Technologies for Upgrading Landfill Gas to a High-Quality Fuel

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USF and T2C-Energy LLC

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T2C-ENERGY

UNIVERSITY of SOUTH FLORIDA

ACKNOWLEDGMENTS

Hinkley Center for Solid and Hazardous Waste Management

Funding 2010

MegaWatt Ventures

Winner 2012

Clean Tech Open Southeast

Winner 2013

tbtf Tampa Bay Technology Forum

Innovation of the Year 2013

VentureWell 20 years of idea to impact

Funding 2014

The Corridor Florida High Tech

Funding 2014

GlobalVenture Challenge™ 2010

Winner 2010

T2C-ENERGY *

Forbes

30 Under 30 2014

FESC Florida Energy Systems Consortium

Universities Addressing Florida's Energy Needs

Funding 2009

Florida Department of Agriculture and Consumer Services Est. 1868

Funding 2018 (REET)

Cleantech Intelligent Innovations

Funding 2016

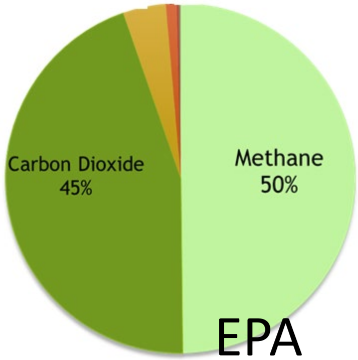
U.S. Department of Energy

Funding 2016 (BES and EERE/BETO)

* Disclosure, USF and T2C-Energy LLC

THE BIG PICTURE

Overarching Goal:
Upgrade biogas to value-added fuels and chemicals



EPA

Biogas (~500 BTU/SCF)

Potential:
Diversify to value-added products, circular economy, minimize flaring

Competing options to mitigate environmental impact of biogas/landfill gas:

FLARING

ELECTRICITY

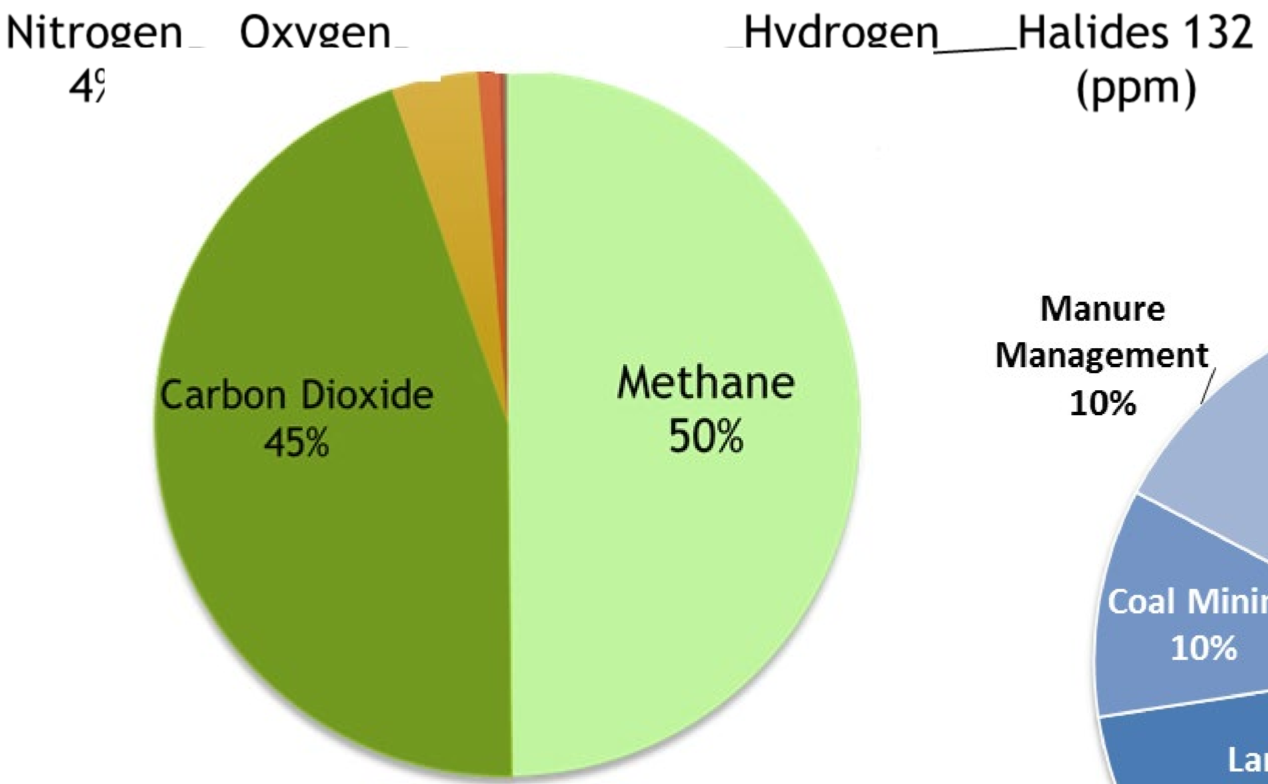
CNG/LNG

FUEL/CHEMICAL

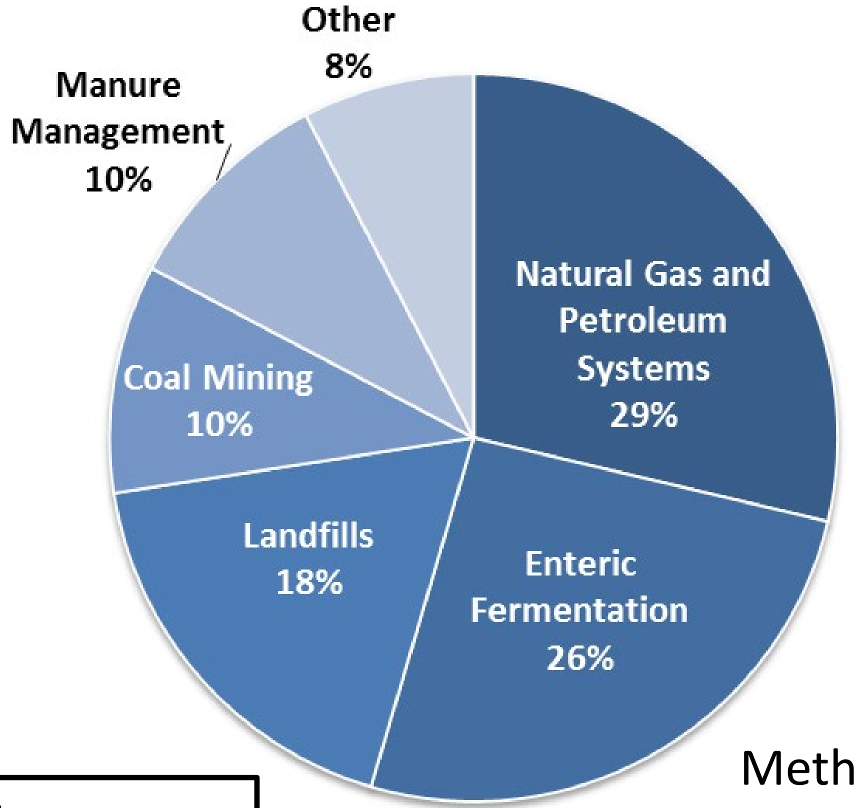
	FLARING	ELECTRICITY	CNG/LNG	FUEL/CHEMICAL
Retail prices* ($/GGE)	n/a	$1.54 (~3 cents/kWh; retail to grid)	$2.88 (CNG) 3.63 (LNG)	$5.17 (diesel) 3.55 (propane)

*Oct. 2022; https://afdc.energy.gov/fuels/prices.html

PROBLEM/OPPORTUNITY



Safety



Energy

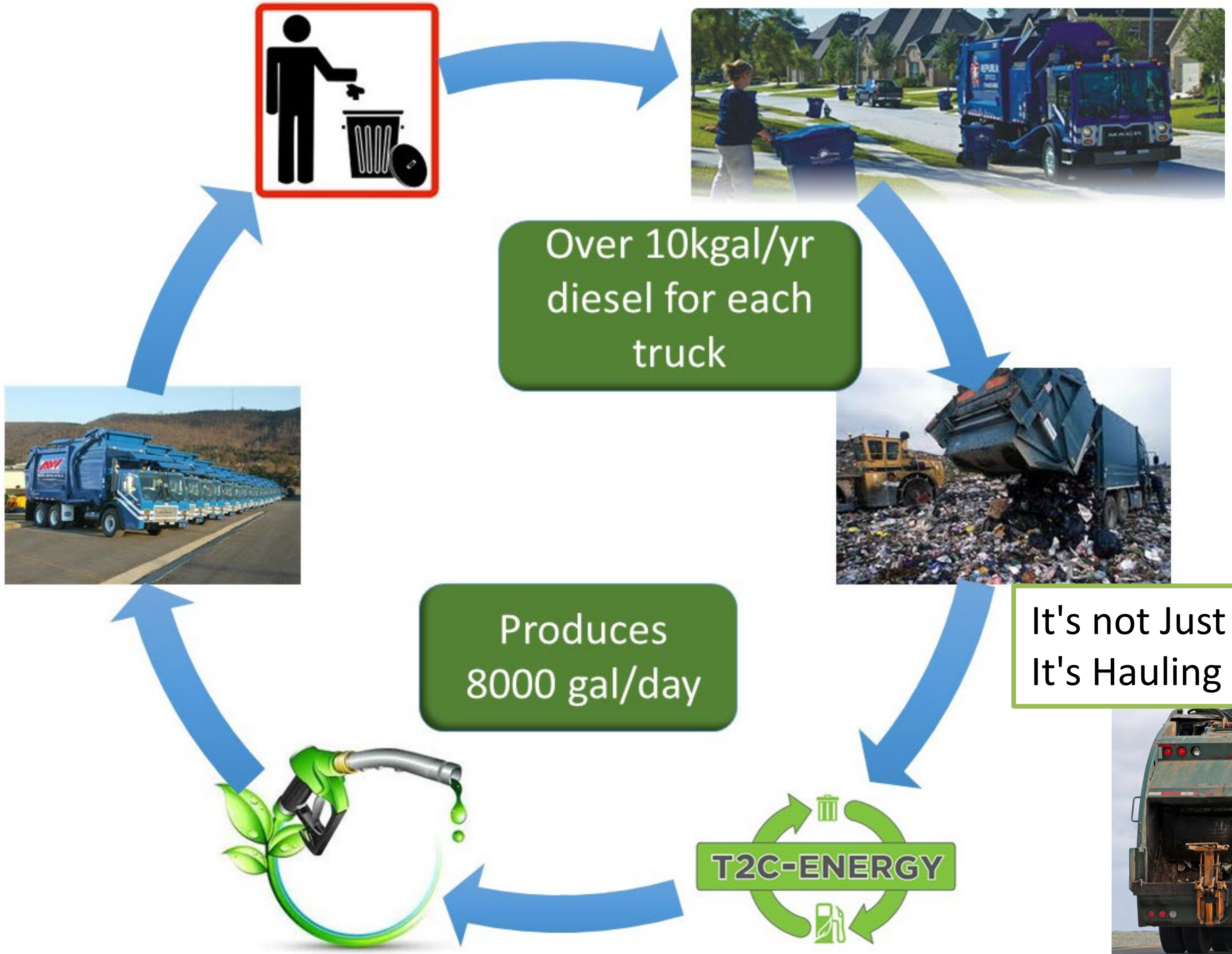
OFMSW (~25% of 350E6 metric tons*/ EREF**)

Environment

Methane emissions in 2013 (EIA)

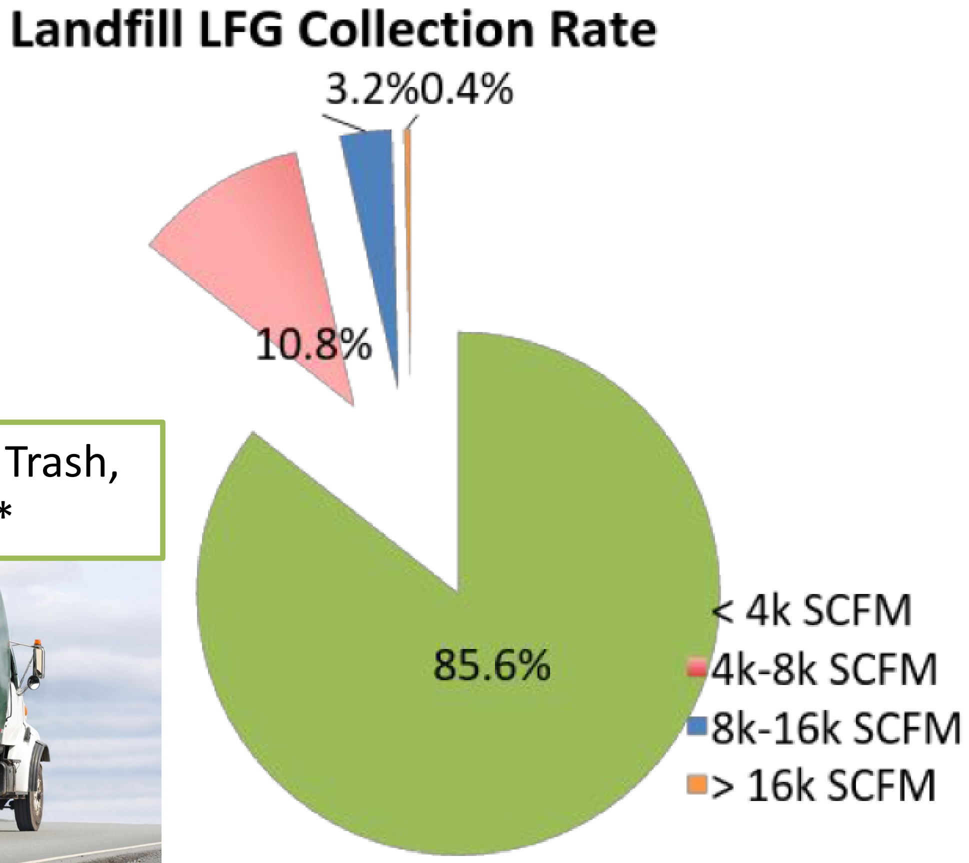
*another 87E6 tons that is recycled and composted / ** 40% higher than EPA

Problem/Opportunity



Total US Biogas generation rate ~ 800,000 SCFM

It's not Just Hauling Trash, It's Hauling its Fuel *



* www.t2cenergy.com

RENEWABLE NATURAL GAS

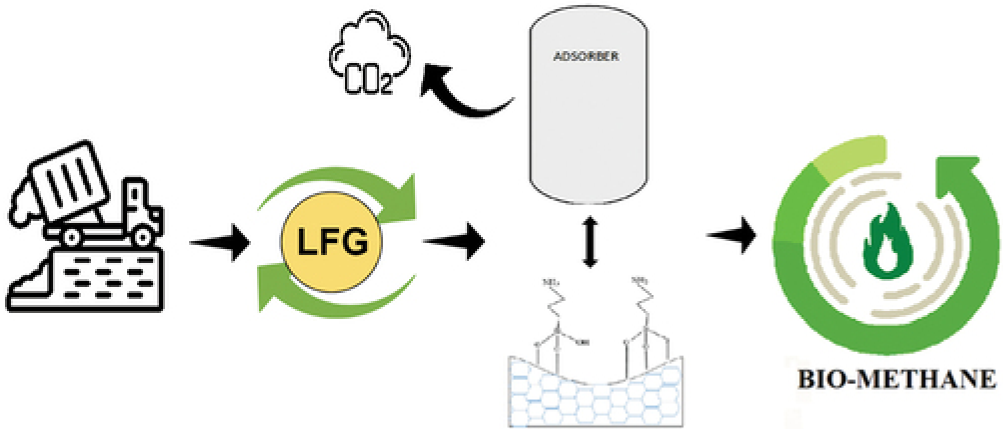
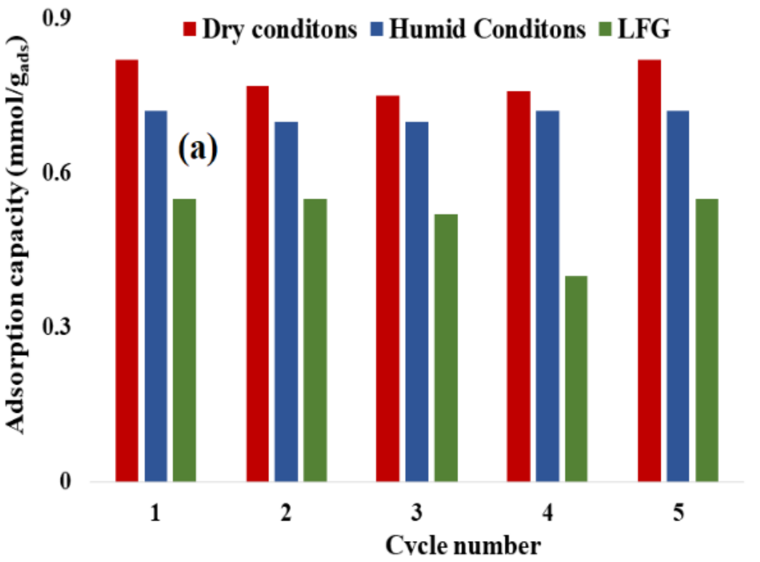
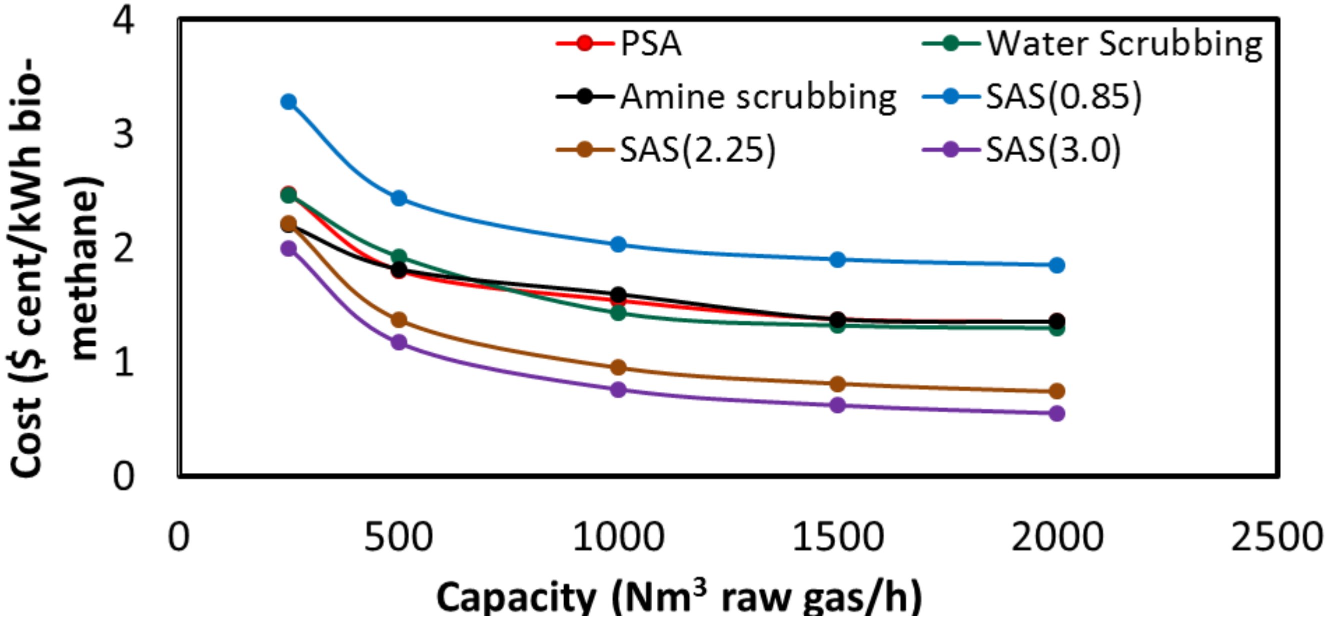


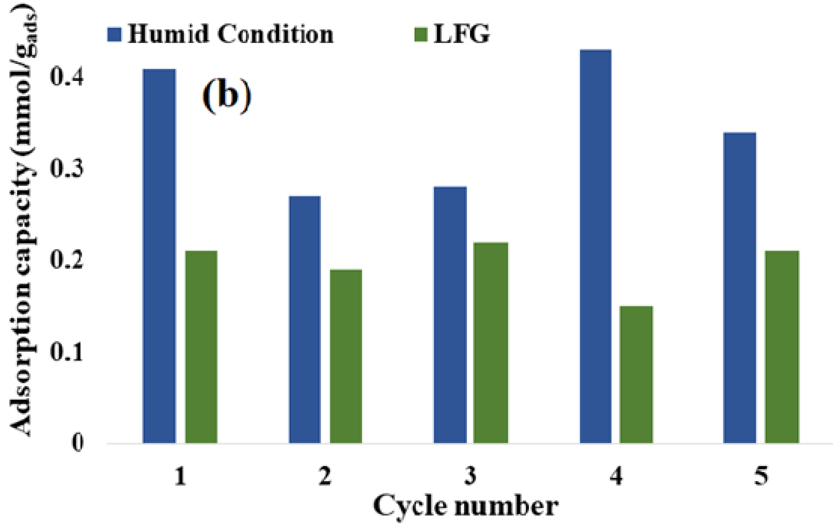
Table 1. Composition of biogas used in this study.

Compound	Mole percent on dry basis (%)[a,b]
CH_4	56.7
CO_2	40.5
N_2	2.4
O_2	0.4
H_2S	68 (ppm)
CO	6 (ppm)
Siloxanes	4 (ppm)
Halides	3 (ppm)

b – LFG is water-saturated
a – Unless stated otherwise.







(PSA, Water scrubbing, and amine scrubbing data from Peterson & Wellinger, 2009)

NEED FOR HYDROCARBON FUELS

Plastics *

- 8300 million metric tons plastics produced to date
- 6300 million metric tons plastics discarded as waste to date
- Of waste, 9% recycled, 12% incinerated, and 79% landfilled
- 12,000 million metric tons anticipated by 2050 (landfilled or in environment)
- Only 4 million metric tons of bio-based biodegradable
- ~13 % of U.S. MSW is plastics in 2013 (before recycling)**

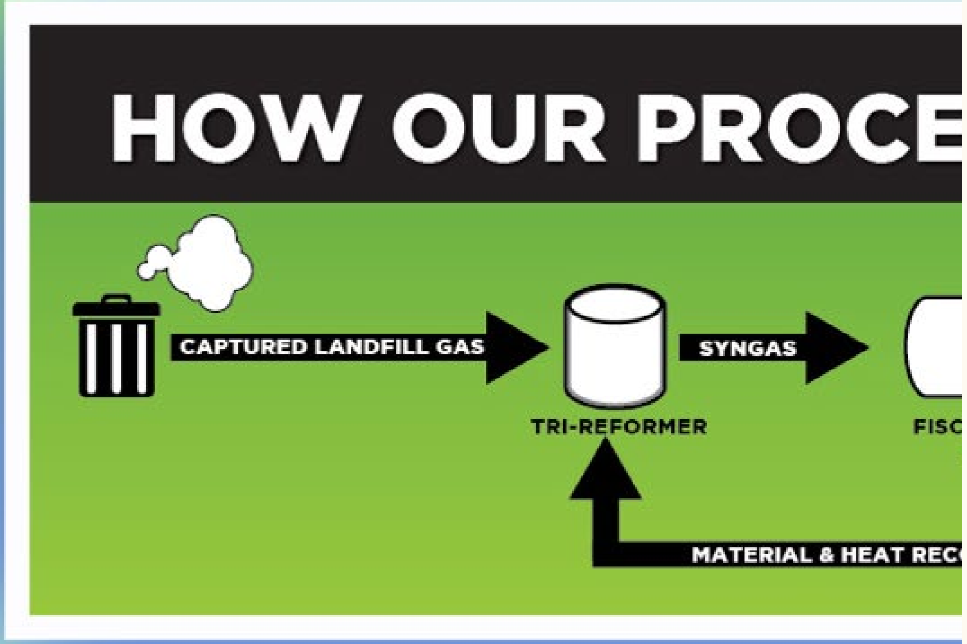
Energy-Dense Liquid Hydrocarbon Fuels (i.e., Diesel)

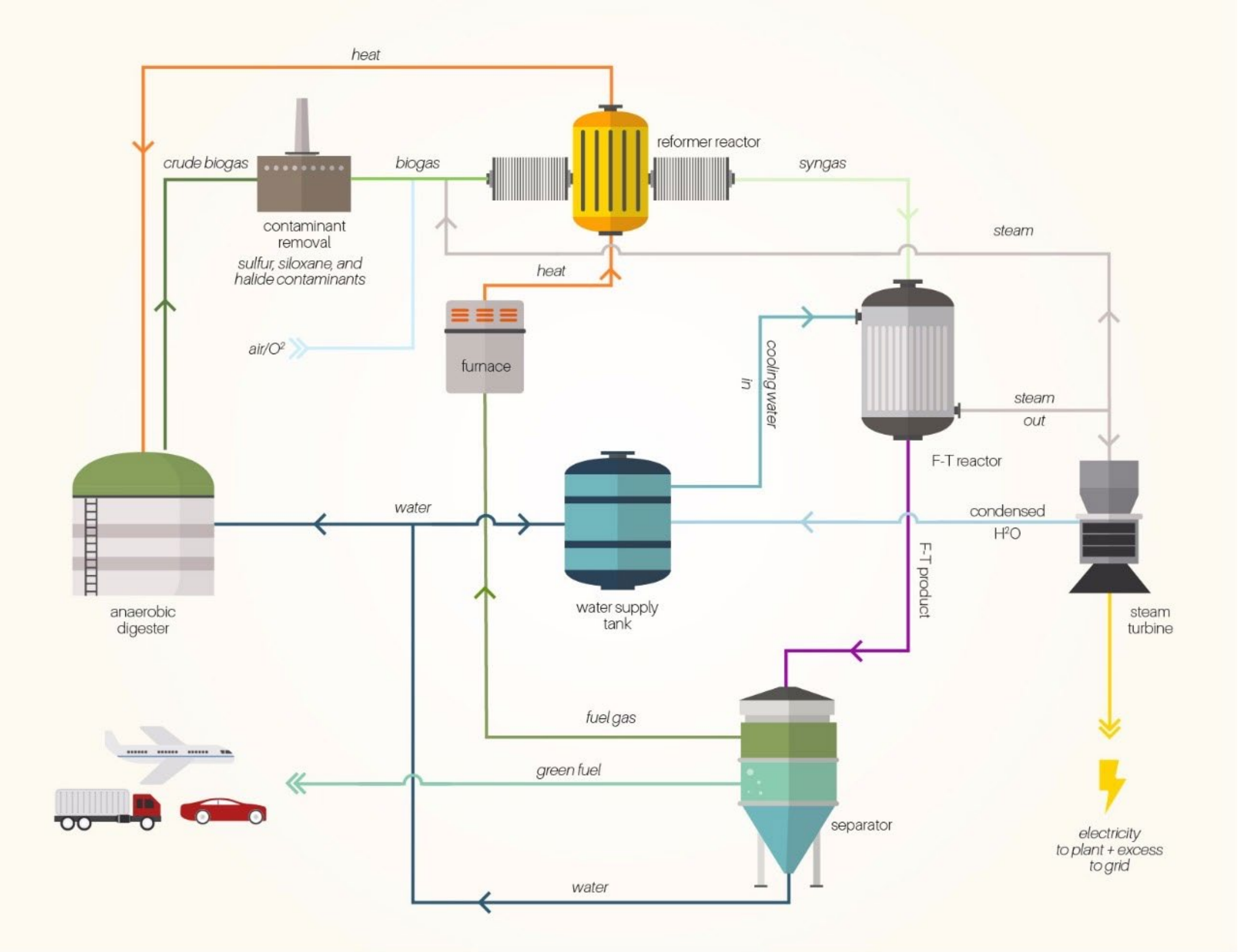
- 100 million bbl crude oil used worldwide per day (~25% in U.S.)
- Equates to 4500 million metric tons per year
- Need for diesel expected to increase
- Waste industry represents 4% of US diesel consumption
- Diesel and jet fuel harder to replace than gasoline

* Geyer at al, Science Advances 2017 ** US EPA

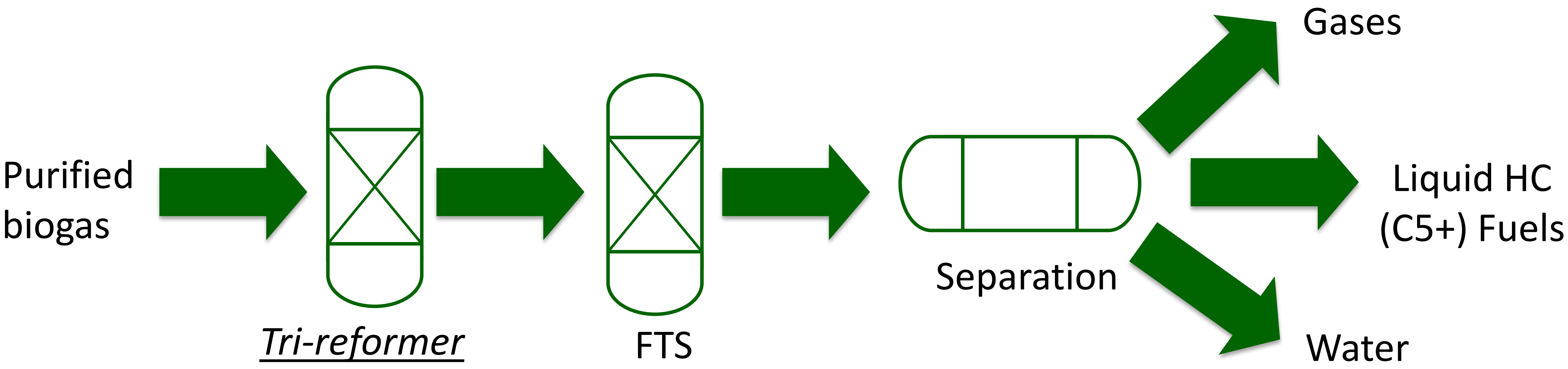
TRIFTS™ PROCESS OVERVIEW*

7,500 gallons/day of fuel





TriFTS Process Overview*

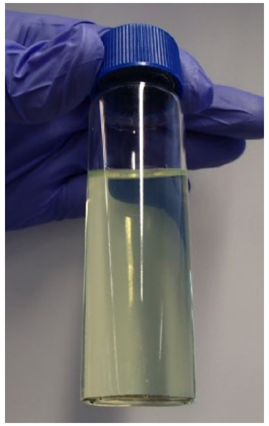


Process simplification:

- CO_2 not removed from feed
- No WGS or hydrocracker (No H_2 needed)
- No/minimal distillation
- No air separation

- Drop-in fuel
- Low sulfur
- Low aromatics

Catalysts are key



* Neglecting purification train here

Lab/Bench Scale TriFTS™ Unit

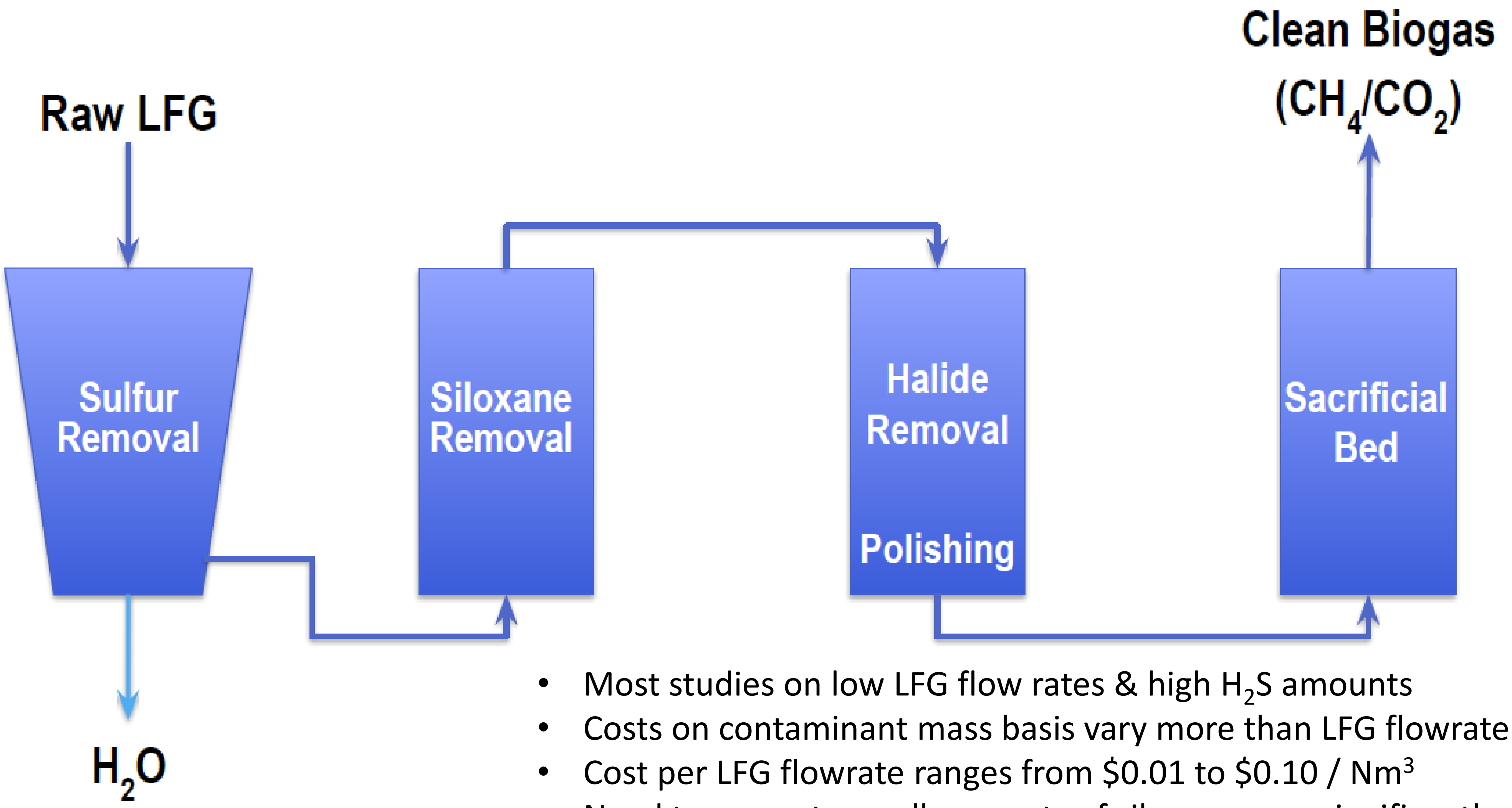
Microreactor

- 100 mg ref. catalyst
- < 100 SCCM
- Powder catalyst
- Low Pressure
- No MTL/HTL

Bench Scale*

- ~ 3 g ref. catalyst
- 1-3 sLPM
- Pellet catalyst
- Pressure < 30 bar
- MTL/HTL ?

Purification Train



- Most studies on low LFG flow rates & high H_2S amounts
- Costs on contaminant mass basis vary more than LFG flowrate
- Cost per LFG flowrate ranges from \$0.01 to \$0.10 / Nm^3
- Need to separate small amounts of siloxanes can significantly add to costs

Kuhn et al *Waste Management* 2017; Elwell et al *Waste Management* 2018; Elsayed et *al Appl Catal A: Gen* 2017

LFG CONTAMINANTS

Siloxanes

Hexamethyldisiloxane[L2]: ($C_6H_{18}OSi_2$)	162	0.38-5.0
Octamethyltrisiloxane[L3]: ($C_8H_{24}O_2Si_3$)	236	0.23-0.05
Decamethyltetrasiloxane[L4]: ($C_{10}H_{30}O_3Si_4$)	310	0.005-0.1
Hexamethylcyclotrisiloxane [D3]: ($C_6H_{18}O_3Si_3$)	222	0.01-0.84
Octamethylcyclotetrasiloxane [D4]: ($C_8H_{28}O_4Si_4$)	297	1.083-15.0
Decamethylcyclopentasiloxane [D5]: ([illegible])	371	0.40-1.135

Sulfur

Hydrogen Sulfide: (H_2S)	34.1	99.9-280
Methanethiol: ([illegible])	48.1	0.56

Halides

[illegible]	[illegible]	[illegible]
CarbonTetrachloride (CCl_4)	154	41.5-124.3 pp
Chloroform ($CHCl_3$)	113	78.6-183.9 pp
Trichloroethene (C_2HCl_3)	131	0.9-2.6
Tetrachloroethene: (C_2Cl_4)	165.8	0.14-0.30
Chlorobenzene: (C_6H_5Cl)	112.6	0.22

NMOCs

Isopropyltoluene: ($C_{10}H_{14}$)	134.2	48.8-73.6
α-pinene: ($C_{10}H_{16}$)	136.2	4.4-85.3
Camphene: ($C_{10}H_{16}$)	136.2	1.5-5.4
Limonene: ($C_{10}H_{16}$)	136.2	15.8-52.9
Terpinene: ($C_{10}H_{16}$)	136.2	3.4-10.7
Octane: (C_8H_{18})	114.2	3.5-6.0
Nonane: (C_9H_{20})	128.2	14.9-18.3
Decane: ($C_{10}H_{22}$)	142.3	18.0-27.9
Undecane: ($C_{11}H_{24}$)	156.3	8.5-16.2
Dodecane: ($C_{12}H_{26}$)	170.3	0.6-1.8
Hexadecane: ($C_{160}H_{34}$)	226.4	<0.10
Benzene: (C_6H_6)	78.1	0.85-4.7
Isopropylbenzene: (C_9H_{12})	120.2	3.3-5.6
Xylenes: (C_8H_{10})	106.2	35.6-74.1
Toluene: (C_7H_8)	92.1	4.96-37.2

Mercury

MonomethylMercury (CH_3Hg)	216	1-47ng/m^3	DimethylMercury $(CH_3)_2Hg$	231	2.1-91 ng/m^3

Kuhn et al *Waste Management* 2017

SULFUR REMOVAL PROCESSES

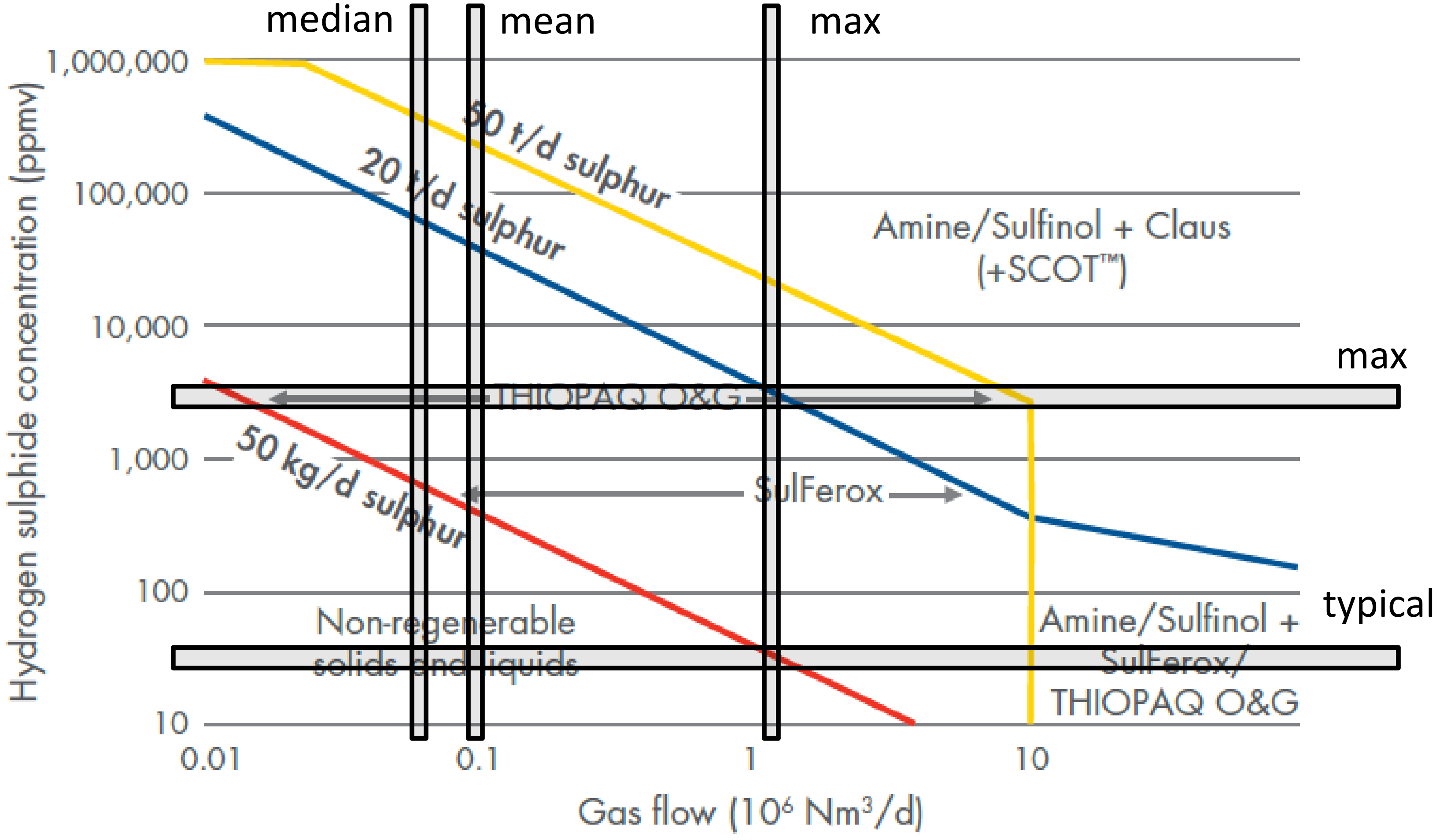
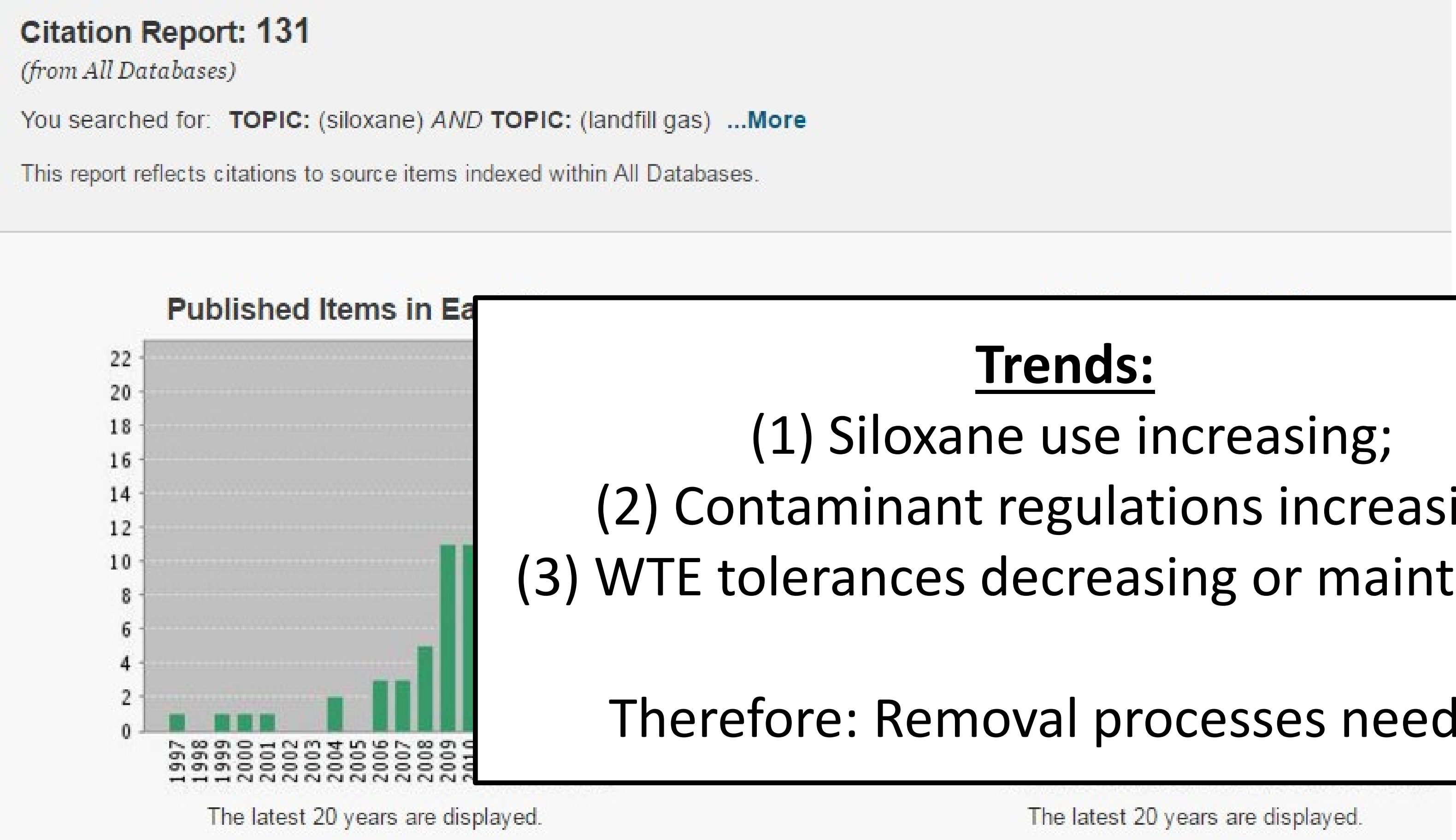


Figure 1: Hydrogen sulphide processing selection chart.

Biogas	Contaminant	Concentration	
		Highest	Typical
LFG	H_2S	5400 ppmv	63 ppmv
	Siloxanes	54 mg/Nm^3	16.8 mg/Nm^3
WWTP	H_2S	3 %	400 ppmv
	Siloxanes	400 mg/Nm^3	46 mg/Nm^3

SILOXANES

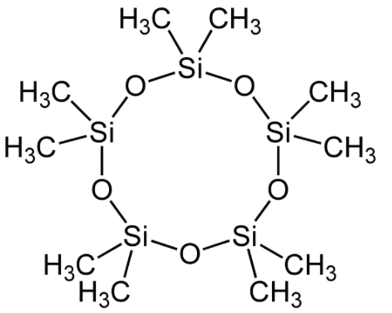


<u>Trends:</u>

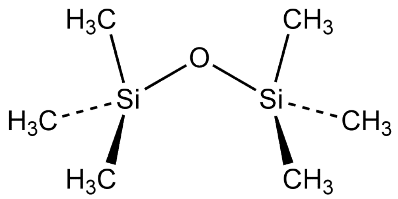
(1) Siloxane use increasing;
(2) Contaminant regulations increasing;
(3) WTE tolerances decreasing or maintaining;

Therefore: Removal processes needed

Search on Web of Science for "landfill gas" and "siloxane", which shows limited number of research publications and citations and an exponential increase in these efforts.



D5: decamethylcyclo-pentasiloxane



L2: hexamethyl-disiloxane

SILOXANES (ACCELERATED TESTING)

Sample	Nomenclature	Theoretical Mass gain SiO_2	Actual Mass Gain SiO_2	% error
1 week NiMg	1W-NiMg	2.6%	1.5%	-43.5%
1 month NiMg	1M-NiMg	11.1%	11.9%	7.5%
6 month NiMg	6M-NiMg	66.7%	65.7%	-1.5%
1week Pt	1W-Pt	2.6%	1.1%	-59.4%
1 month Pt	1M-Pt	11.1%	10.5%	-5.4%
6 month Pt	6M-Pt	66.7%	61.9%	-7.2%

Fresh Catalyst

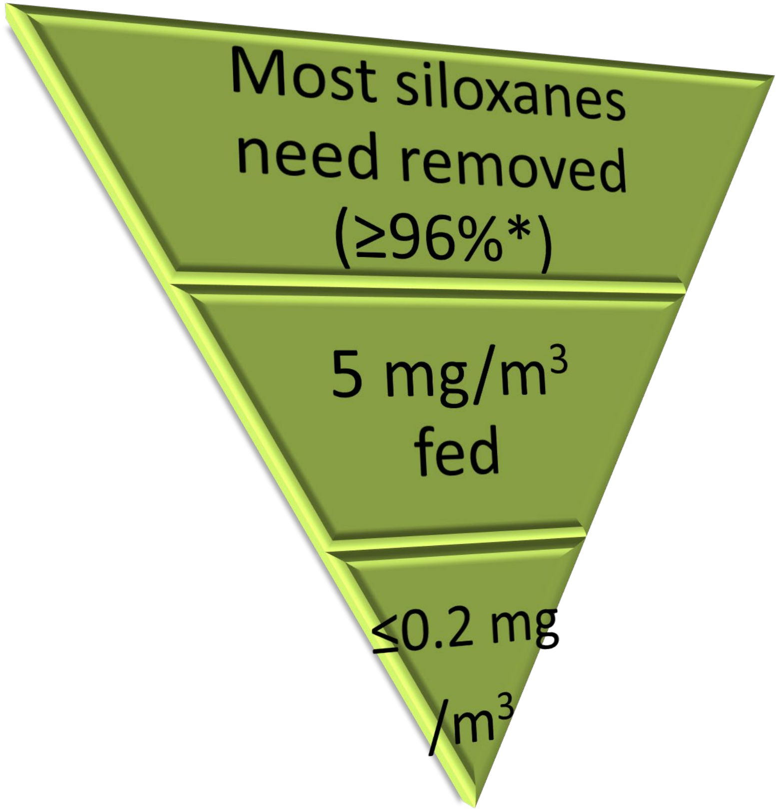
6 month poisoned

Elsayed et al, *Appl Catal A:Gen* 2017

SILOXANES (ACCELERATED TESTING)

Pt Catalysts	CH_4 Conversion Temperature (°C)		CO_2 Conversion Temperature (°C)		H_2:CO (@450°C)
	X_{10}	X_{50}	X_{10}	X_{50}	
Fresh*	454	603	432	578	0.30
1W-Pt	518	630	503	613	0.22
1M-Pt	535	675	510	657	0.20
6M-Pt	587	752	566	726	0.11
NiMg Catalysts	**CH_4 Conversion Temperature (°C)**		**CO_2 Conversion Temperature (°C)**		**H_2:CO (@800°C)**
	X_{10}	X_{50}	X_{10}	X_{50}	
Fresh	762	848	742	813	0.31
1W-NiMg	810	900	790	875	0.13
1M-NiMg	842	nr	827	900	0.09
6M-NiMg	nr	nr	900	nr	n/a

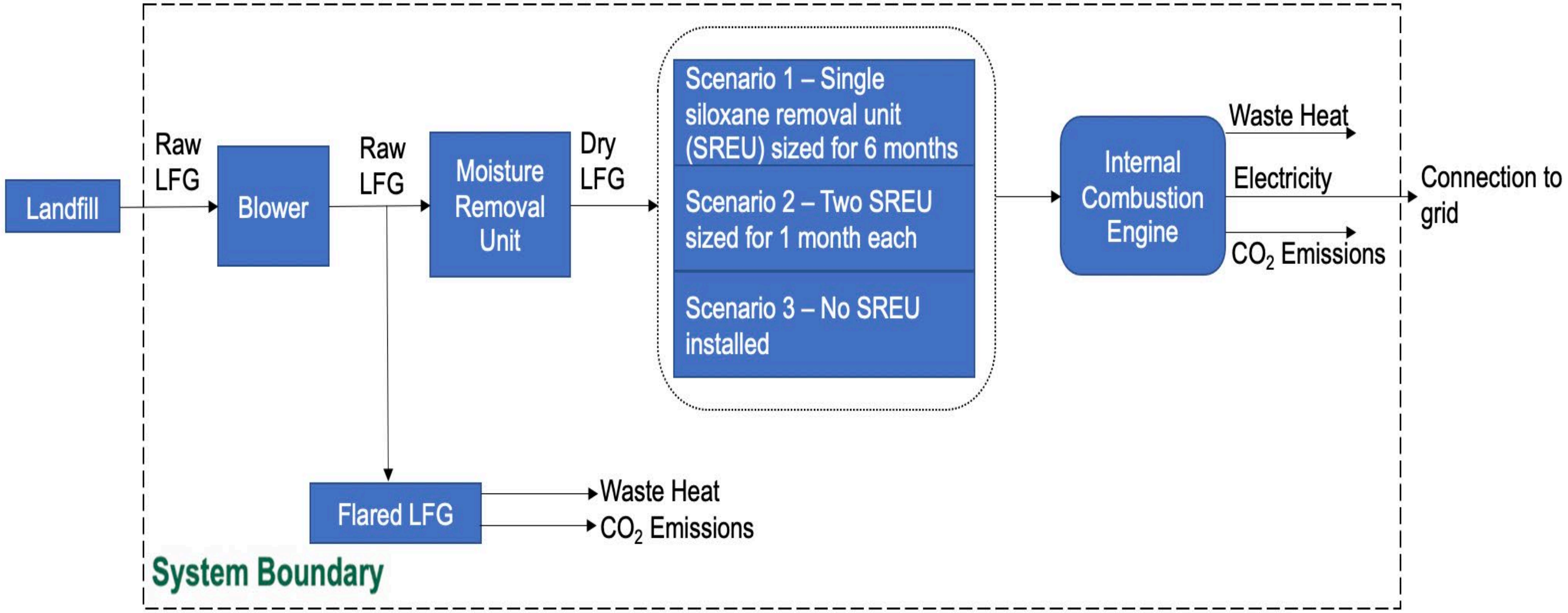
Conversions for methane dry reforming
-nr: Not reached
n/a: not applicable since there was no reactant conversion



* Based on speculation that performance 1 week samples may be acceptable

Elsayed et al, *Appl Catal A:Gen* 2017

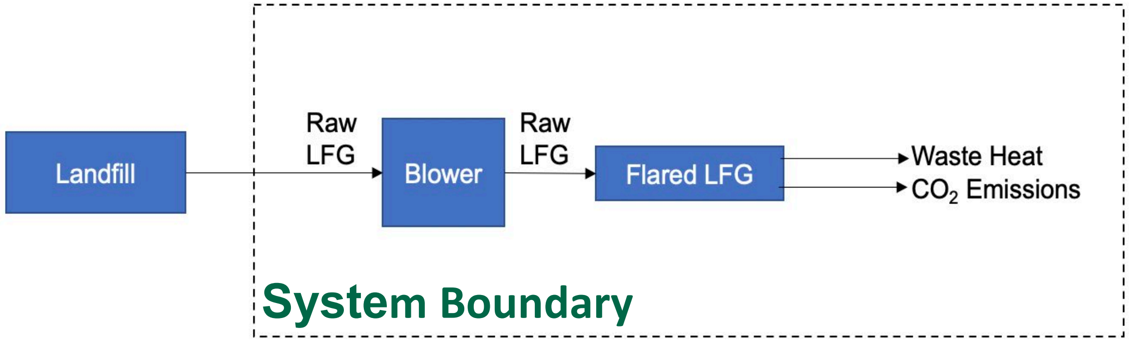
SILOXANE REMOVAL FROM LFG



- Four Scenarios studied.
- 1st , 2nd and 3rd scenarios generated electricity.
- 4th scenario flared LFG.

Facilities that generates electricity (Scenarios 1 - 3)

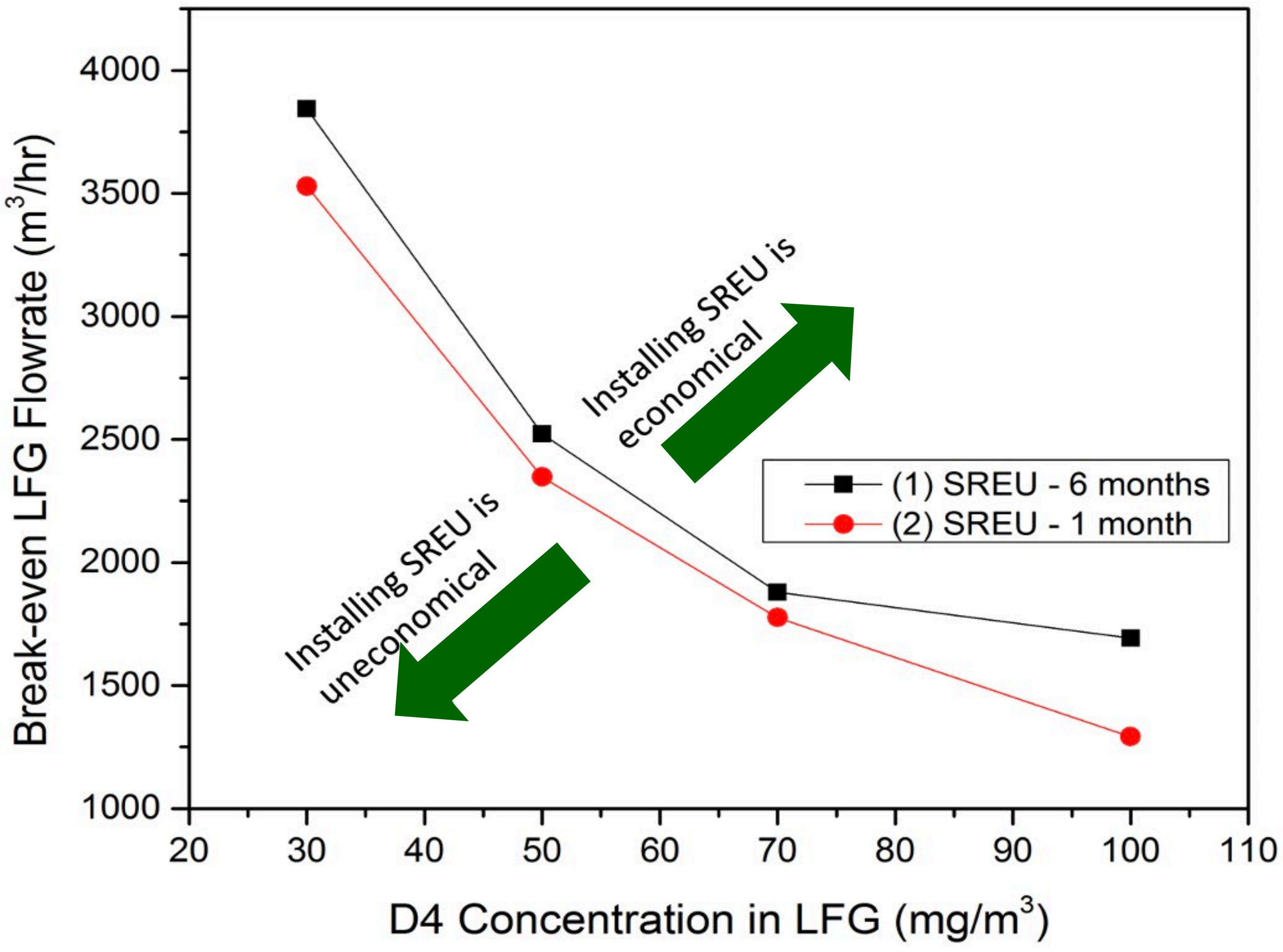
- 1st and 2nd scenarios installed siloxane removal units.
- 3rd scenario did not install siloxane removal unit.



Facility that flares all LFG captured (Scenario 4).

Amaraibi et al, *J Env Manage* 2021

TEA Results

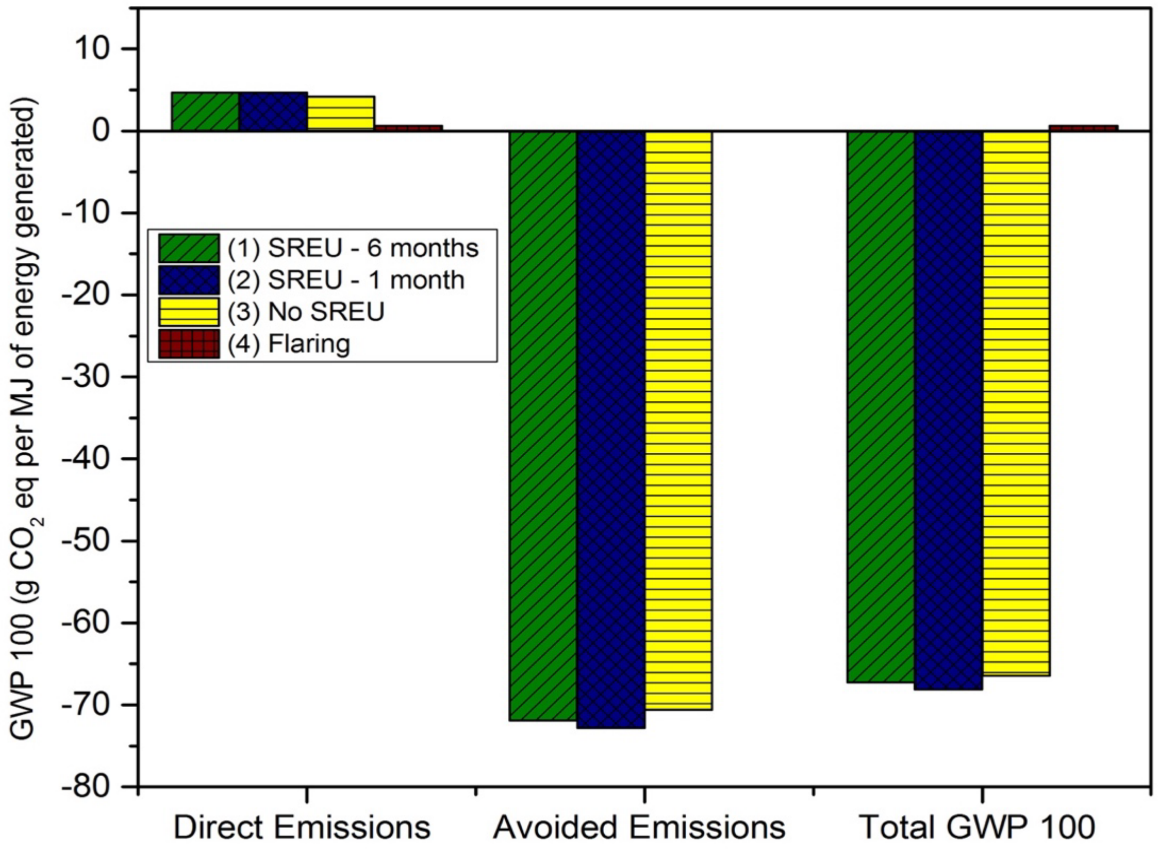


Effect of D4 concentration and biogas flowrate on the annual net cash income.

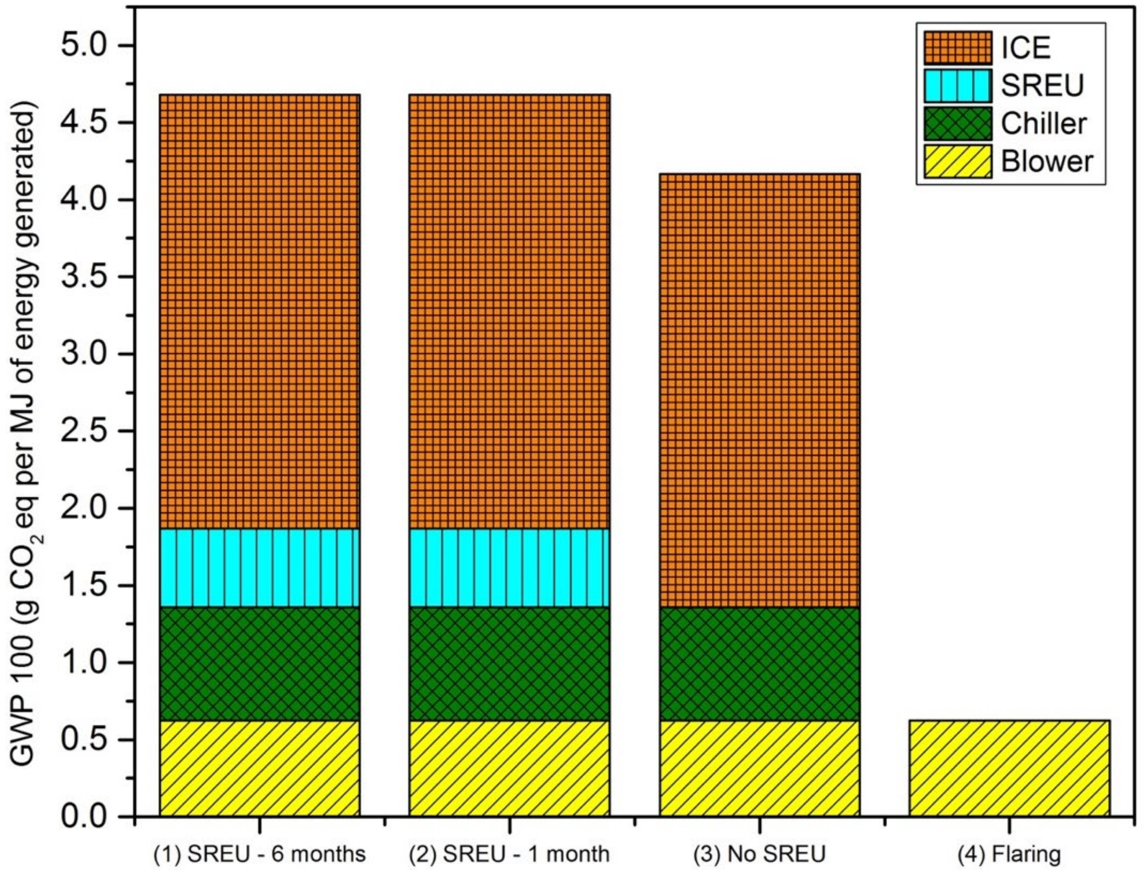
- The figure shows the LFG flowrate at which it becomes economical to install a SREU as a function of siloxane concentration in LFG.
- SREU – Siloxane Removal Unit.
- It is seen that as the siloxane concentration increases, the break-even LFG flowrate reduces.

Amaraibi et al, *J Env Manage* 2021

LCA Results



Comparison of Direct, Avoided and Total Emissions in terms of GWP 100 among the four scenarios (Base case: 1700 m^3/hr. LFG (50% CH_4), 50 mg/m^3 D_4).



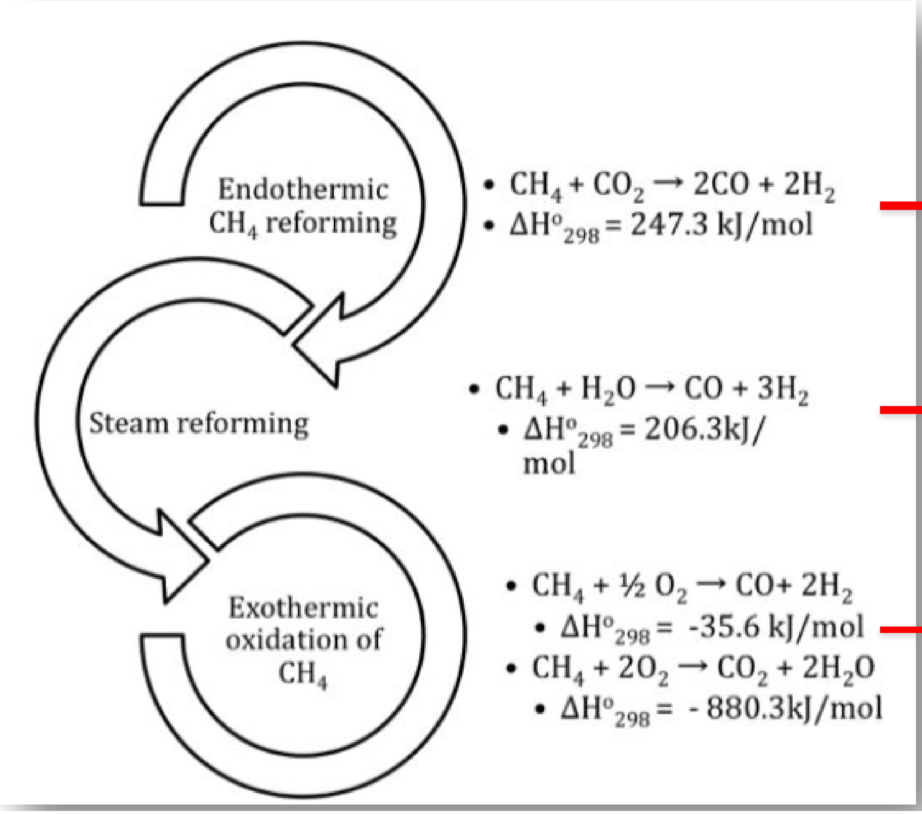
GWP 100 of the LFG blower/treatment system and ICE for the four scenarios (Base case: 1700 m^3/hr. LFG (50% CH_4), 50 mg/m^3 D_4).

CATALYTIC TRI-REFORMING

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

Global reaction (within constraints)

$$CH_4 + 0.2O_2 + 0.2CO_2 + 0.4H_2O$$
$$\Rightarrow 1.2CO + 2.4H_2 \rightarrow \Delta H^\circ = 117.3\ \mathrm{kJ\,mol^{-1}}$$



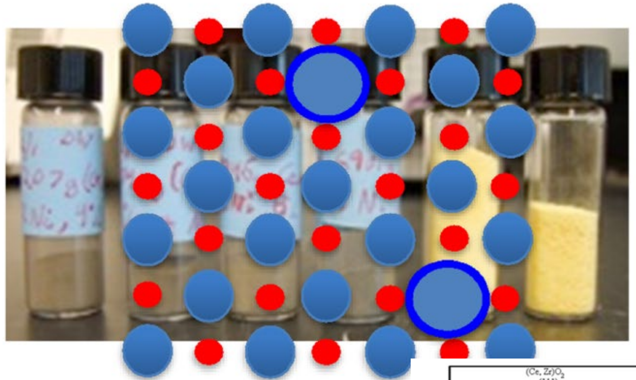
Utilize 100% of biogas as feedstock

Control H2 and CO selectivity

Generate heat in-situ

From our results, we estimate ΔH_r (T=800°C) = 135 kJ/mol CH_4 X

CATALYTIC TRI-REFORMING

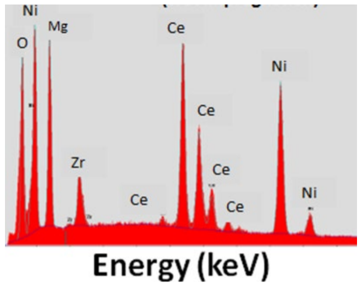


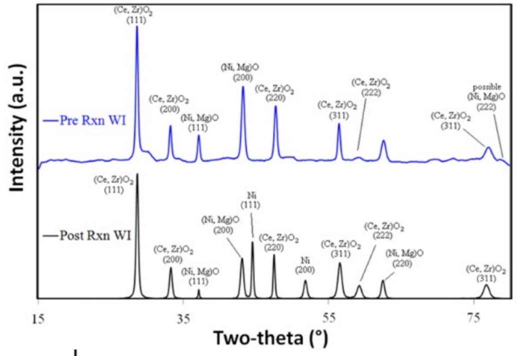
Ni-Mg-(Ce,Zr)O_2 catalysts *

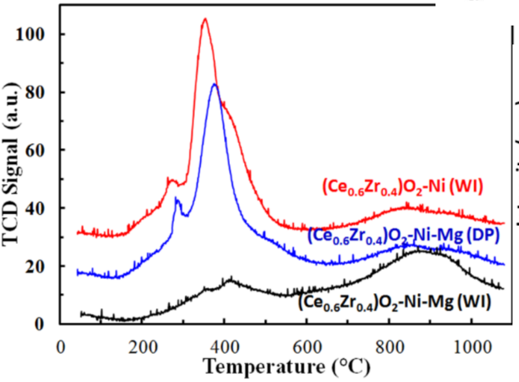
● = Zr (0.84Å)

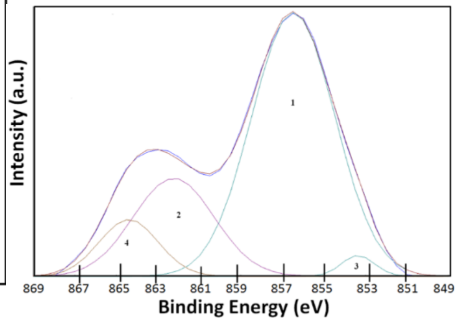
● = Ce^{4+} (0.97Å)

◯ = Ce^{3+} (1.14Å)









Tri-reforming of LFG (LFG : air : H_2O = 1.00 : 0.56 : 0.36)

Catalyst Bed temp. (°C)	GHSV (h^{-1})	CH_4 conv. (%)	CO_2 conv. (%)	H_2:CO
770-810	30,000	92-99	52-72	1.70-2.23

Catalyst Optimization

Thermally Stable

High Surface Area

Coke Resistant

High OSC

Excellent Redox Properties

High Dispersion

Excellent Selectivity

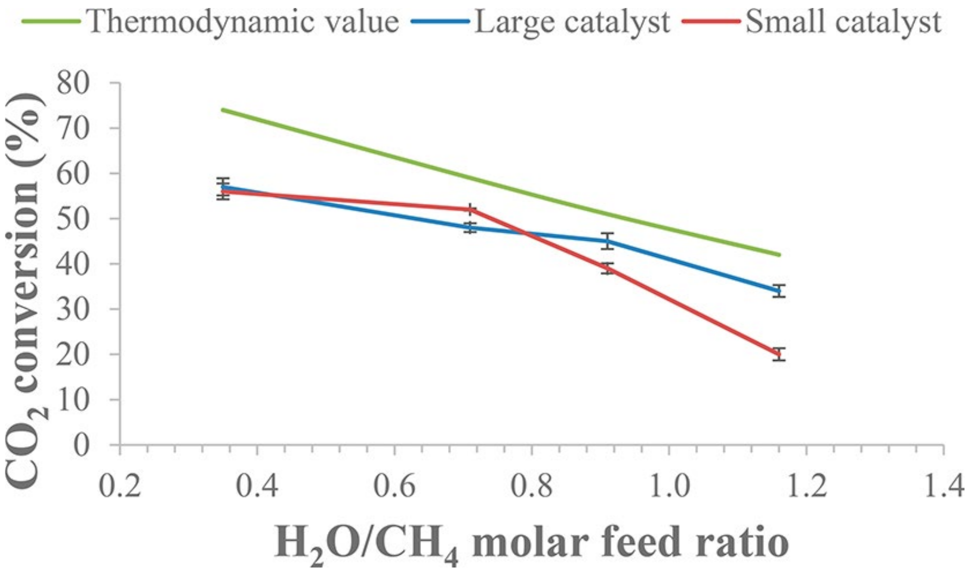
High Activity

Economical

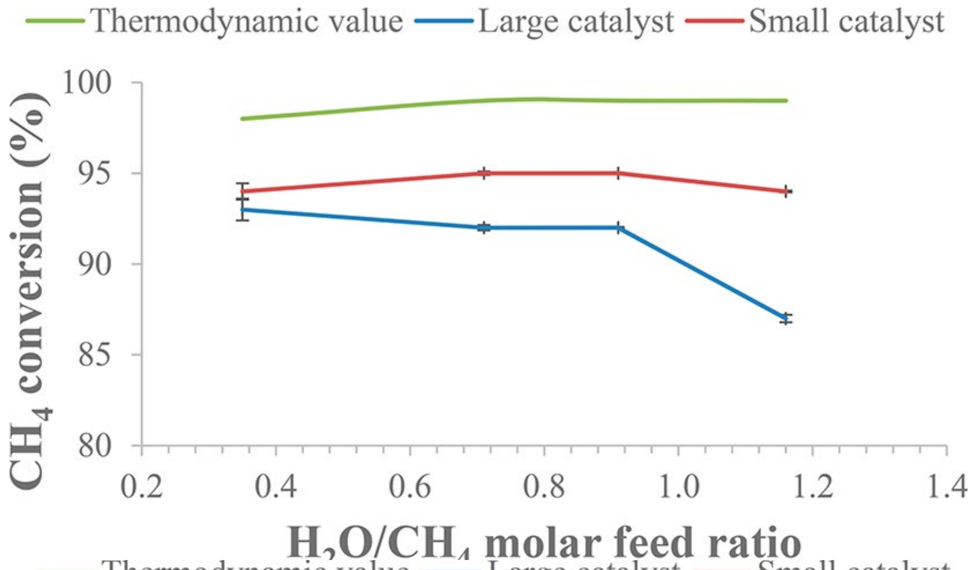
Low Pressure Drop

* Powders: Walker et al *Appl Catal A:Gen* 2012; Pellets: Zhao et al *IECR* 2018 and *Powder Tech* 2019

COMPETITION OF CO_2 & H_2O

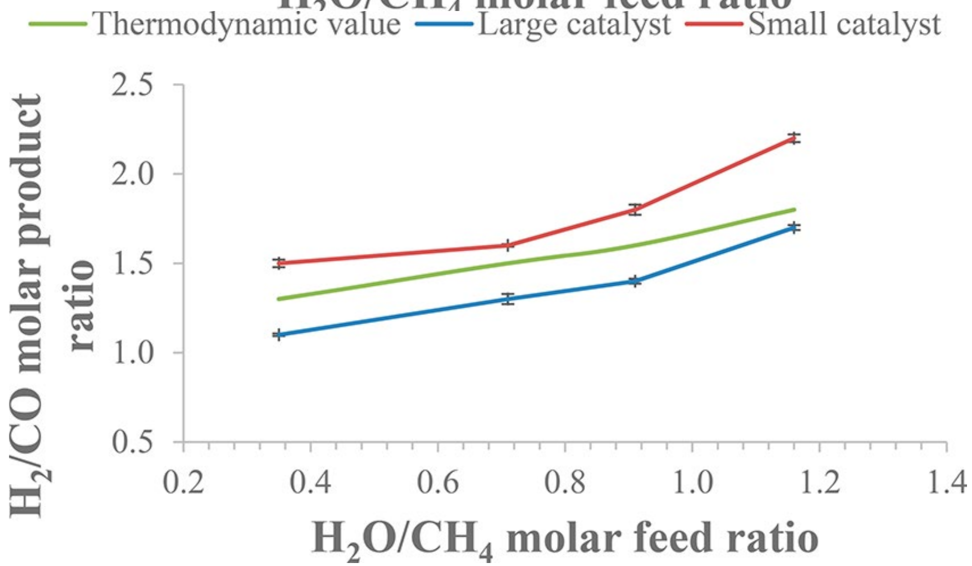


- CO_2 X => 0 at 2:1 ratio
- Coking rate ~ 1E-4 g/g/hr



Analysis of Internal Diffusion Limitations

	internal diffusion limitation, C_{wp}	Thiele modulus, Φ_n	effectiveness factor, η	radius (mm)	length (mm)
large catalyst	38	6.2	0.16	1.59	7.0
small catalyst	7	2.7	0.37	0.75	2.0
NiMg/ $Ce_{0.6}Zr_{0.4}O_2$ powder	0.12	<1	1.0	0.06	N/A



Zhao et al, *IECR* 2019

P = 3 bar, T = 882°C, CH_4 / CO_2 = 1.4

Real LFG

Conditions	Feed (CH_4:CO_2:H_2O:air by mole)	CH_4 X (%)	CO_2 X (%)	H_2:CO ratio
*, 3 bar, ~30k h^{-1}	LFG + air + steam*	92-99	52-72	1.7-2.2
882 °C, 3 bar, ~26k h^{-1}	1: 0.7: 1.16: 0.95	87	34	1.7
Control: powder (800 °C, 1 bar, 61k h^{-1})	1: 0.7: 0.23: 0.2 (O_2)	97	78	2.1

powders

pellets

pilot

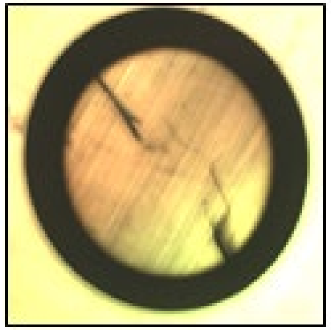
commercial

* Temperature and steam added varied, LFG purified, raw LFG ~ 56% methane and 40% CO_2

Co-based FTS Catalyst

FTS Eggshell Catalyst

- Overcome mass and heat transfer limitations
- Selective product distribution in middle distillate region
- Avoid wax production

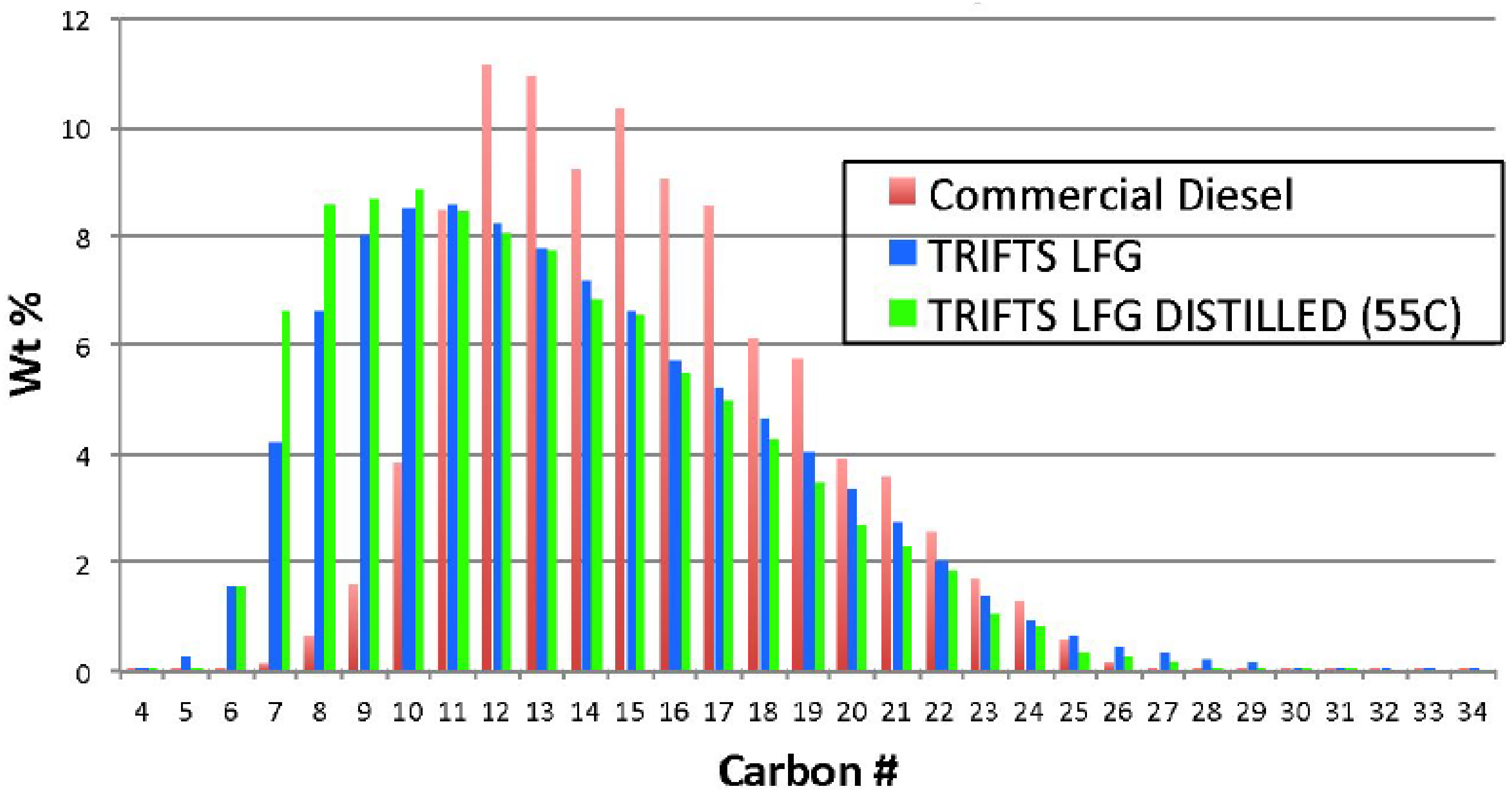


CO % Conv	LFG Energy Recovery In Liq Fuel (%)	Selectivity (%)		
		C_{1-4}	CO_2	C_{5+}
71	40	43.7	1.4	55.0

Zhao et al, *Sust. Energy & Fuels* 2019

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



HC Family/Diesel	TriFTS	Commercial
P – I – O	99.7%	53%
Cyclics (+A)	0.3%	47%

FUEL ANALYSIS

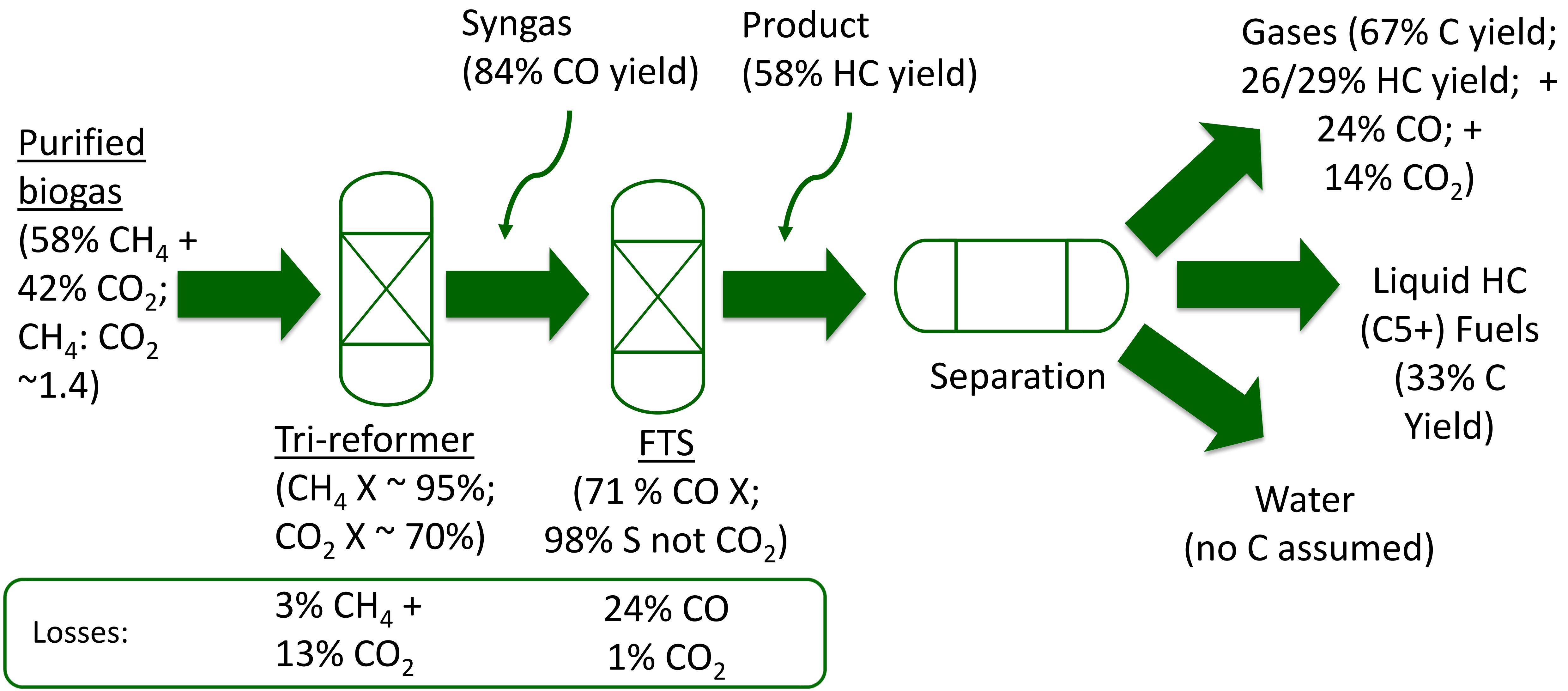
ASTM D975 "Standard Specification for Diesel Fuel Oils"

Fuel Analysis Results

Fuel Analysis, ASTM Standard	Spec (No. 2 Diesel)	Commercial Diesel	TRIFTS LFG	TRIFTS LFG (Dist 55C)
Specific Gravity, ASTM D4052 (g/cc)		0.8215	0.7386	0.7489
Cetane Index, ASTM D976	≥ 40	57.6	84.5	72.7
Cetane Index, ASTM D4737	≥ 40	59.7	92.3	83.4
Flash Point, ASTM D93 (°C)	≥ 52	87	49	57
Cloud Point, ASTM D2500 (°C)		-6	-6	-3
Pour Point, ASTM D97 (°C)		-9	-9	-6
Distillation, ASTM D86 (°C)				
IBP: 0.5wt%		203	143	142
10%		220	164	154
50%		269	234	216
90%	282-338	329	327	314
FBP: 99.5%		378	388	378
Net Heat Comb., ASTM D3338 (MJ/kg)		43.164	44.520	44.355

Zhao et al, *Sust. Energy & Fuels* 2019

TRIFTS PROCESS OVERVIEW*

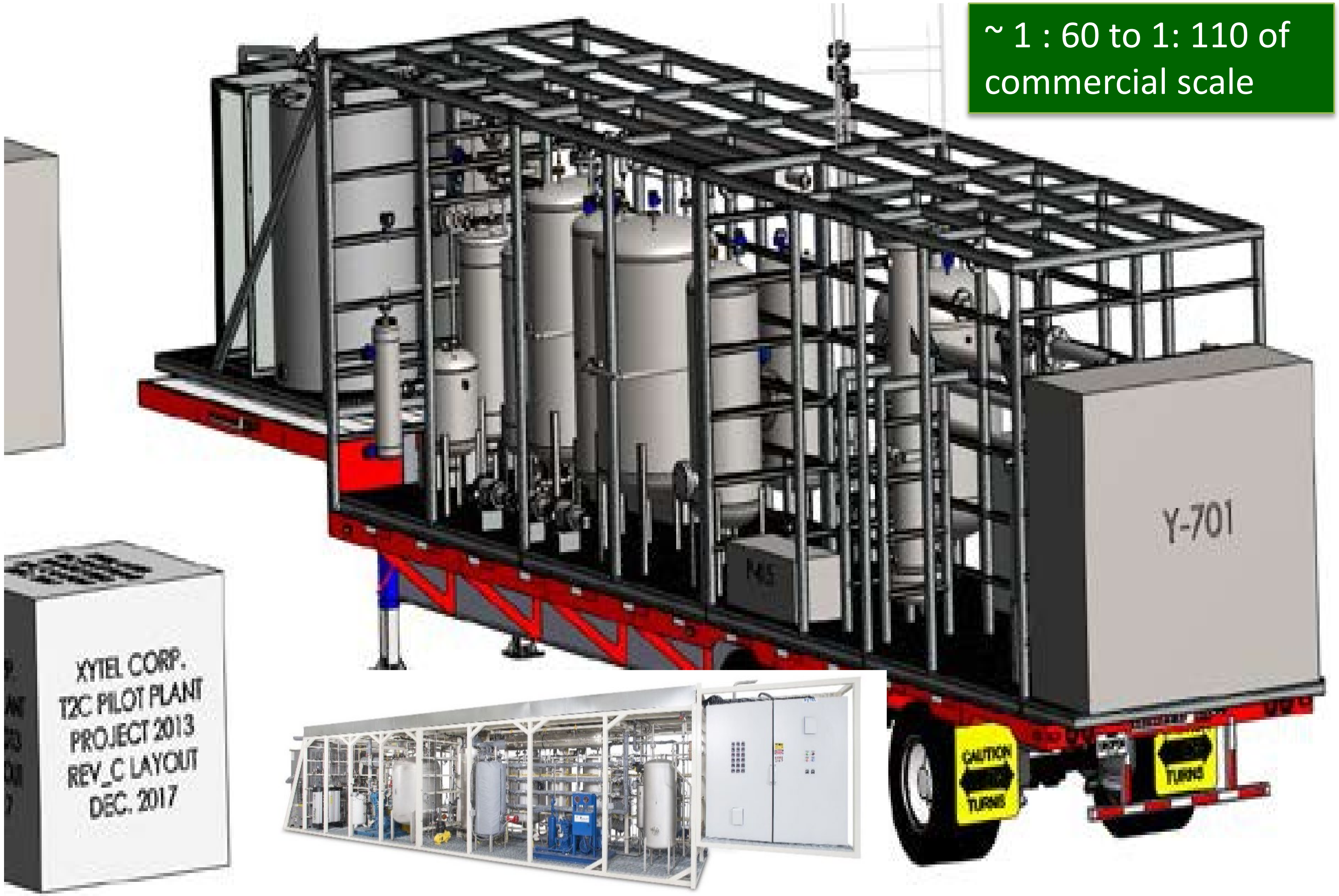


* Neglecting purification train here (material losses minimal; energy losses vary)

PILOT SCALE (THE DREAM ~ 2013)

(24 scfm feed → 75 gal/day diesel)

PILOT SCALE (THE PLAN 2017-18)



~ 1 : 60 to 1: 110 of commercial scale

Pilot Scale (The First Test Site 2019)

PILOT SCALE (CITRUS COUNTY 2019-20)

DOE site visit
“verification”
Feb. 2020

Pilot Scale (Pinellas County 2021)

South Cross Bayou Advanced Water Reclamation Facility (AWRF): ***Environmental Commitment through Resource Recovery***

Image: https://www.pinellascounty.org/utilities/south-cross.htm

First biogas from WWTP test Oct. 2021

MAJOR DOE MILESTONE: 2022

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

JULY 26, 2022

Bioenergy Technologies Office »

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

Author: Josh Messner, Technology Manager, Systems

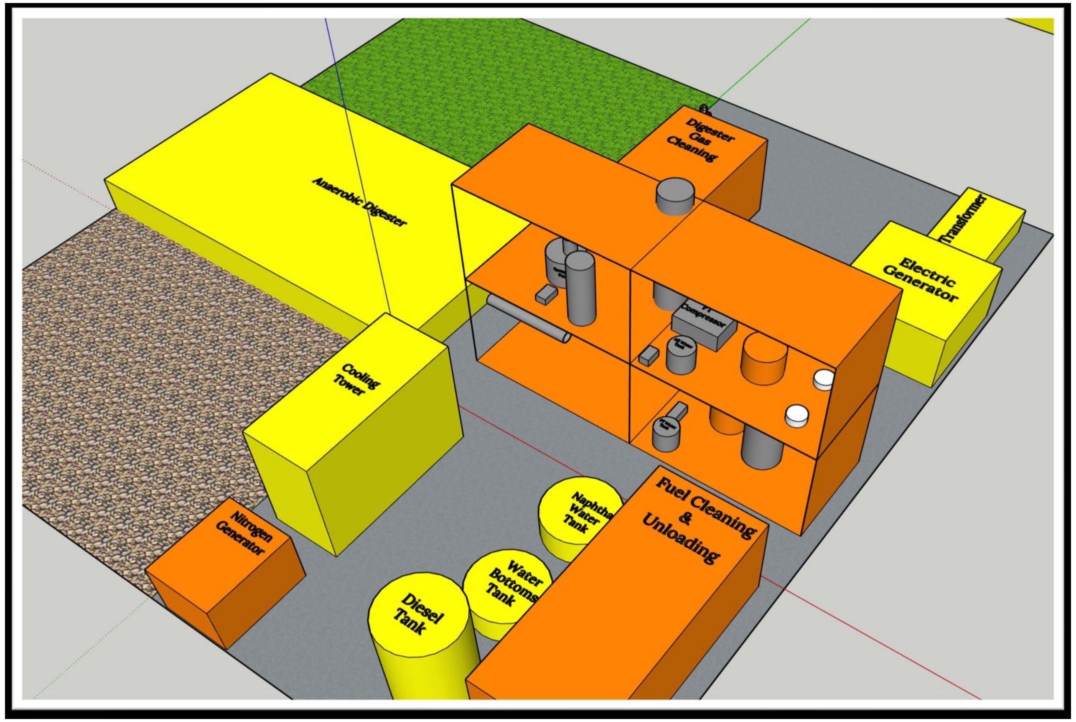
The U.S. Department of Energy Bioenergy Technologies Office (BETO) has achieved a significant milestone in decreasing the minimum fuel selling price (MFSP) of drop-in biofuels, which are fuels made from biomass and other waste carbon sources, and that are compatible with existing petroleum fuel infrastructure and conventional vehicles. BETO partnered with T2C-Energy, LLC (T2C) to validate pilot-scale production of drop-in biofuels with a price of $3 per gallon of gas equivalent (GGE) and at least 60% lower greenhouse gas emissions than petroleum, using T2C's TRIFTS® process.

https://www.energy.gov/eere/bioenergy/articles/department-energys-bioenergy-office-achieves-major-biofuel-technology-and

WHAT'S NEXT?! 2 DOE AWARDS FOR FULL SCALE

Project Title: Demonstration Scale-up: TRIFTS Biogas to Renewable Fuel
Lead Organization: T2C-Energy, LLC
Principal Investigator: Devin Walker

T2C-Energy developed and patented a proprietary process, we have trademarked TRIFTS®, by which to convert biogas (or landfill gas) to liquid transportation fuels. This project seeks to scale the TRIFTS technology to enable the design and construction of a demonstration plant achieving a TRL of 7 by the end of the project. The TRIFTS process has been thoroughly tested at the pilot scale (over the past two years) processing a 9-24 scfm slipstream of raw biogas into drop-in renewable transport fuel. The process is capable of utilizing both the carbon dioxide and methane portions of biogas and incorporates the biogenic carbon from them into the hydrocarbon backbone of the final fuel product of the process. In doing so the technology essential uses 100% of the biogas as a feedstock. The use of carbon dioxide (CO_2) is a critical cost reduction step as it represents 40-50% of the total makeup of biogas effectively doubling the utilizable carbon compared to technologies that remove CO_2 utilizing expensive pretreatment processes. We have previously identified a candidate landfill with our project partners to implement a 1,300 scfm biogas capacity plant and produce over 1,000,000 gal/yr of renewable cellulosic diesel. This renewable source of diesel resembles its petroleum counterpart both physically and chemically, passing ASTM D975 specifications, and can be used in current

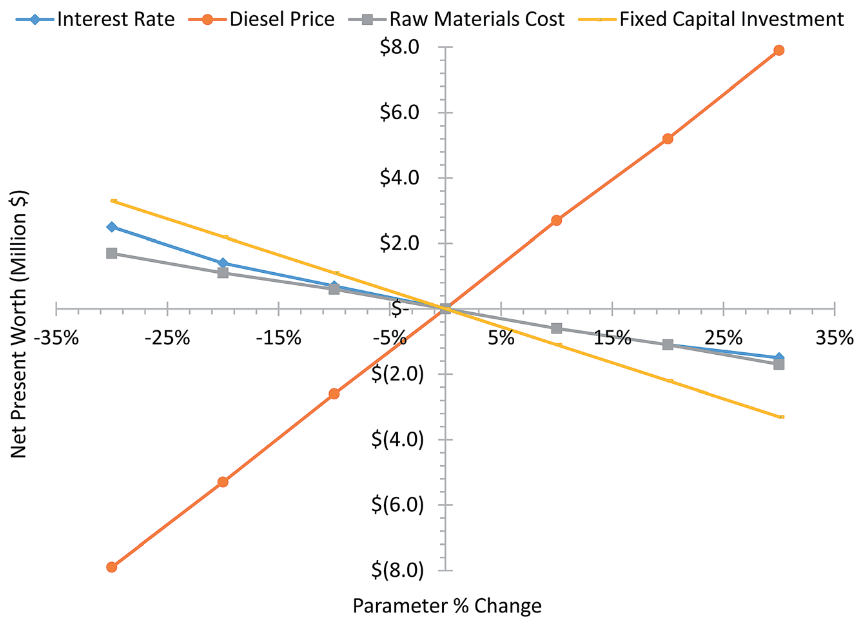


Project Title: TRIFTS Biogas to Renewable Fuel Technology Evaluation
Project Applicant: Yolo County
Project Director/Principal Investigator: Ramin Yazdani
Project Investigators: Mr. Devin Walker (T2C-Energey), Dr. Troy Hawkins (Argonne National Lab), Professor Anthony Wexler (UC Davis-Air Quality Research Center)

The Yolo County Department of Community Services, Division of Integrated Waste Management is applying to evaluate the Tri-reforming and Fischer Tropsch Synthesis (trademarked TRIFTS®) Biogas to Renewable Fuel Technology. This project seeks to perform feasibility and technical demonstration testing to determine the best strategy to convert waste gas to energy at the Yolo County Central Landfill (YCCL). The main objective of this project is to

PROCESS ECONOMICS

Scale (LFG Flowrate SCFM)	CAPEX	Annual OPEX	Annual Revenue	Annual Profit
500	$3.5 MM	$550 k	$3.5 MM	$2.1 MM
1000	$5.2 MM	$800 k	$7 MM	$4.5 MM
1500	$6.7 MM	$1 MM	$10.5 MM	$7.0 MM
2000	$7.9 MM	$1.2 MM	$14 MM	$9.5 MM
2500	$9.1 MM	$1.4 MM	$17.5 MM	$11 MM
3000	$10.1 MM	$1.6 MM	$21 MM	$14 MM
3500	$11 MM	$1.8 MM	$24.5 MM	$16.8 MM
4000	$11.9 MM	$2 MM	$28 MM	$19 MM



Sensitivity analysis results. Base case is based on 15% interest rate, $3.24 per gal diesel price, $2.09 per MMBtu for LFG cost and total FCI of $8.5 million.

Assumptions

- 15% Interest Rate
- 35% Corporate Tax
- 5.5% FCI Maintenance Budget
- 7 Full Time Staff
- Wholesale Pump Price = $1.63
- RIN = $4.47/gal diesel (D3 ~ $2.63/RIN) EV=1.7

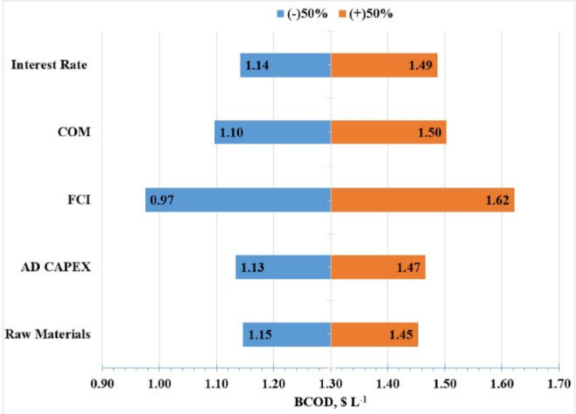
- Breakeven No RIN credit at 900 SCFM biogas production rate

Process Economics

Effect of tipping fee on feedstock on BCOD and NPW.

Tipping Fee ($ tonne^{-1})	Feedstock Cost ($ tonne^{-1})	BCOD ($ L^{-1})	NPW (Million $)
0	55	1.57	−10.9
0 (base case)	**28**	**1.30**	**0.00**
0	0	1.02	10.9
28	0	0.80	19.7
55	0	0.58	28.6
83	0	0.36	37.4

This Includes AD (~doubles the CAP-EX)



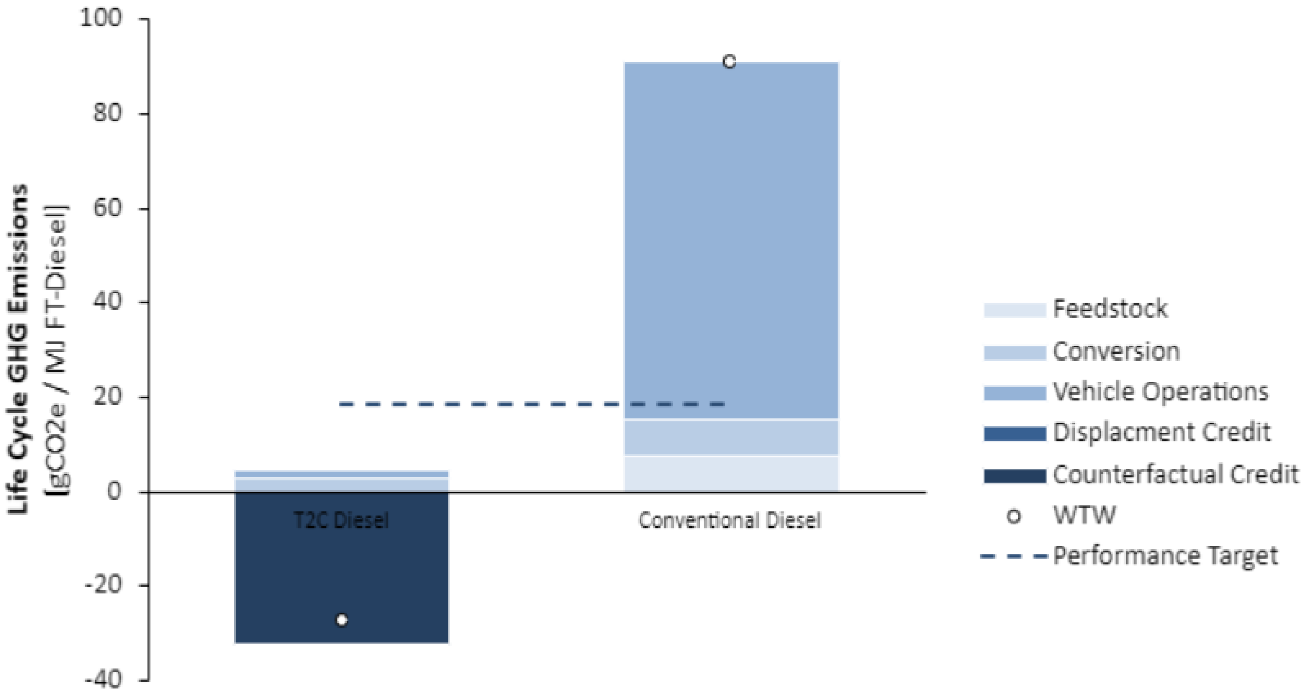
Economic comparison with published BTL modelling studies [72–74].

BTL Techno-economic Study	Interest on Capital Investment	Biomass Feed Capacity (dry tonne day^{-1})	Production Cost of Diesel ($ L^{-1})
Gasification-FT synthesis [72]	10%	2,016	0.56
AD-BGTL	15%	186	1.20
Gasification-FT synthesis [73]	10%	1,920	0.73
Gasification-FT synthesis followed by hydroprocessing [74]	10%	2,000	1.19

ENVIRONMENTAL IMPACT

- HYSIS fully integrated with heat and mass recycle
- Biogas composition impacts (reactant feed auto tuning)
- ANL GREET model updated with TRIFTS Life Cycle Analysis
- Basic engineering design package (Global Docs completed)
  - Heat and mass balances
  - PFD's
  - General arrangement
  - P&ID's
  - Equipment / Instrument spec list
  - Control architecture
  - Pipe sizing and metallurgy study
- Engineering package Issued for Bids

ANL GREET Model Carbon Intensity Score

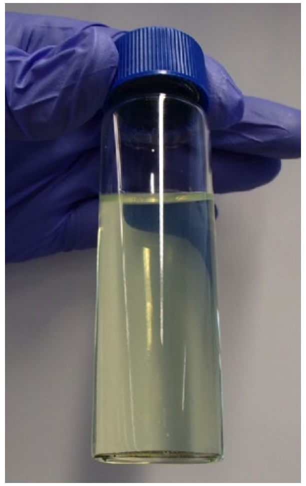


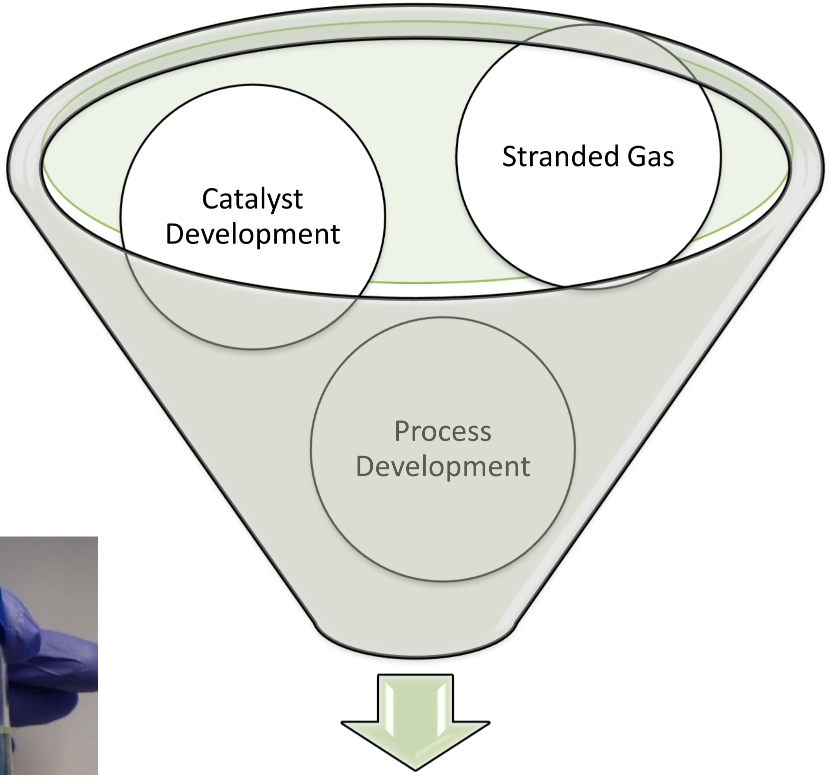
Landfill Application CI ~ - 36gCO2e/MJ

https://www.energy.gov/sites/default/files/2023-05/beto-04-project-peer-review-sdi-sup-apr-2023-walker.pdf

SUMMARY

- Utilize most of Biogas Feedstock (CO_2 Utilization)
- Significant Reduction of Unit Operations
- Compatible with Current Infrastructure
- High Quality Value Added Product (Drop-In Diesel)
- Self Sufficient Process
- Produce D3/D7 RIN
- Vastly Improved Economics and Profitability, even in face of economies of scale

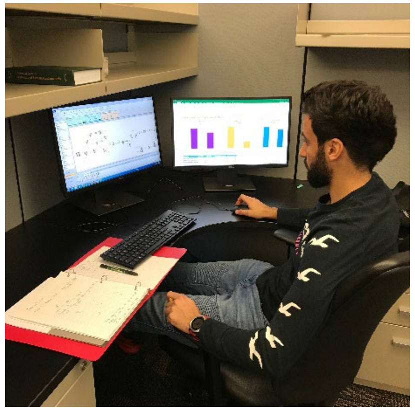


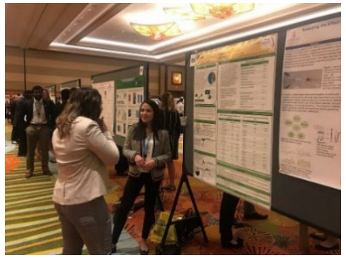


Viable Drop-in Fuels

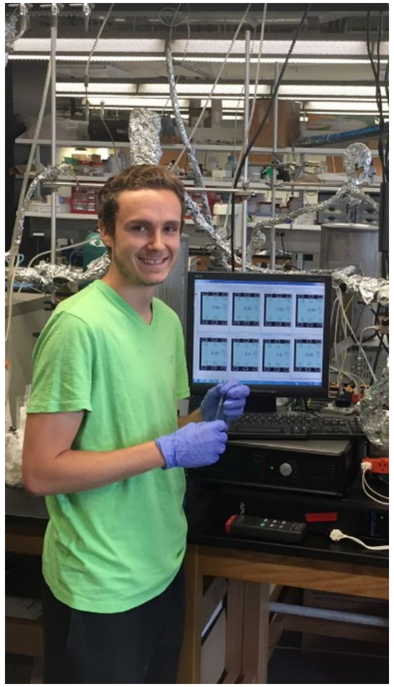
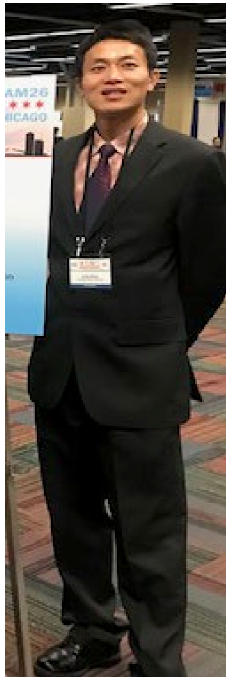
~ 40% Energy & Carbon recovery

THE TEAM



Technologies for Upgrading Landfill Gas to a High-Quality Fuel

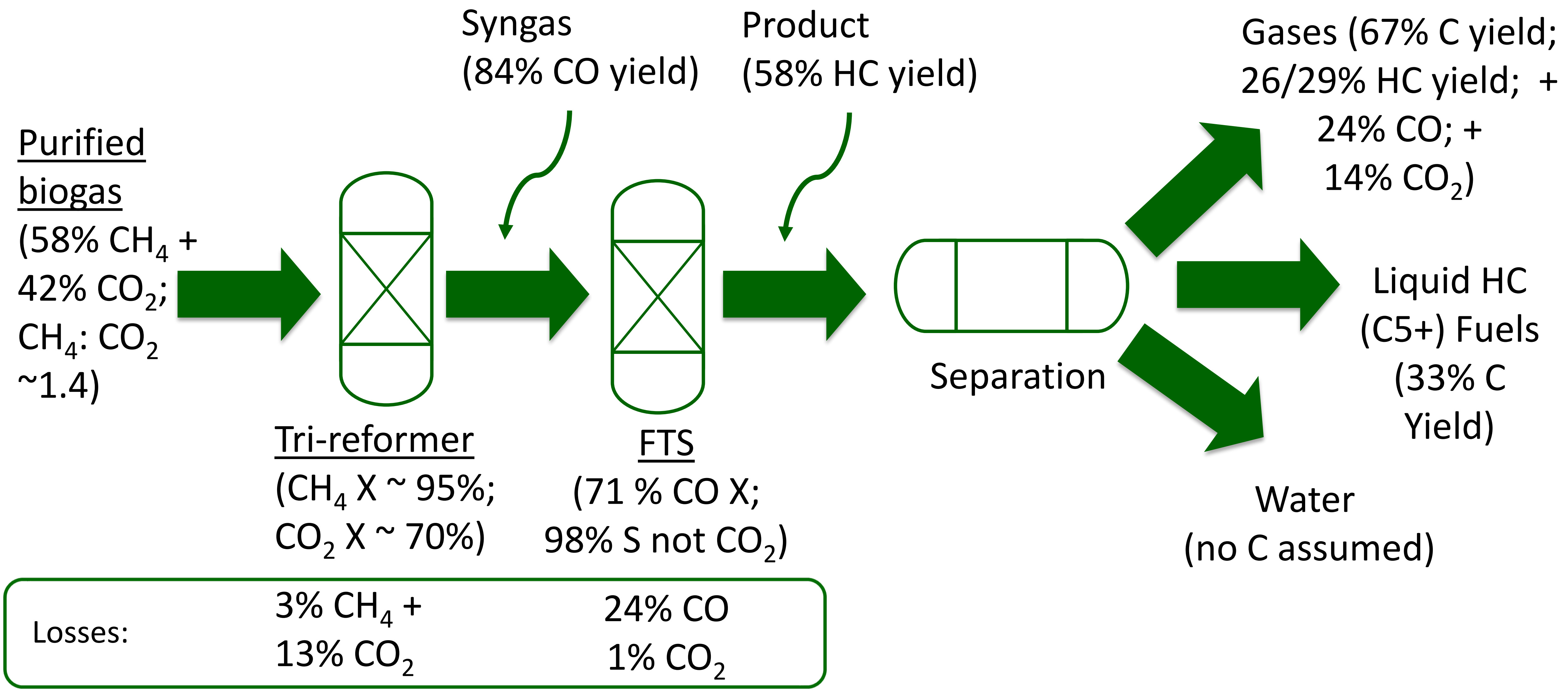
John N. Kuhn

USF and T2C-Energy LLC

2023 SWANA FL Summer Conference

PARKED

TriFTS Process Overview*



* Neglecting purification train here (material losses minimal; energy losses vary)

OVERALL M&EBs