ 3 and acid titers > 9.5 g/L
  - Serum bottle experiments demonstrate this is achievable with an accessible substrate (data to right)
- **Future work:** (1) ISPR system build for high solids handling. (2) Prospect ideal consortia for titer and pH targets in semi-continuous conditions. (3) Demonstrate integrated system.

ARRESTED METHANOGENESIS FOR VOLATILE FATTY ACID PRODUCTION

Tailoring Microbial Consortia and Dynamics for VFA Production



Conversion of LAc to HAc

Appl. Environ. Microbiol., **2001** vol. 67 no. 1 **125-132**

Two different reactor configurations due to waste stream characteristics and application point and size of the AD

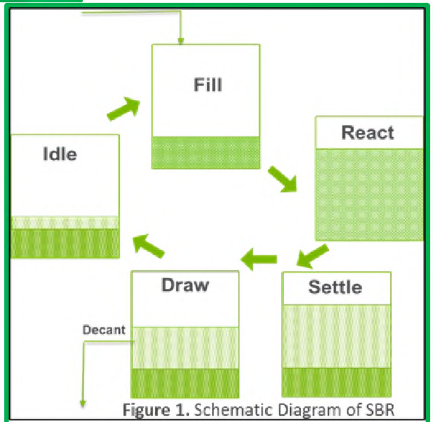


Figure 1. Schematic Diagram of SBR

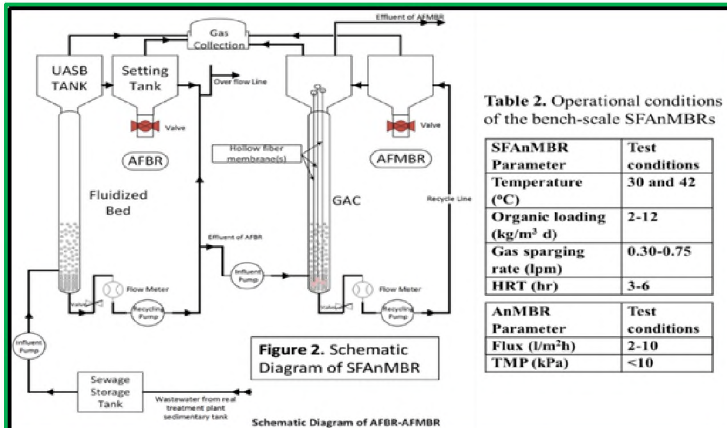
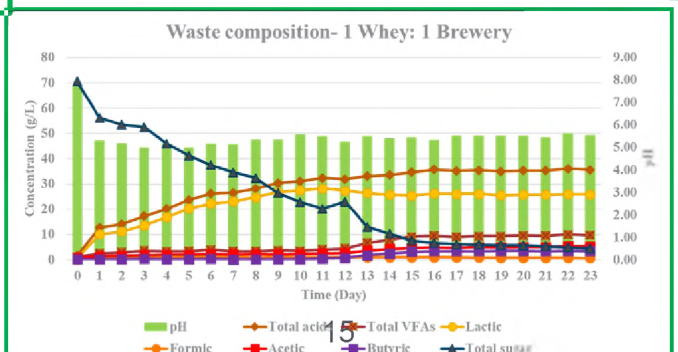


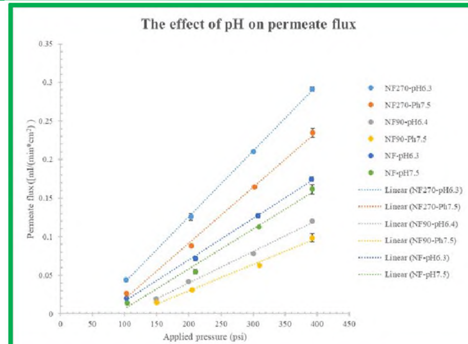
Figure 2. Schematic Diagram of SFAnMBR

Table 2. Operational conditions of the bench-scale SFAnMBRs

SFAnMBR Parameter	Test conditions
Temperature (°C)	30 and 42
Organic loading (kg/m³ d)	2-12
Gas sparging rate (lpm)	0.30-0.75
HRT (hr)	3-6
AnMBR Parameter	Test conditions
Flux (l/m²h)	2-10
TMP (kPa)	<10

Solving challenges in product separations





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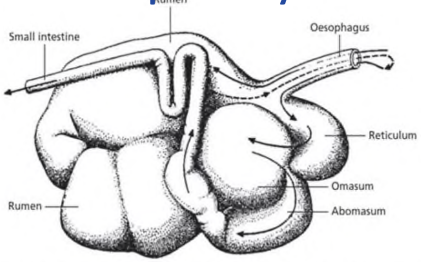
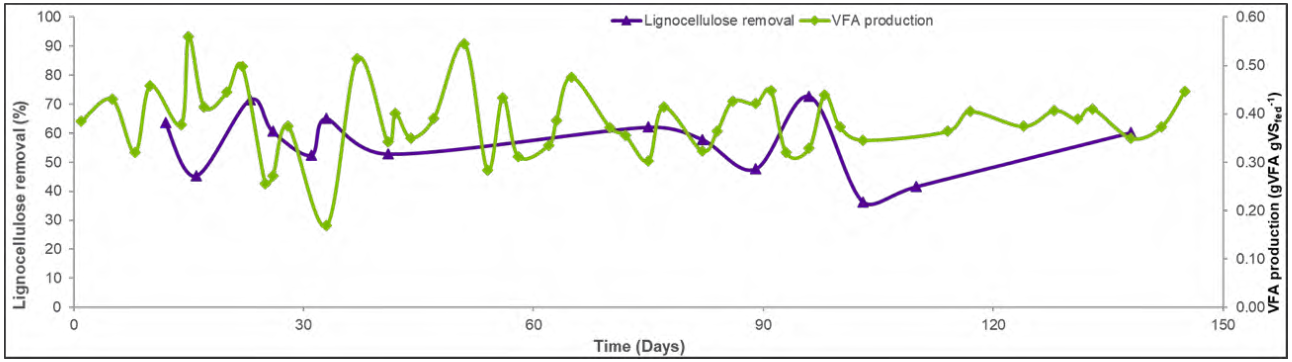
Ruminant Inspired Dynamic AnMBR hydrolyzes a high fraction of lignocellulose in a short time





The rumen is a natural ecosystem with efficient lignocellulose hydrolysis-

Food waste acidogenesis

Conventional	Rumen Inspired Novel AnMBR
HRT = 5-10 days	HRT= 12 h
OLR <11 g VS L_R^{-1} day^{-1}	OLR = 18 ± 3 g VS L_R^{-1} day^{-1}
VFA= 0.3 – 0.4 g VFA g VS_{in}^{-1}	VFA = 0.38 g VFA g VS_{in}^{-1}

Dynamic Membrane: Filtering biofilm formed on support structure of ~ 10 – 100 microns

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Dynamic AnMBR

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Key Wet and Gaseous Feedstocks Messages

- Wet and gaseous feedstocks constitute significant resources that already exist in distributed form. In many cases, collection systems are already in place.
- They frequently constitute a clear and present disposal problem
  - This issue has garnered serious Congressional attention
  - A.B. 1383 is a significant driver in CA
  - The anthropogenic streams are only going to get larger as population grows
- These feedstocks require conversion solutions that are both geographical proximal to their sources, and tailored to the unique streams.
- While market challenges remain, these resources could present leading-edge niche opportunities for the bioeconomy of the future

Questions?

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