DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

Synergistic Thermo-Microbial-Electrochemical (T-MEC) Approach for Drop-In Fuel Production from Wet Waste

April 7, 2023
Organic Waste Conversion

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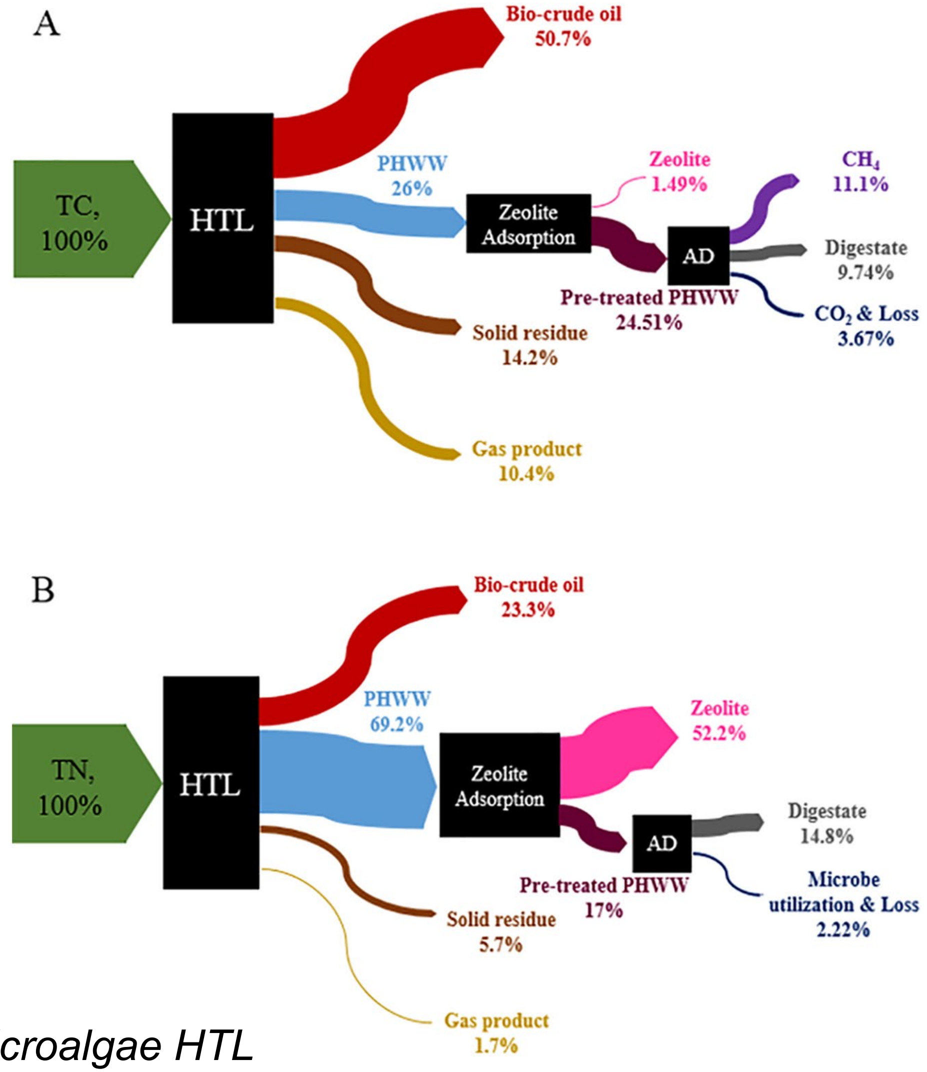
Project Overview

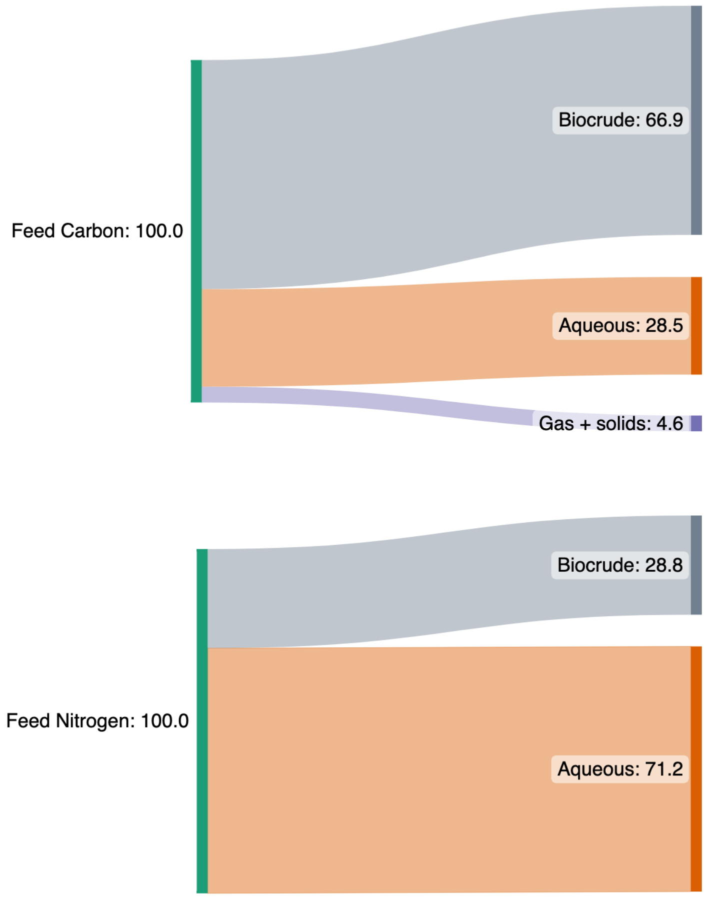
The post-hydrothermal liquefaction wastewater (PHW) is a burden (and opportunity) for hydrothermal liquefaction (HTL).

Total carbon (TC) flow

Total nitrogen (TN) flow



Li, et al., 2019, microalgae HTL



This study, mixed food waste HTL

Project Overview

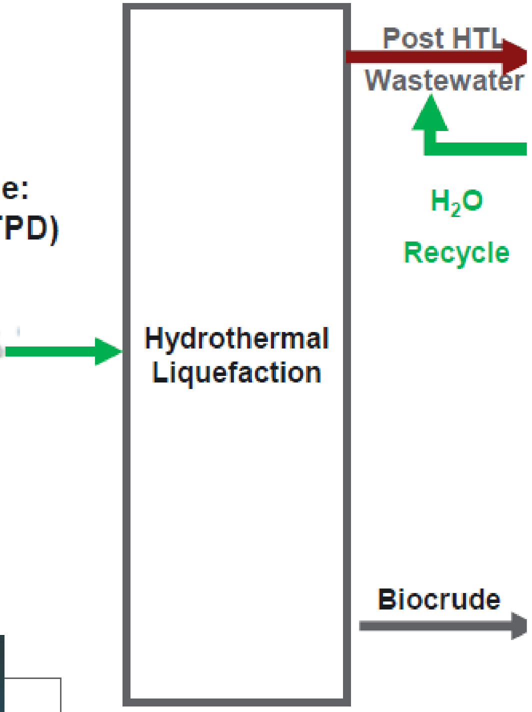
Process Optimization

Techno-economic and Life-cycle Assessment

1. Hydrothermal liquefaction of food waste
2. Biocrude hydrotreating and fractionation
3. Kerosene ASTM testing

Base Case Scale:
5 dry ton/day (TPD)

Food Waste



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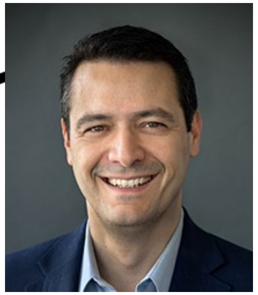
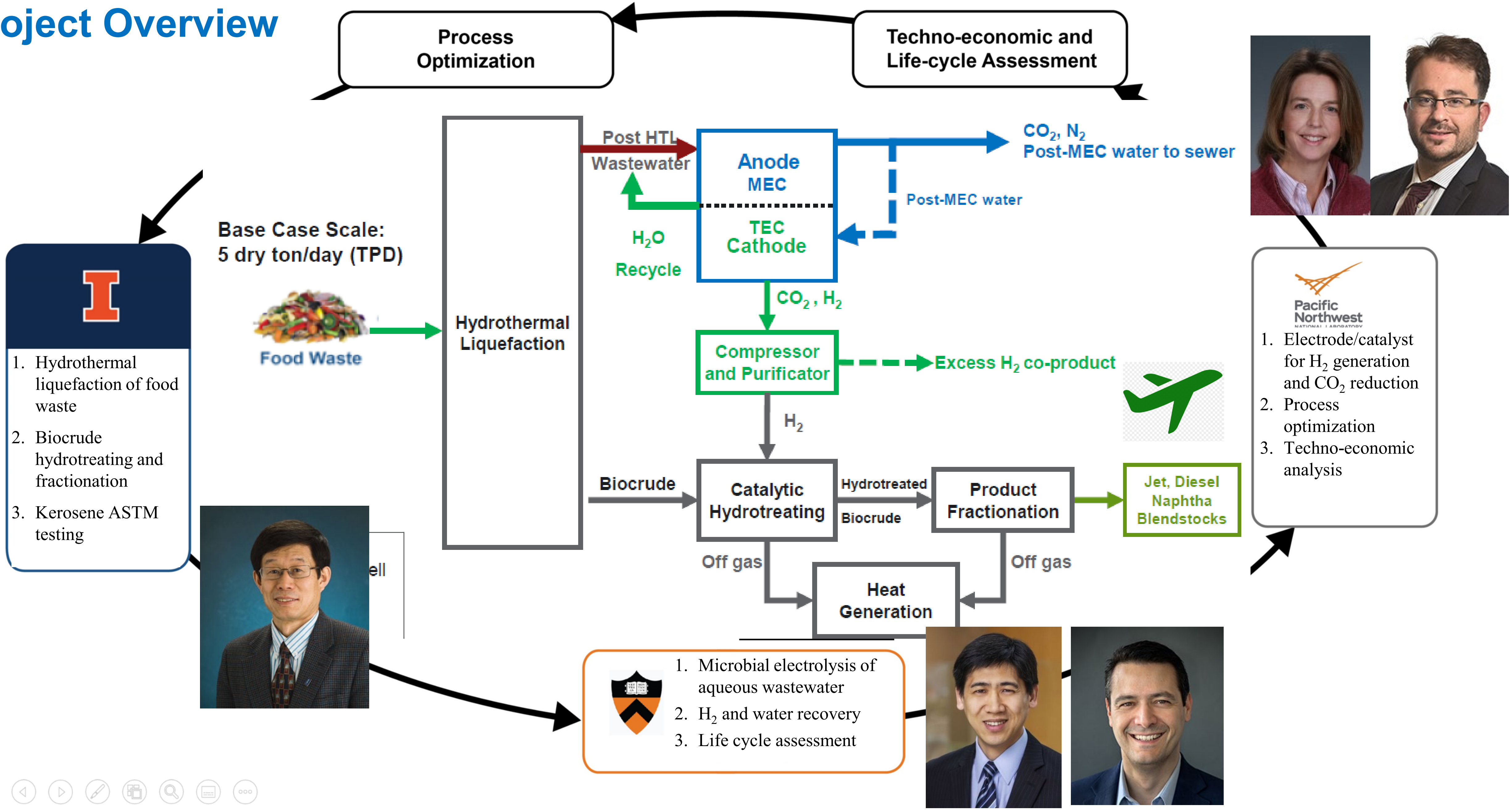
Pacific Northwest

1. Electrode/catalyst for H_2 generation and CO_2 reduction
2. Process optimization
3. Techno-economic analysis

1. Microbial electrolysis of aqueous wastewater
2. H_2 and water recovery
3. Life cycle assessment



Project Overview



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1 – Approach

Project Goals:

Develop a synergistic thermo-microbial-electrochemical (T-MEC) process that converts food waste to jet fuel blendstocks and simultaneously treats HTL aqueous wastewater, thereby recovering H_2 and nutrients. The process targets include:

1. improve carbon yield by >50% compared to the anaerobic digestion baseline
2. decrease waste processing cost by >25% compared to baseline

Proposed Budget Period	Tasks	Go/No-Go Decision
01/2021-03/2021	Initial verification	All baseline data will be verified successfully
04/2021-03/2023	Reactor development, product upgrading, and material innovation	Carbon conversion efficiency improves by >25% from AD baseline and/or Disposal costs are reduced by > 15%
03/2023-12/2024	Pilot reactor development and operation, system analyses	Carbon conversion efficiency improves by >50% from AD baseline and/or Disposal costs are reduced by > 25%

2 – Progress and Outcomes – HTL tasks

Pilot HTL Reactor Upgrading

System Volumes	Length (in)	Diameter (in)	Volume (gal)
HP to HEX Hose	140	0.75	0.268
HEX to R Hose/Pipe	64	0.75	0.122
R to HEX Hose/Pipe	71	0.75	0.136
HEX to BPR Hose/Pipe	47	0.75	0.090
HEX Tubing	2550	0.742	4.773
Reactor	4076	0.742	7.630
Total			**13.019**

The team at UIUC developed and upgraded a plug-flow continuous HTL reactor:

Reactor: 7.63 gal (28.9 L)

Counterflow heat exchanger: 4.77 gal

Processing capacity: 1.5 ton/day wet feedstock

2 – Progress and Outcomes – HTL tasks

Food Waste Collection and Pretreatment

Combining HMFW

Homogenize HMFW

Diluted to 20% solids

Two food wastes:

1) Harvest Market food waste (HMFW)
2) Food processing plant: Salad dressing waste (SDW)

Collect SDW

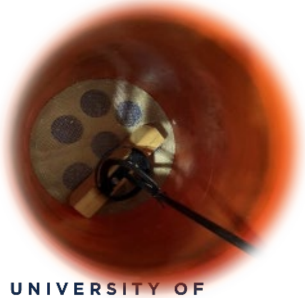
2 – Progress and Outcomes – HTL tasks

Food Waste Collection and Pretreatment

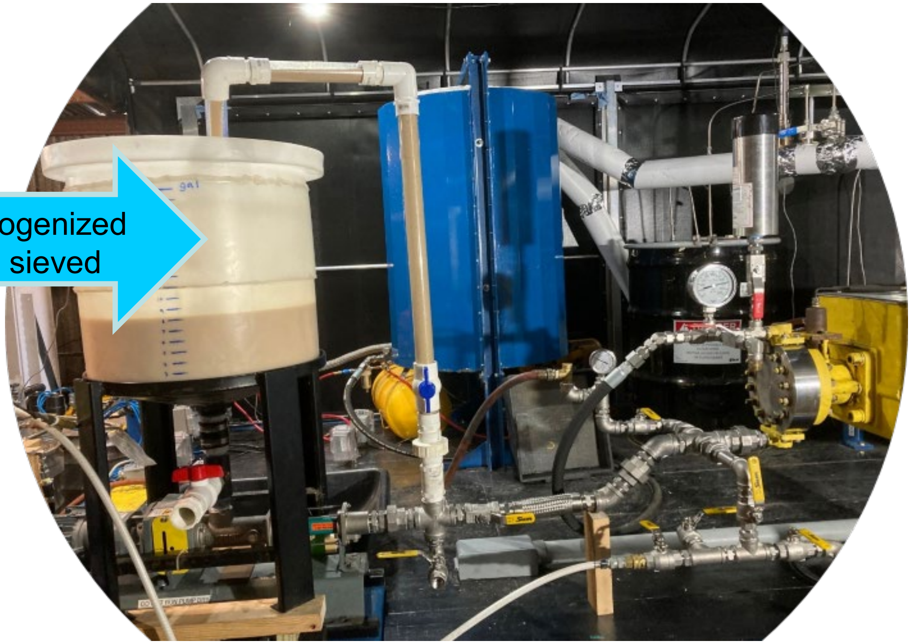
Feedstock pretreatment process:

- Grade 16 mesh to sieve the shredded feedstock
- Semi-manual pressure-sieve
- Automated pretreatment is needed for large quantity feedstock – Future work

Proximate Analysis	HMFW	SDW
Moisture (wt%)	66.73	75.66
Dry matter (wt%)	33.27	24.34
Protein (wt%)	32.76	2.38
Fat (wt%)	29.10	62.45
Ash (wt%)	7.15	5.71
Carbohydrate* (wt%)	30.99	29.46



Homogenized and sieved



Elemental Analysis	HMFW	SDW
Carbon (wt%)	55.38	60.94
Hydrogen (wt%)	7.69	8.27
Nitrogen (wt%)	5.62	0.70
Oxygen (wt%)*	27.21	27.45
Sulfur (wt%)	0.33	<0.01
HHV(MJ/kg)**	25.74	28.04

*Calculated by difference

**HHV= 0.3516 × C + 1.16225 × H – 0.1109 × O + 0.0628 × N

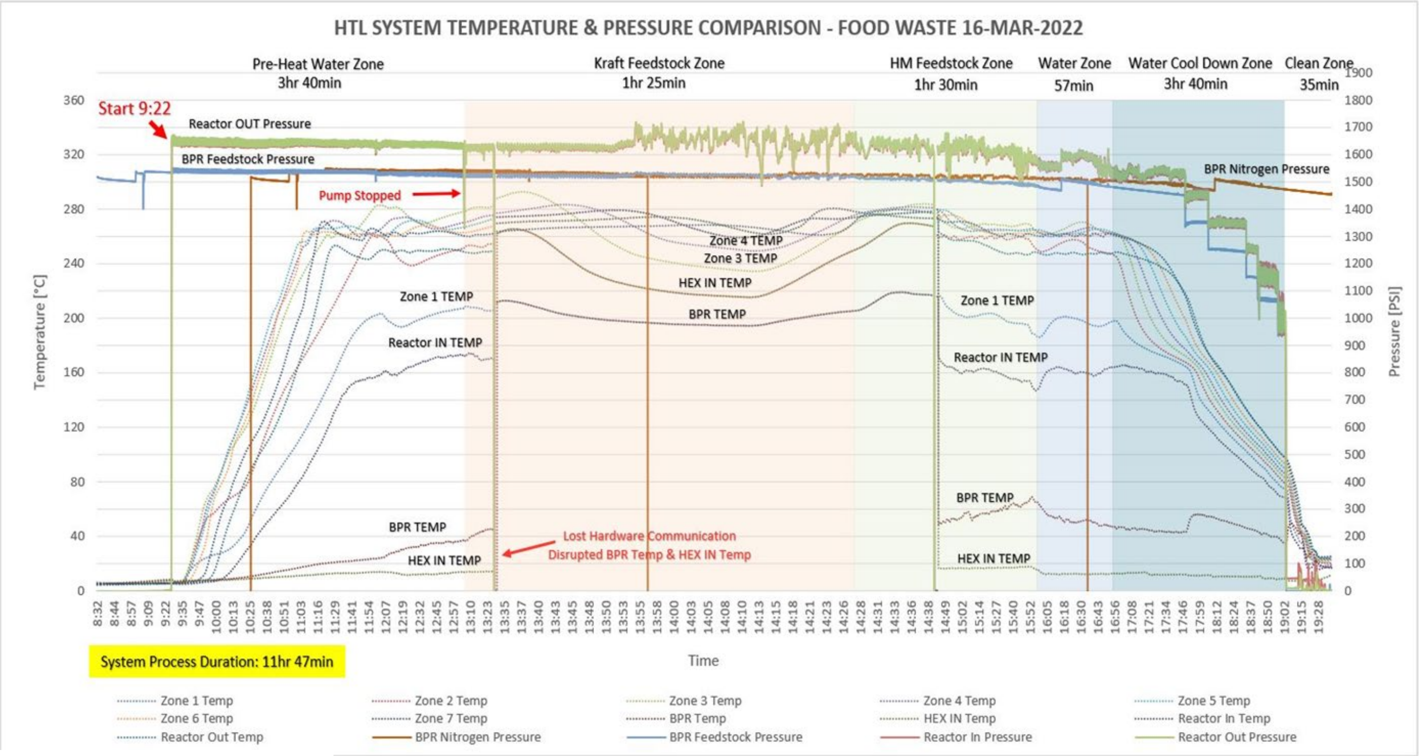
2 – Progress and Outcomes – HTL tasks

HTL System Performance

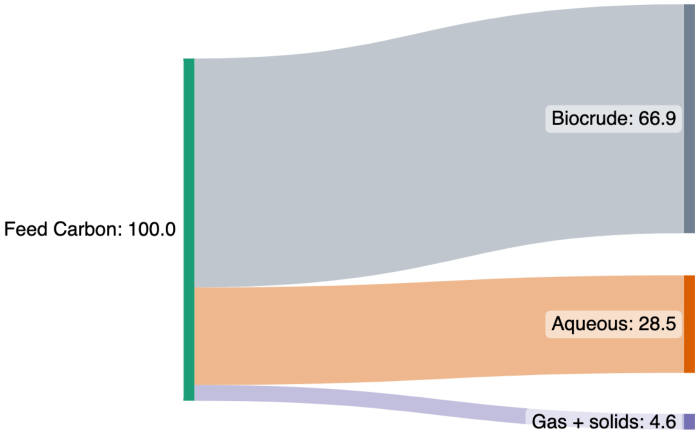
Runs with water and feedstock were performed to determine ideal system operating conditions and avoid HTL run disruptions from charring/plugging:

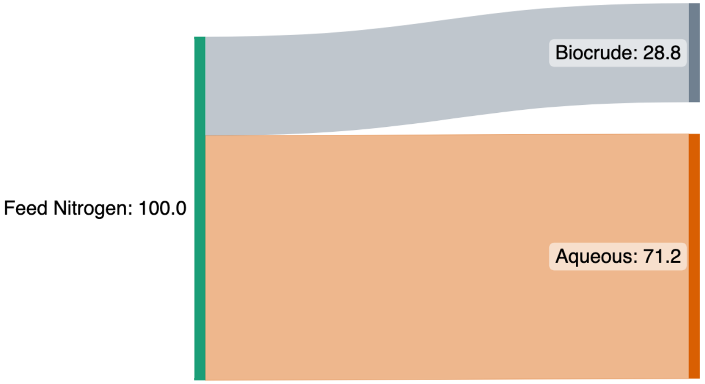
$$Q = f\,[P_{pump}, C, F, P_{bpr}, T, \eta]$$

Q = flowrate in mL/min
P_{pump}= pressure of HP pump
P_{bpr} = nitrogen back pressure
C = pump capacity
F = frequency of pump motor
T = temperature in reactor
η = viscosity of the feedstock



Mass Flow for HMFW:





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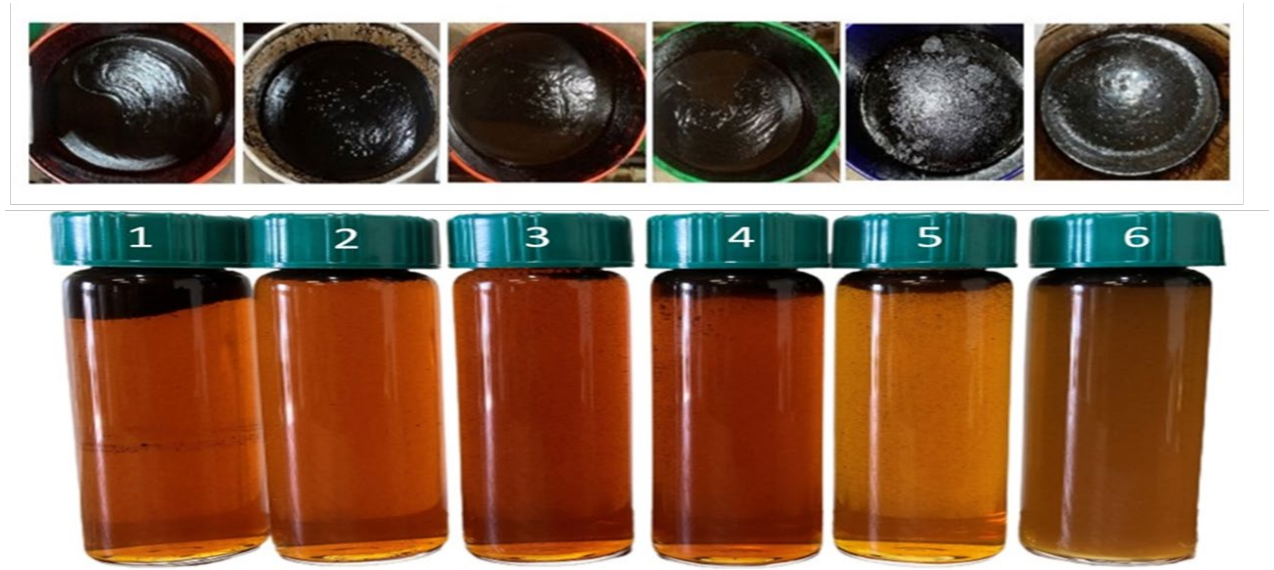
2 – Progress and Outcomes – HTL tasks

HTL Pilot Reactor Products

20 gallons of each feedstock at 20 wt% solids content were successfully processed, producing biocrude oil (top) and post-HTL wastewater (PHW, bottom). Samples were collected in sequence during the run.



Biocrude	HMFW	SDW
Carbon (wt%)	78.74	75.64
Hydrogen (wt%)	11.31	11.42
Nitrogen (wt%)	3.36	0.76
Oxygen (wt%)	6.46	12.16
Sulfur (wt%)	0.12	0.01
HHV (MJ/kg)	40.32	38.57
Mass yield (wt%)	47.06	52.19
Energy yield (%)	68.17	70.77
Carbon yield (wt%)	66.91	64.78

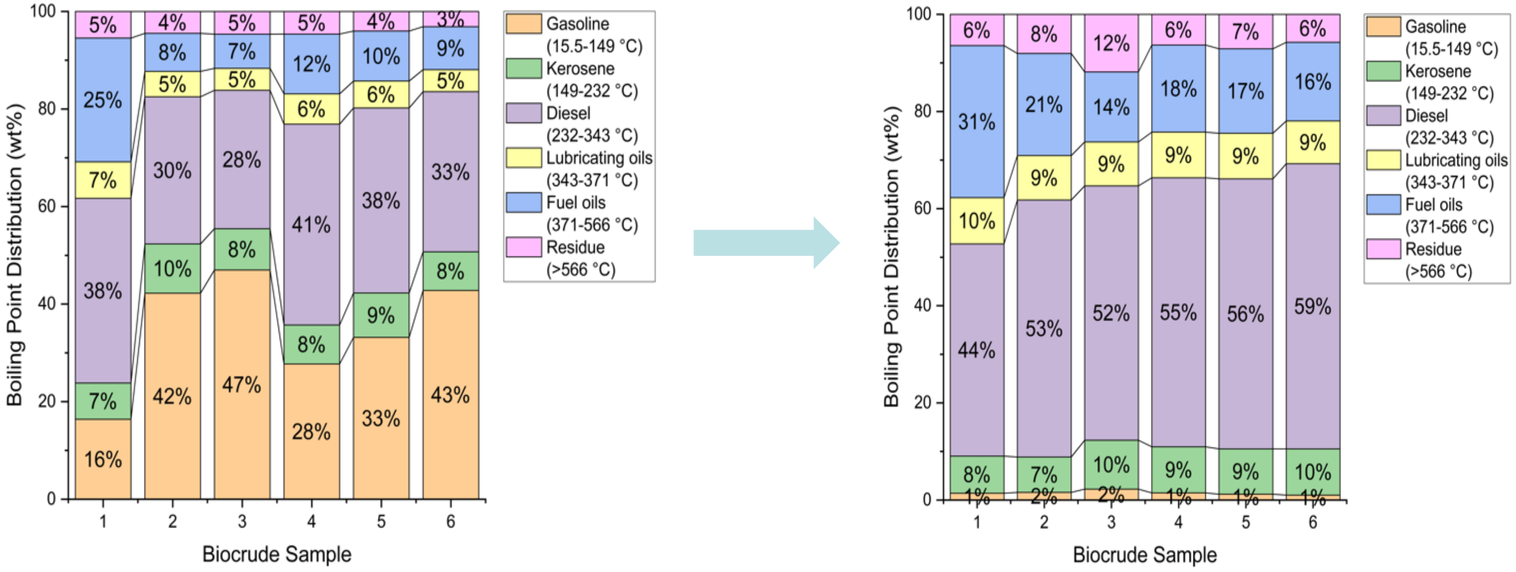
PHW	HMFW	SDW
COD (mg/L)	101,850	42,380
pH	5.3	3.5
Total nitrogen (mg/L)	8,725	349
Ammonia nitrogen (mg/L)	2,330	14.8

HTL operation conditions:

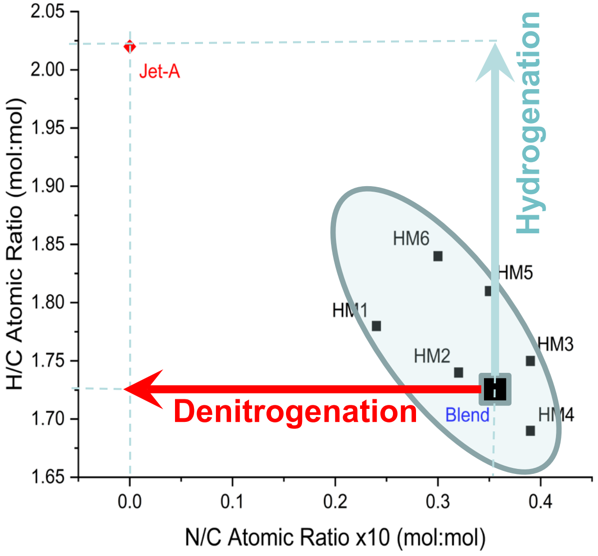
- Temperature: 280 ± 20^{o}C
- Retention time: 30 min
- Pressure: 1,800 psi
- Feed rate: 1 L/min

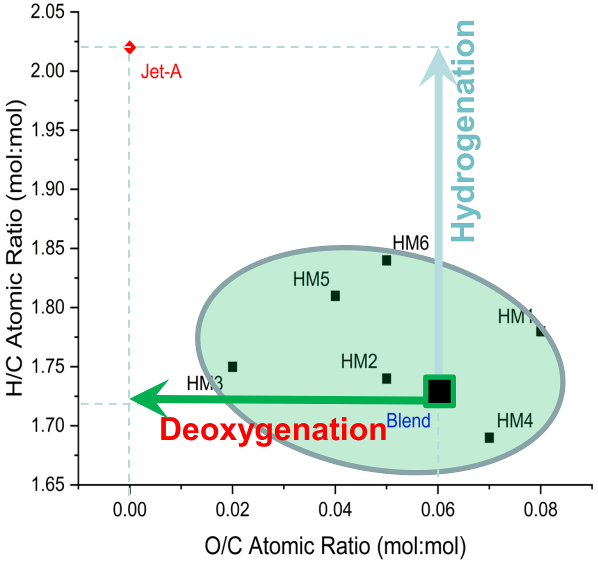
2 – Progress and Outcomes – HTL tasks

HTL Biocrude Characterization, Treatment, and Upcoming Work



***Pretreatment**: Biocrude dewatered (ASTM D2892 Annex X1) to remove residual moisture*

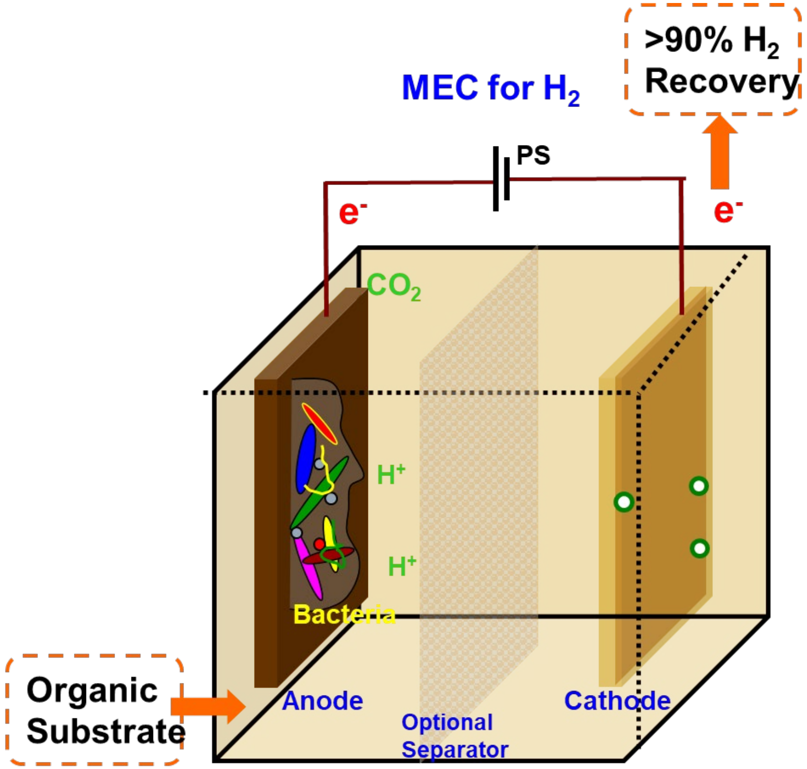




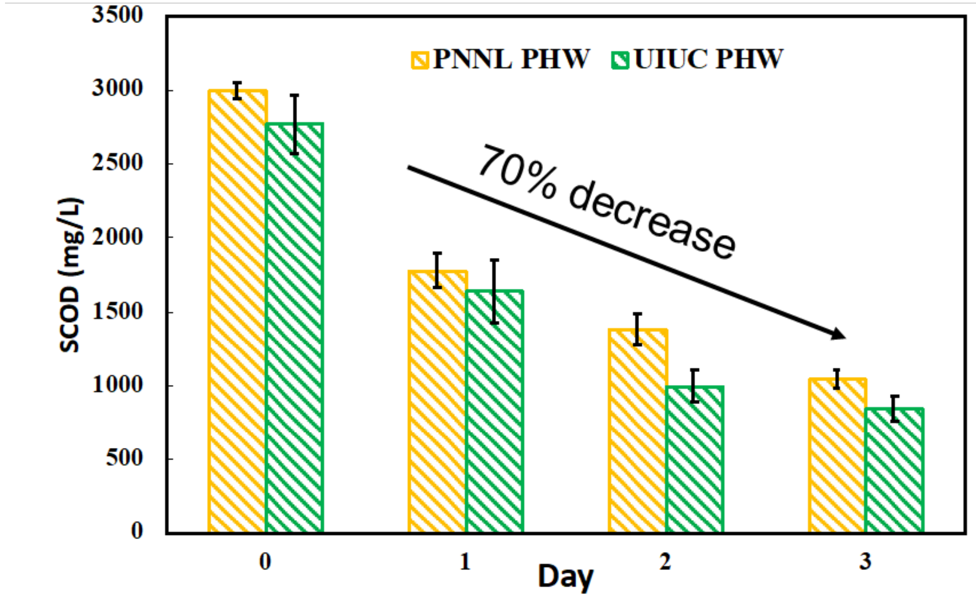
***Hydrotreating**: required to further upgrade biocrude oil (hydrogenate, deoxygenate, denitrogenate)*

2 – Progress and Outcomes – MEC tasks

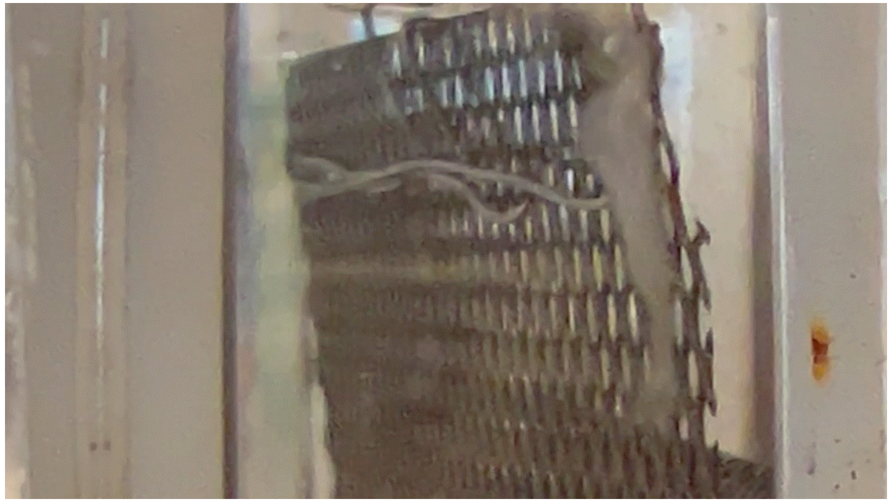
MEC (microbial electrolysis cell) recovers high purity H_2 while degrading the organic pollutants in **PHW** (Post-hydrothermal liquefaction wastewater)



- Two types of PHW feedstocks were tested in MECs
- Lab batch reactors delivered consistent good COD removal

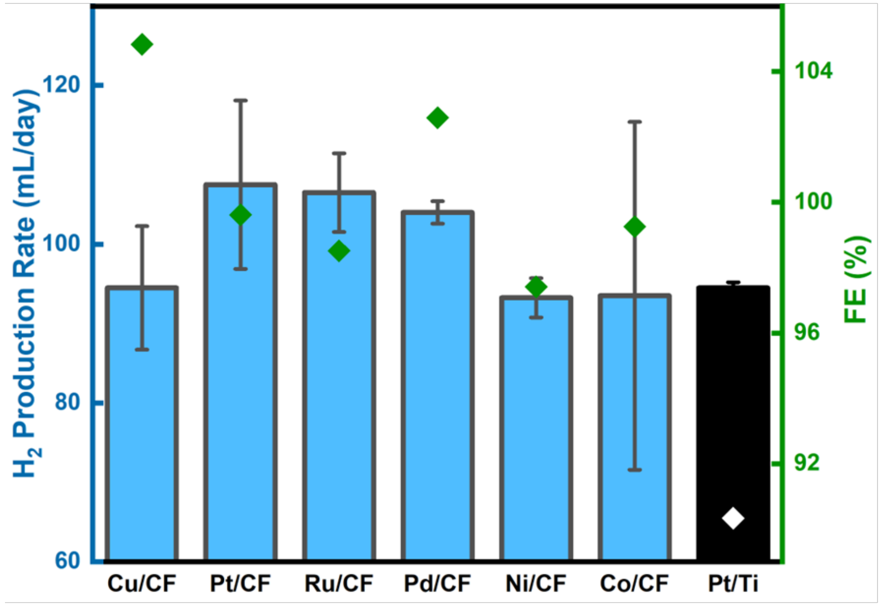


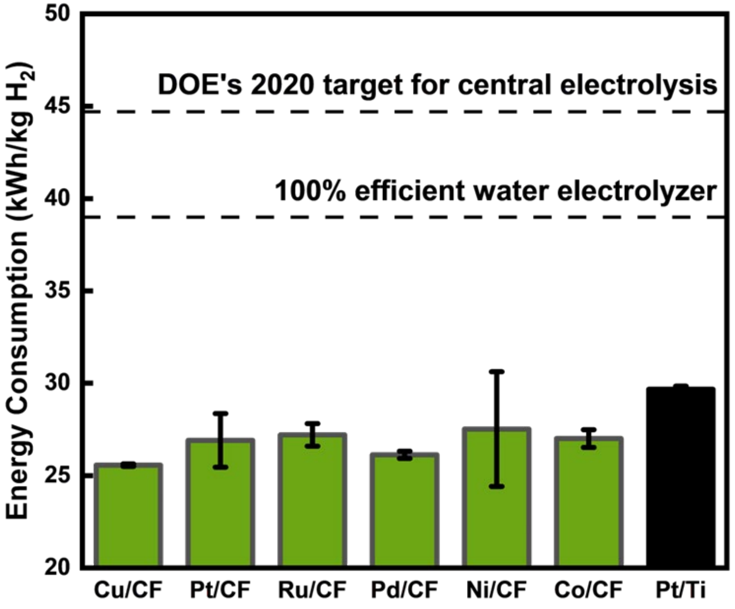
2 – Progress and Outcomes – MEC tasks

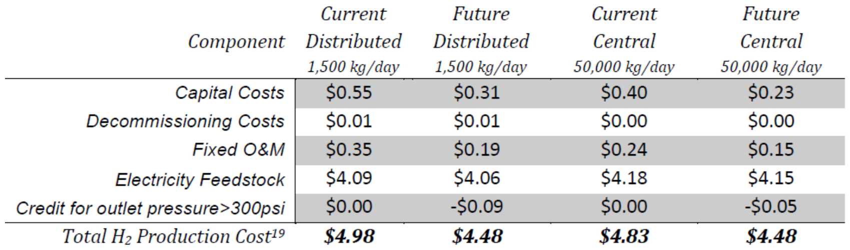


- New alloy cathodes were provided by PNNL and tested in MECs for H_2 production during PHW treatment.
- High H_2 production rate was up to 2.69 L/L/day in batch with Pt/CF, higher than commercial Pt/Ti electrode, (1.81 L/L/day).
- All cathodes had FE > 90%
- MEC energy consumption was < 30 kWh/kg H_2 – 25% lower than abiotic water electrolysis

(DOE TEA has shown electricity cost could contribute **> 80%** of total H_2 production cost)



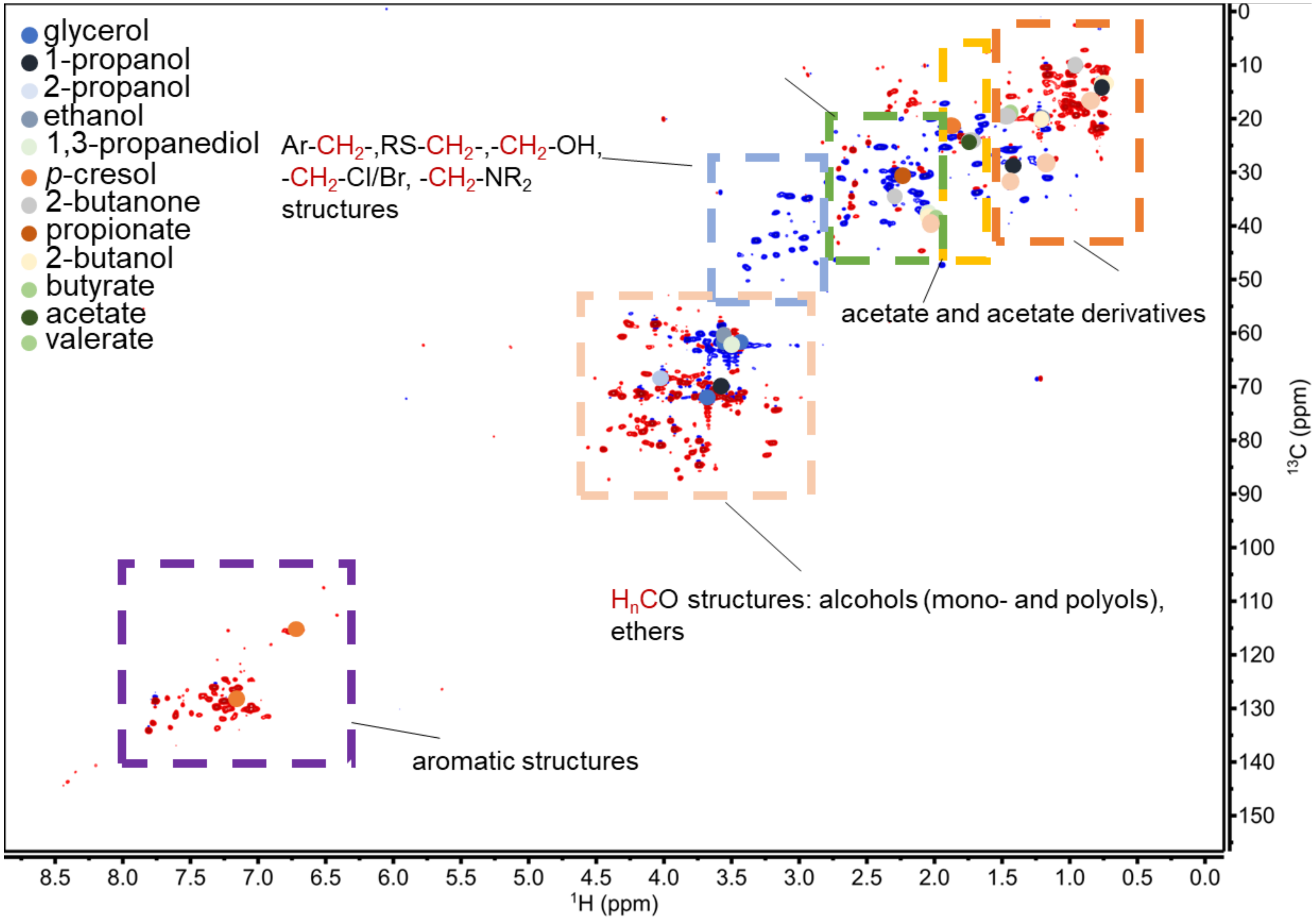




Component	Current Distributed 1,500 kg/day	Future Distributed 1,500 kg/day	Current Central 50,000 kg/day	Future Central 50,000 kg/day
Capital Costs	\$0.55	\$0.31	\$0.40	\$0.23
Decommissioning Costs	\$0.01	\$0.01	\$0.00	\$0.00
Fixed O&M	\$0.35	\$0.19	\$0.24	\$0.15
Electricity Feedstock	\$4.09	\$4.06	\$4.18	\$4.15
Credit for outlet pressure>300psi	\$0.00	-\$0.09	\$0.00	-\$0.05
Total H_2 Production Cost[19]	***\$4.98***	***\$4.48***	***\$4.83***	***\$4.48***

DOE Hydrogen and Fuel Cells Program Record, 2020

2 – Progress and Outcomes – MEC tasks



Ar-CH_2-,RS-CH_2-,-CH_2-OH, -CH_2-Cl/Br, -CH_2-NR_2 structures

acetate and acetate derivatives

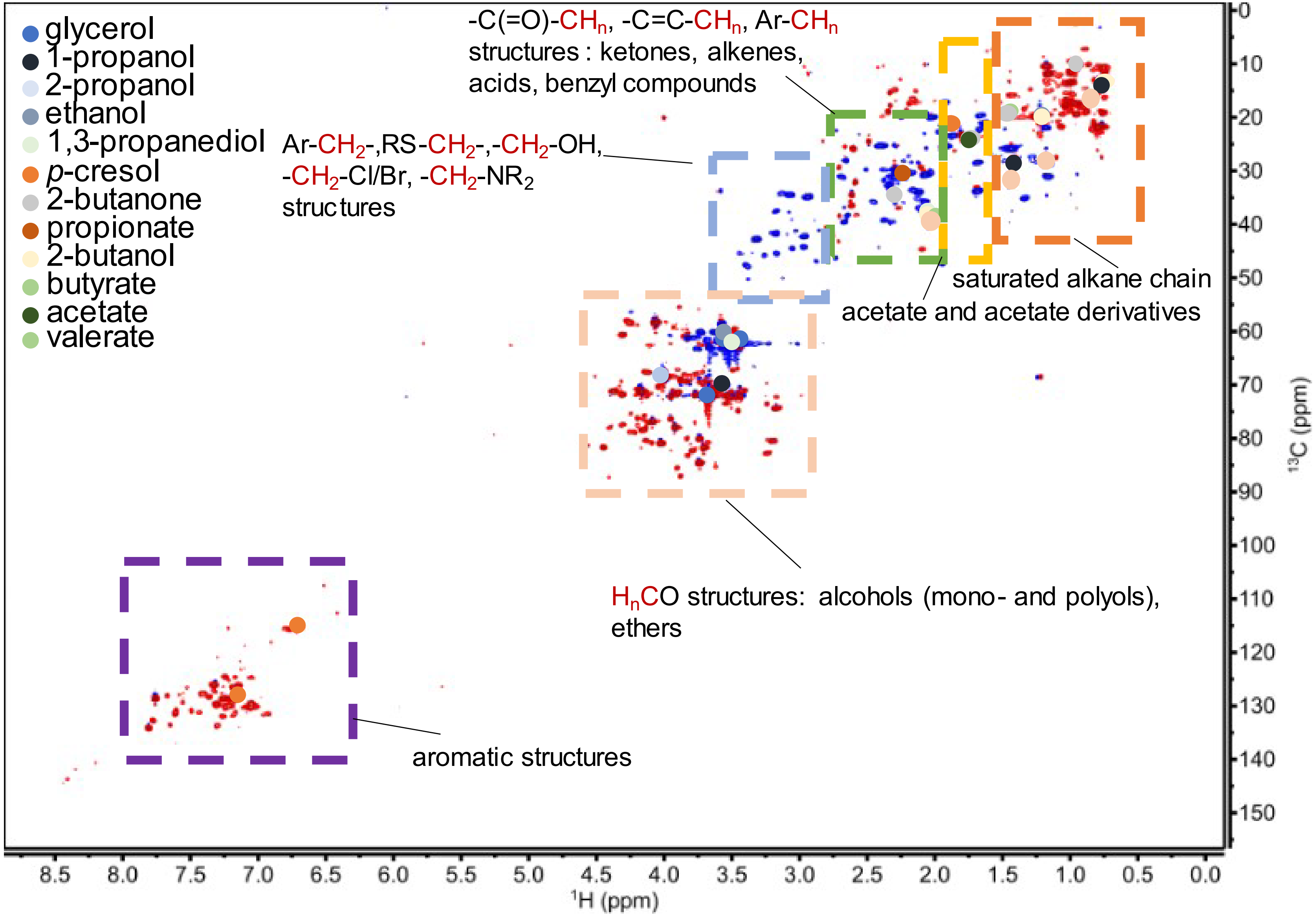
H_nCO structures: alcohols (mono- and polyols), ethers

aromatic structures

2D HSQC NMR along with HPLC on PHW analysis indicates the organic degradation process:

- Many signals in the saturated alkane region;
- Multiple signals exhibit carbonyl group and alkene group;
- Strong presence of HCO structures, indicating alcohols, polyols and ethers

2 – Progress and Outcomes – MEC tasks



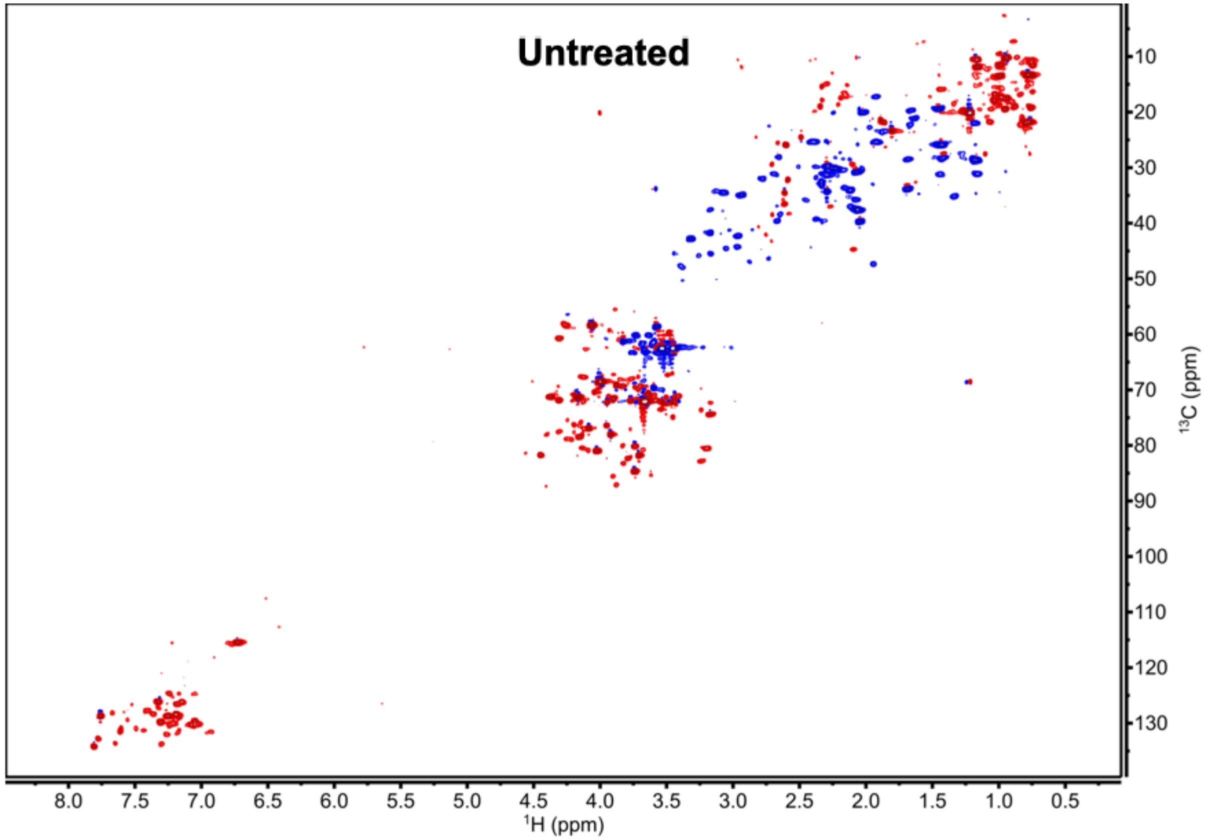
2D HSQC NMR along with HPLC on PHW analysis indicates the organic degradation process in MEC:

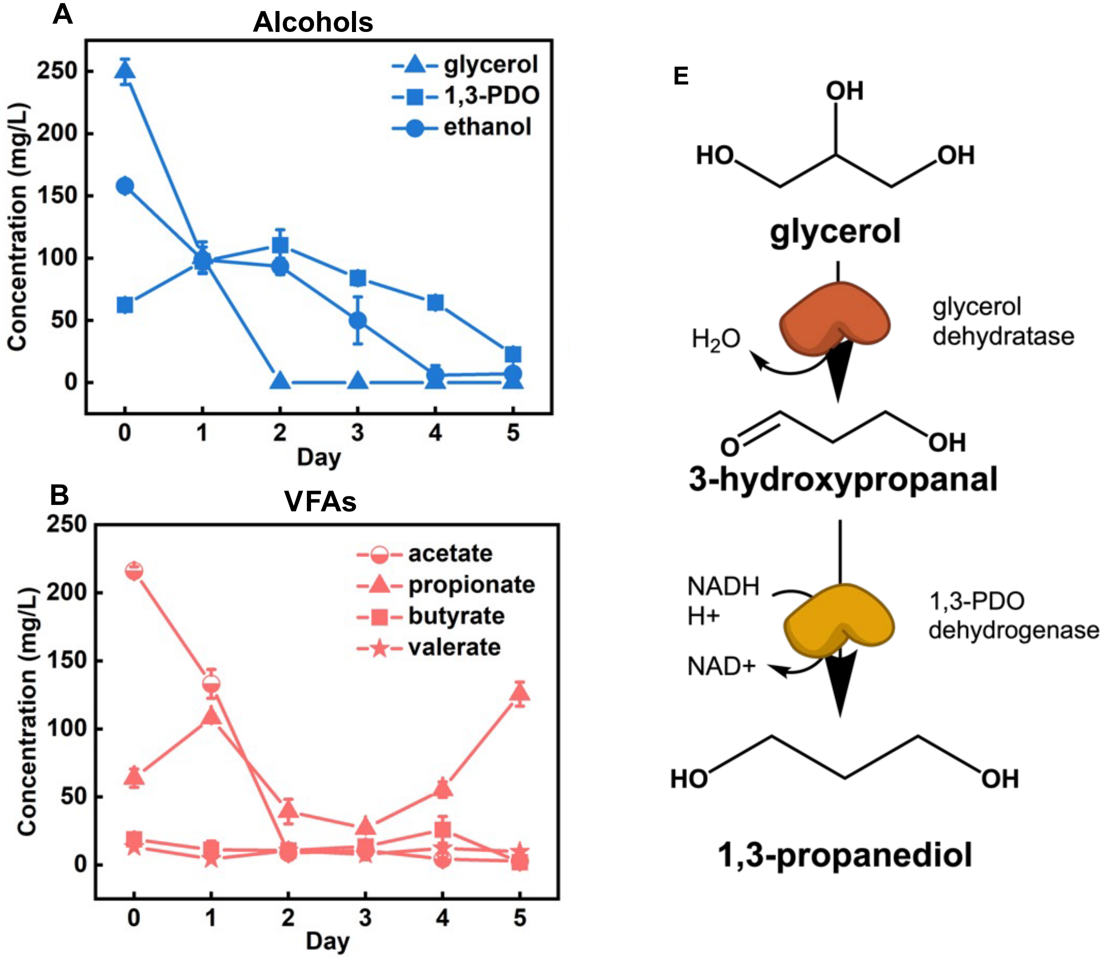
Many signals in the saturated alkane region;

Multiple signals exhibit carbonyl group and alkene group;

Strong presence of HCO structures, indicating **alcohols, polyols and ethers**

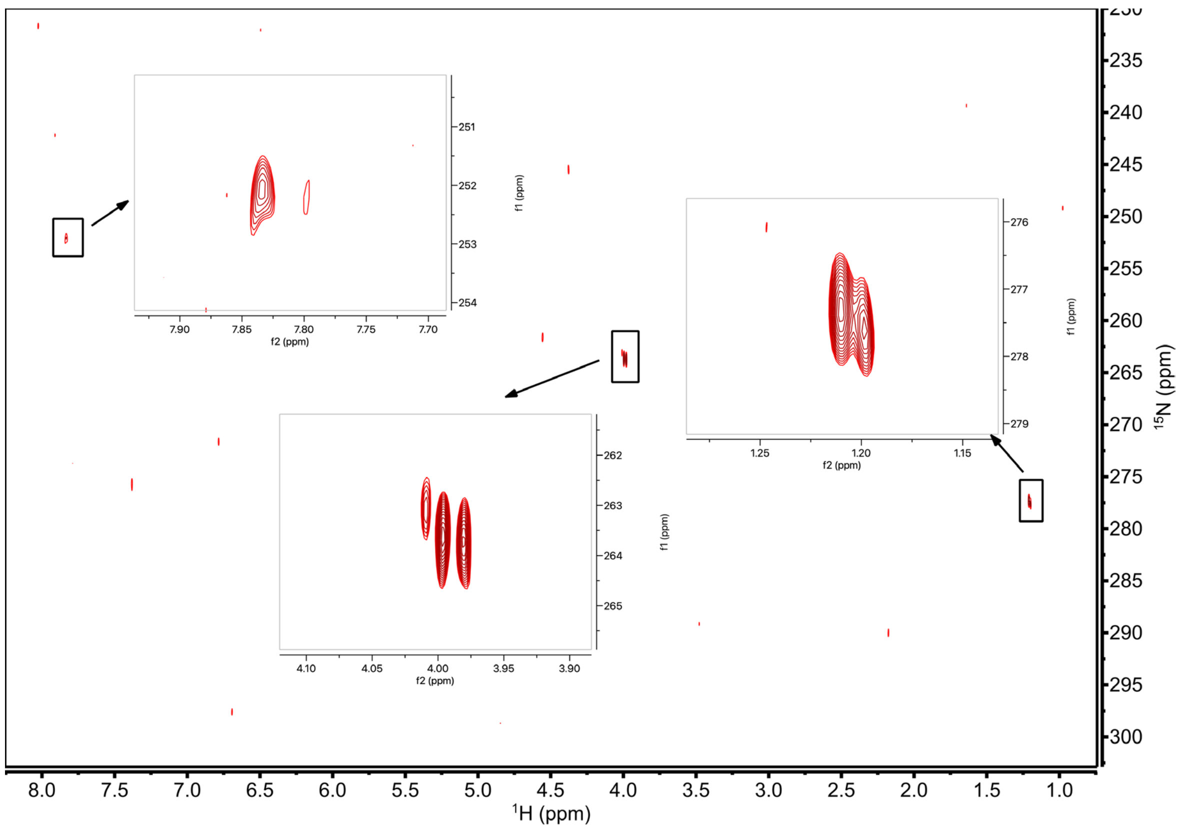
2 – Progress and Outcomes – MEC tasks





- Most easily degradable organics (VFAs, alcohols) in PHW were removed within a day.
- Glycerol mainly went through fermentation process, and produced 1,3-propanediol (1,3-PDO), ethanol, propionate
- Ethanol and VFAs can be both produced (via fermentation) and consumed in the MEC anode.

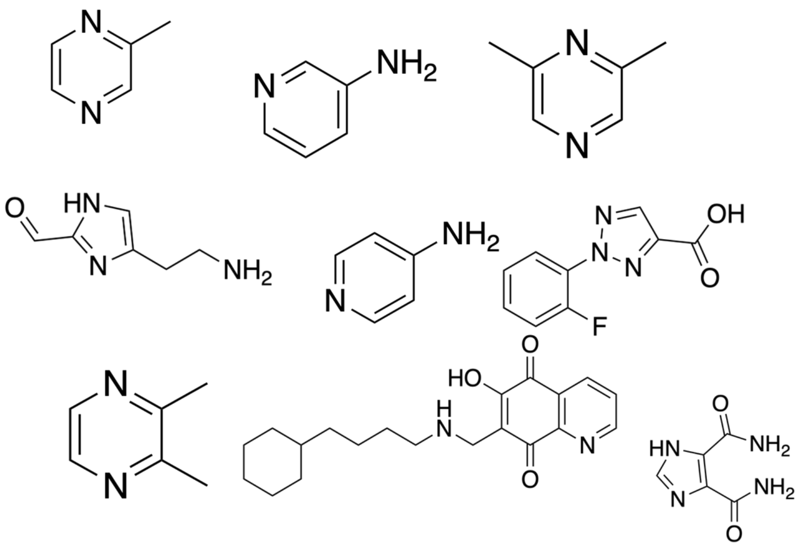
2 – Progress and Outcomes – MEC tasks



- Organic/aromatic N species generated during HTL are new to conventional wastewater treatment

- To characterize the composition, solution state ^{15}N NMR was successfully applied to wastewater for the first time

- Results indicated the major org-N form was **heteroaromatics** with pyridine-like N

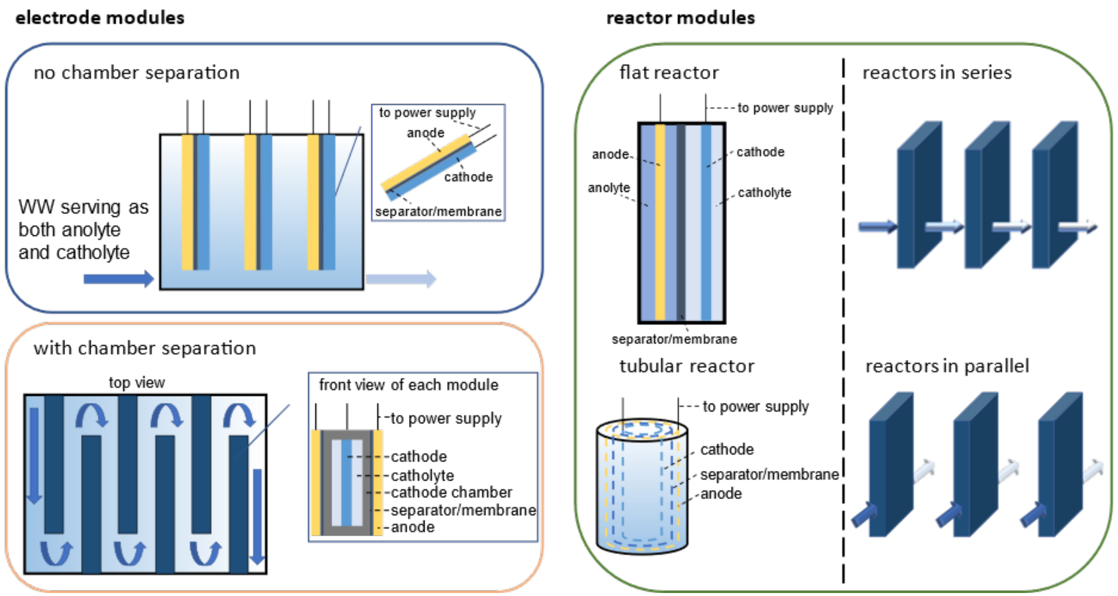


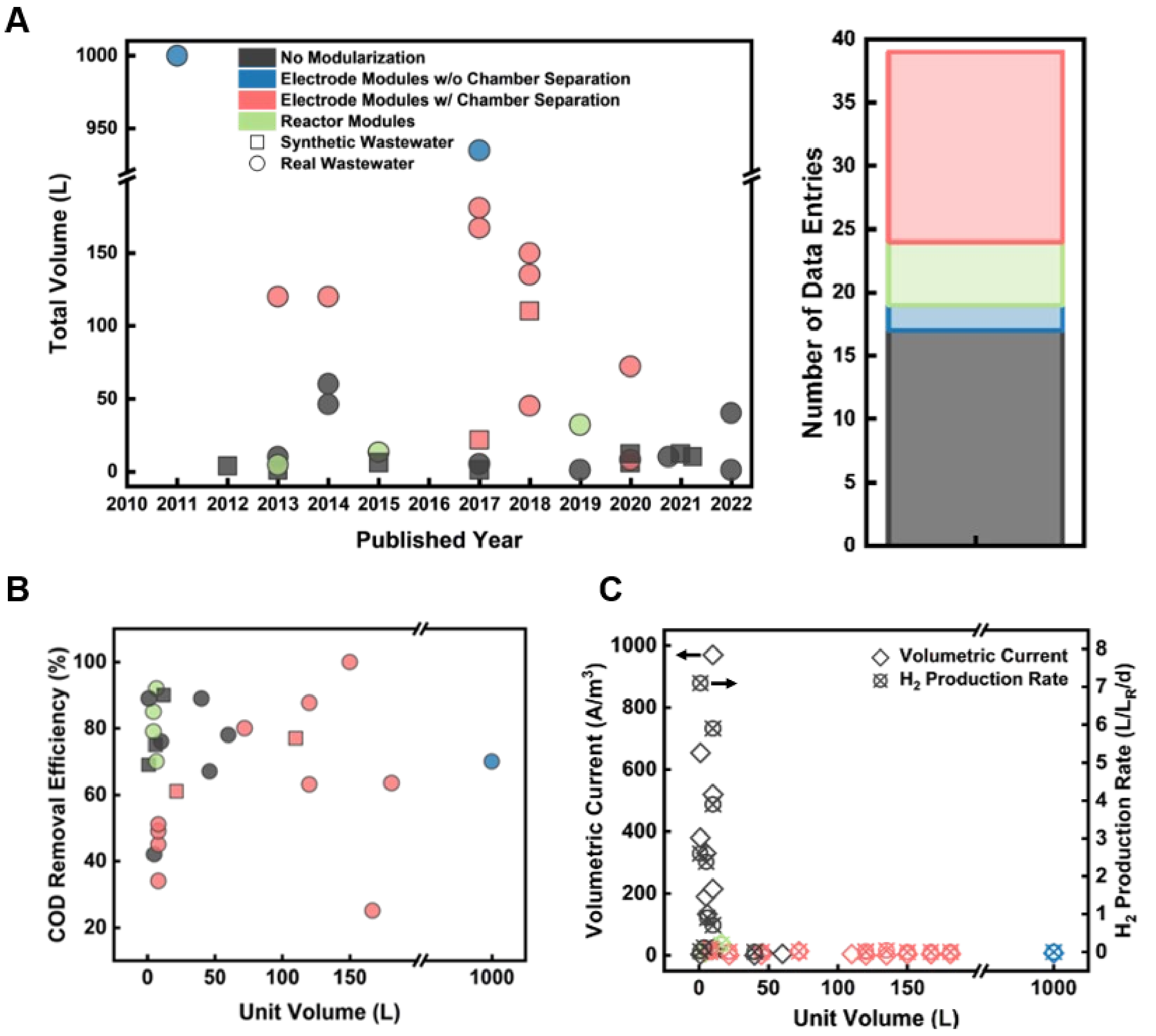
Heteroaromatics confirmed by GC-MS

2 – Progress and Outcomes – MEC tasks

To develop scaled reactors, literature review and system design analyses were carried out.

MEC pilot studies categorized by reactor operation volumes, configurations, and anode substrates.

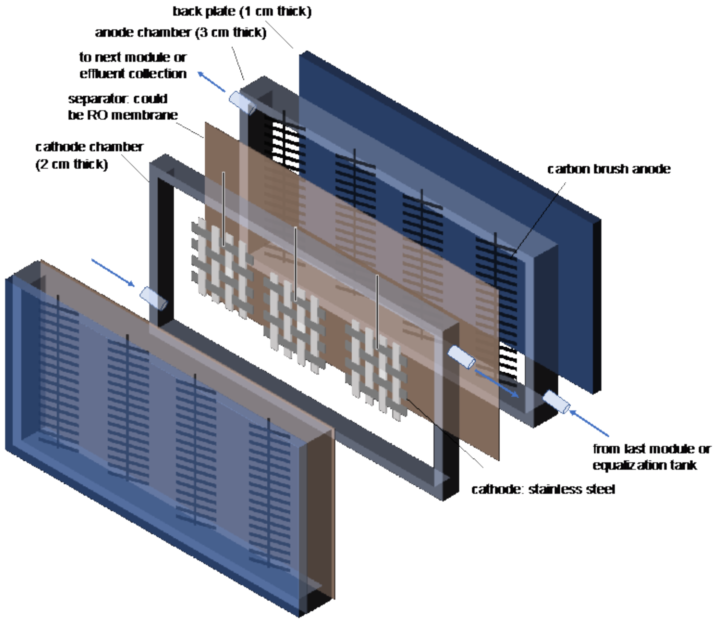




2 – Progress and Outcomes – MEC tasks

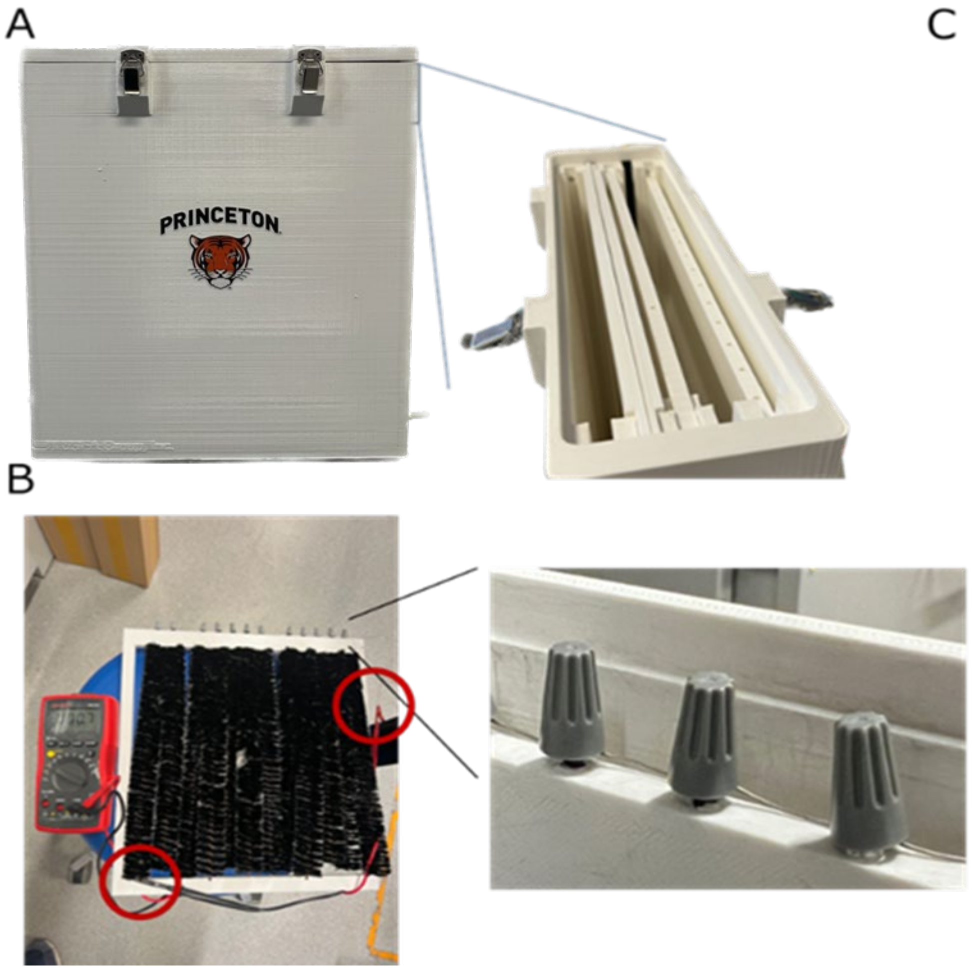
Through extensive literature review, our takeaways on constructing pilot MEC reactors:

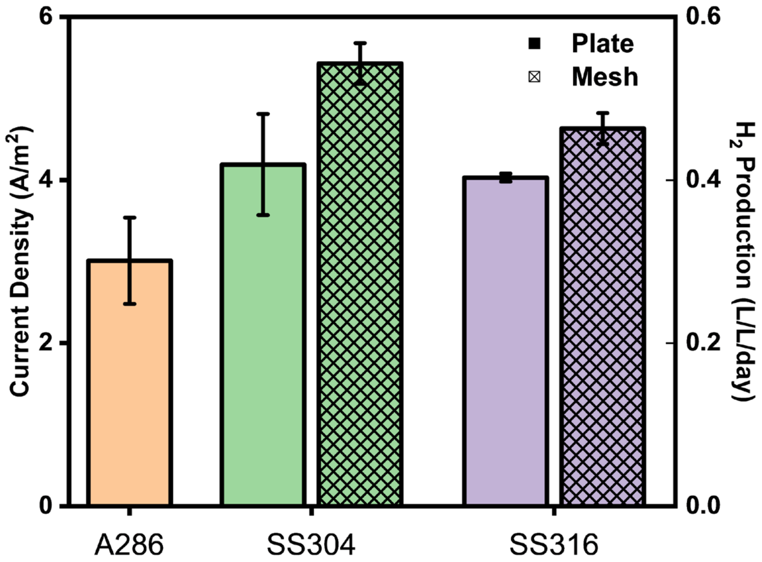
- Current density is the key metric to be improved for MEC;
- Good conductivity (which PHW has) is a prerequisite to high current density;
- Lessons from electrolysis industry – the best design should be easy to modularize, and minimize the electrical resistance between electrodes: **compact & modular;**
- Lessons from TEA: material for MEC should be low in price.



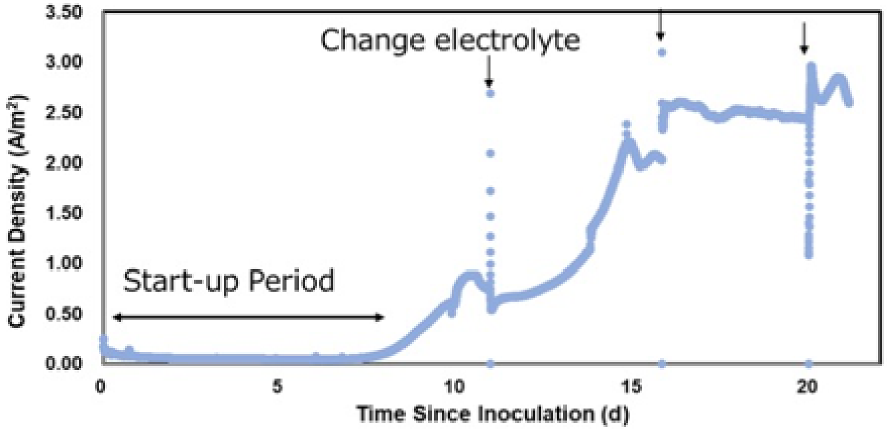
2 – Progress and Outcomes – MEC tasks

3D-printed pilot reactor (10 L)





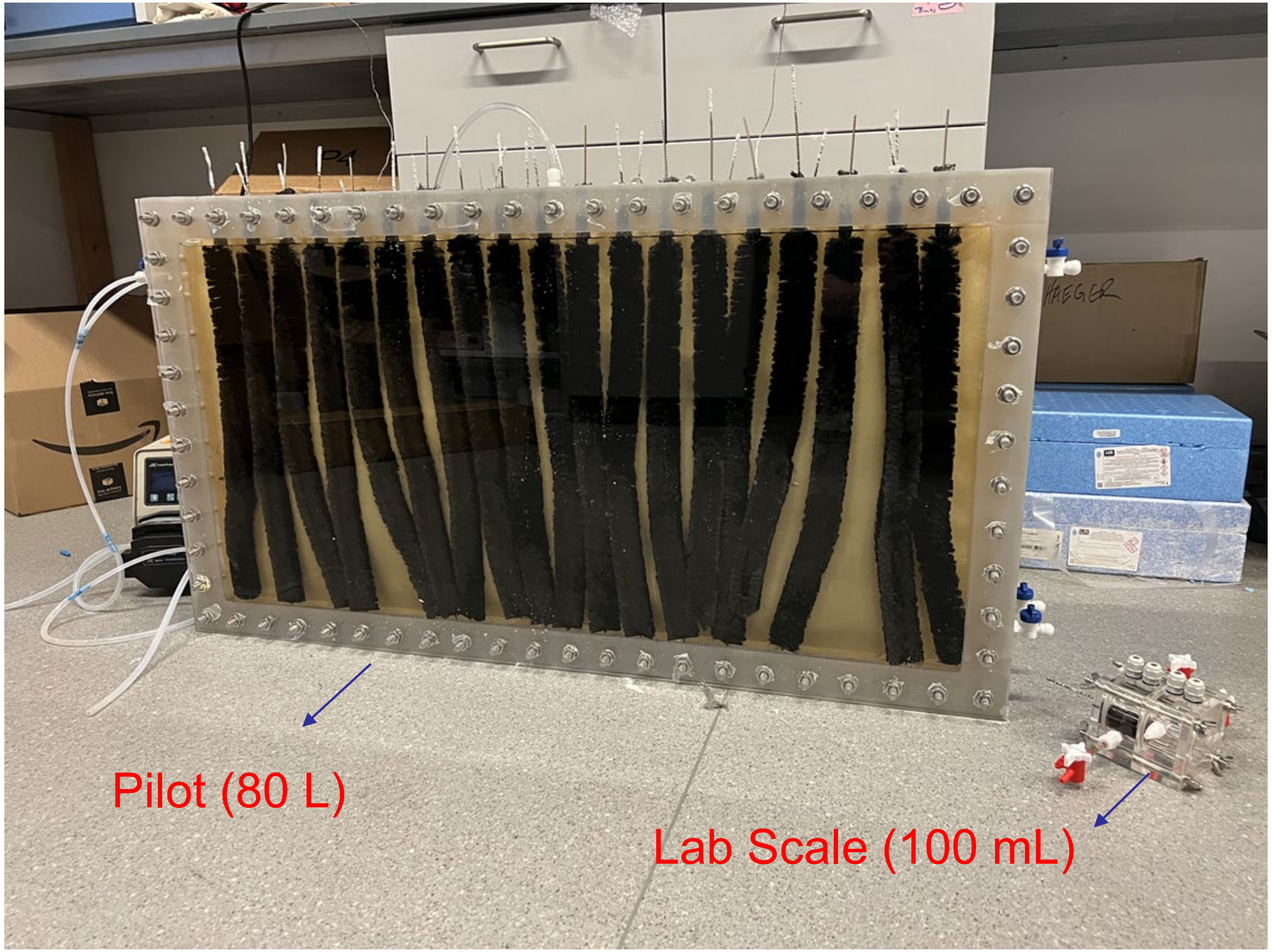
Different SS cathodes were tested. SS304 mesh showed the highest current density (>90% of pilot MEC studies) with low cost (~ \$50/m²).



Quick startup at around 1 week

2 – Progress and Outcomes – MEC tasks

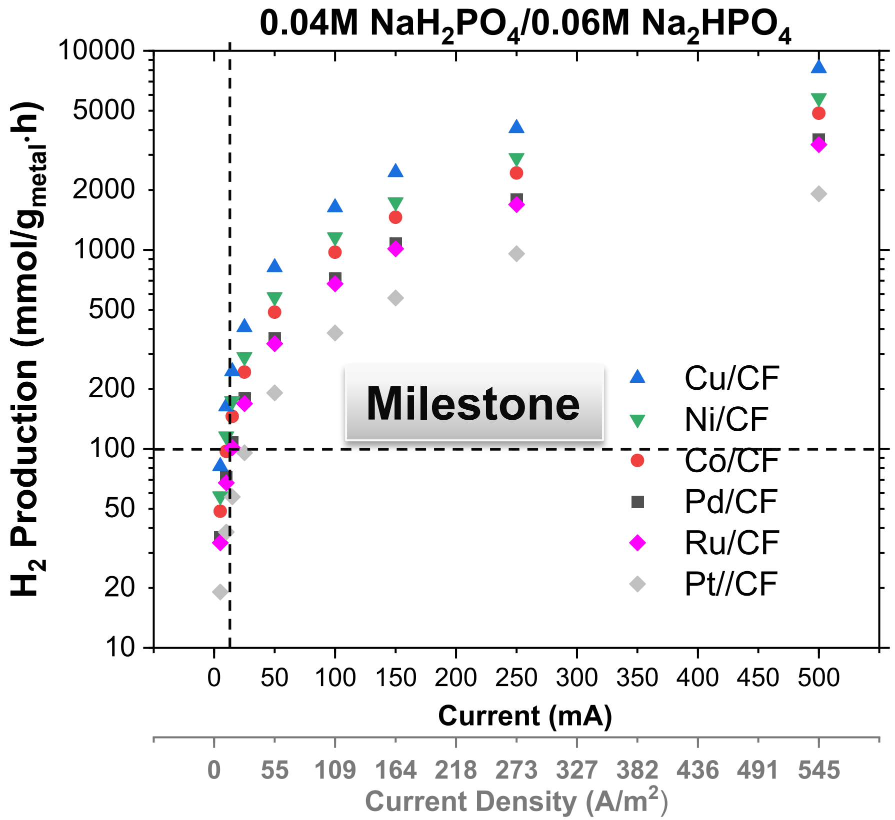
- Another acrylic pilot reactor was assembled and is in operation (~ 80 L)
- Inoculation took 2-3 weeks
- Waiting for more PHW supply

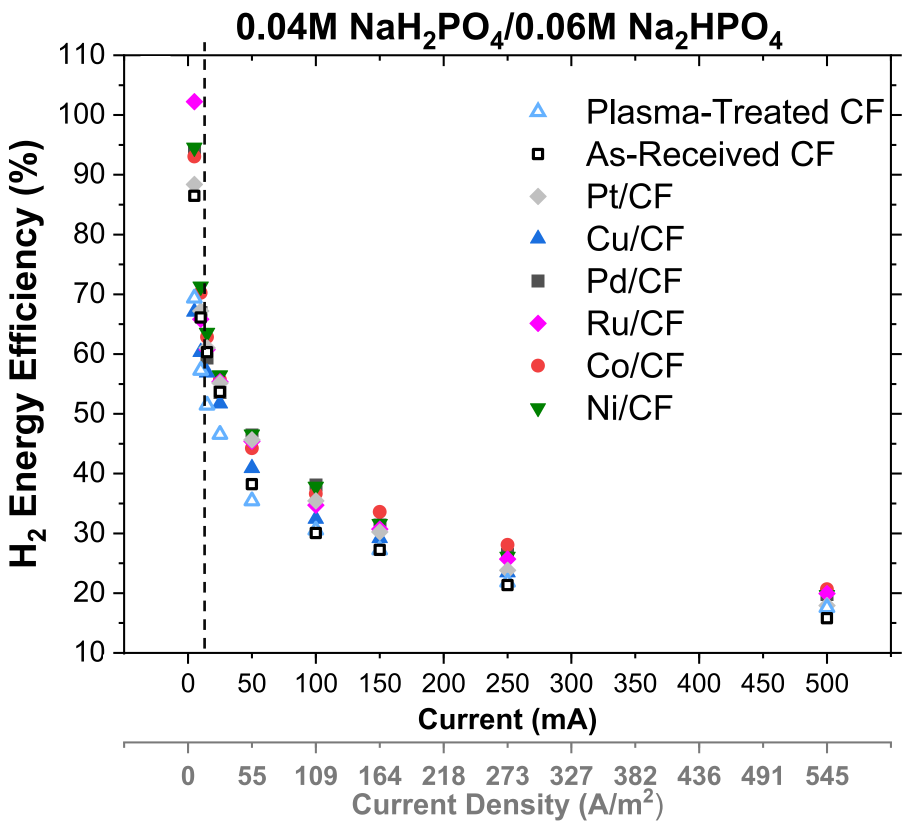


2 – Progress and Outcomes - TEC

The H_2 production performance of base-group metals (BGMs) is better than that of Platinum-group metals (PGMs)

Full-Recycle. Continuous Flow Configuration. Filtered and 5X diluted PHW derived from food waste. COD ≈ 17,000 ppm.



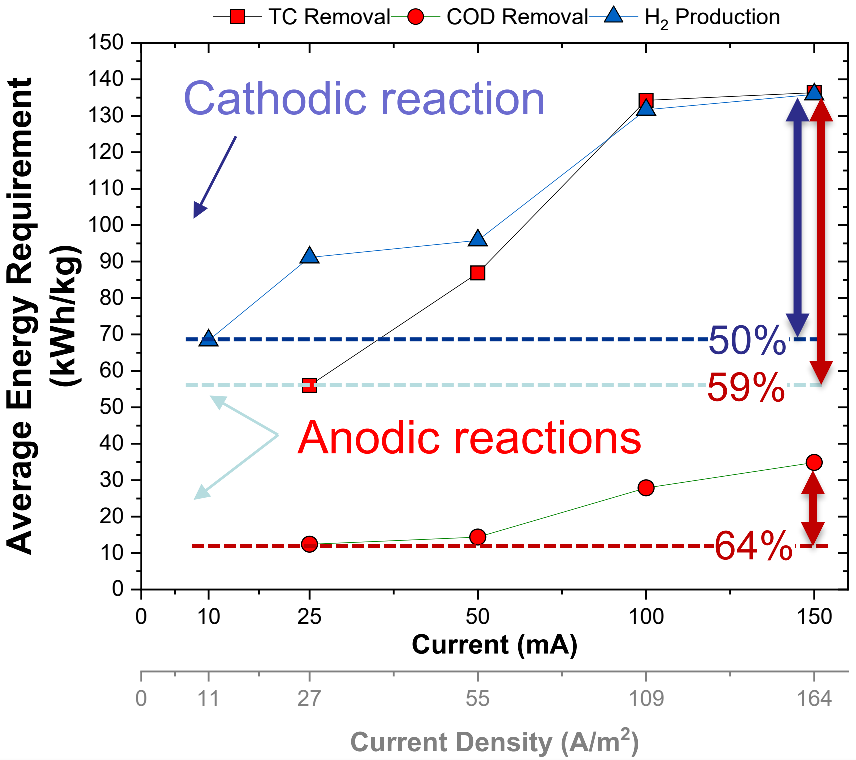


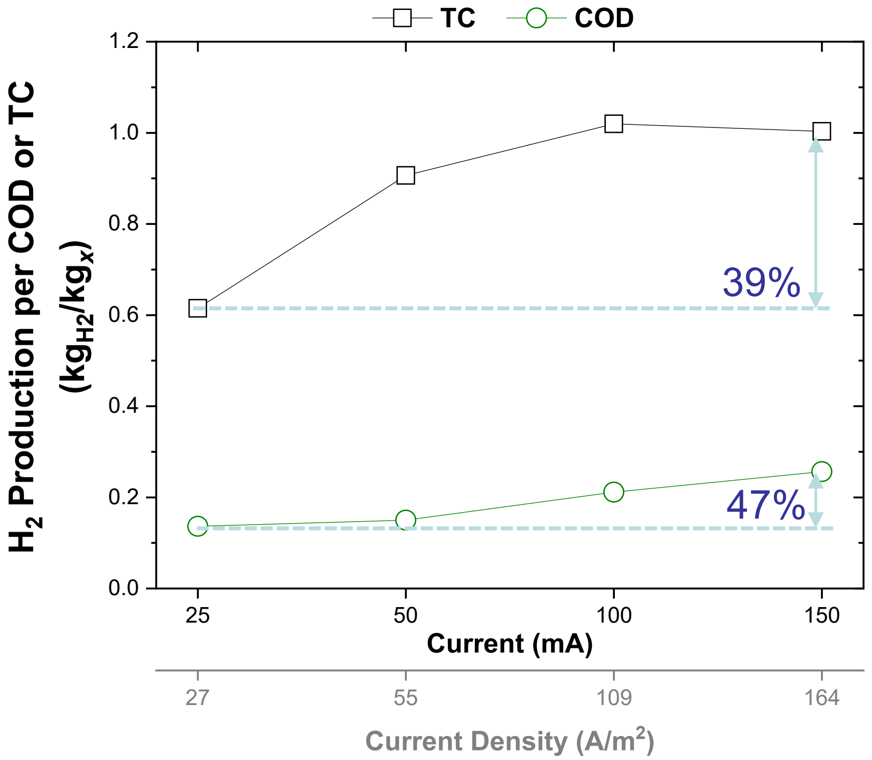
BGM outperforms PGM by 2-5X at a fraction of the metal cost ($0.30/oz Cu, $6.5/oz Ni, and $2,321/oz Pd). Energy Efficiency is ≥100% at low current (densities).

2 – Progress and Outcomes – TEC

The power requirement in TEC for H_2 production and kg of H_2 per kg COD or TC removed decreases with current

Full-Recycle. Continuous-Flow Configuration. Filtered and 5X diluted Food Waste-derived PHW with 0.1 M Na_2HPO_4/ NaH_2PO_4. COD ≈ 17,000 ppm





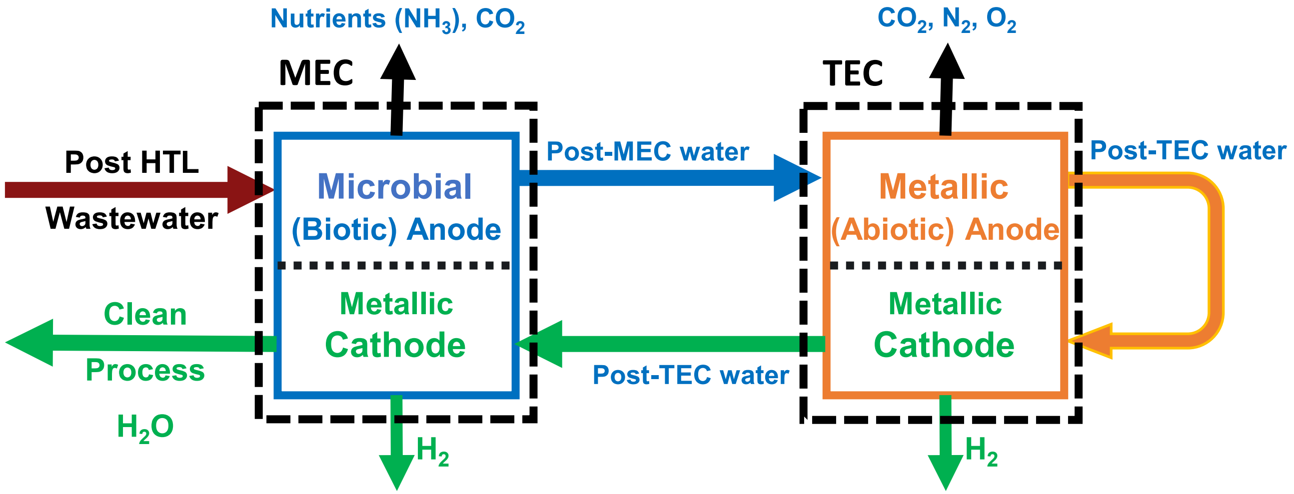
The current TEC electrode composition (and reactor configuration) is limiting the performance. Future experiments will focus on optimizing cathode composition to lower energy requirement for H_2 production.

2 – Progress and Outcomes – TEC/MEC

Sufficient H_2 can be produced with MEC, but yield is tied with PHW COD and bio-crude carbon yield

PNNL-Derived PHW scaled for 5 dry ton/day, 68.2 kg COD/h and 6.71 kg H_2/h needed

System	COD Removal	Energy Cost for H_2 Production	H_2 produced per COD Removed	Energy Efficiency 39.4 kWh/kg H_2	Power Requirement	H_2 Produced For 100% COD Removal	H_2 Produced For 90% COD Removal
	kWh/kg COD	kWh/kg H_2	kg H_2/kg COD	%	**kW**	kg/h	kg/h
H_2O Electrolyzer	-	45 - 54	-	73 - 86	302 – 362	-	-
MEC	2.3	22	0.104	179	148	7.12 (0.41 excess)	6.40 (0.30 deficit)
TEC	12 - 35	68 - 91	0.136	43 – 59	456 - 611	9.30 (2.59 excess)	8.37 (1.66 excess)

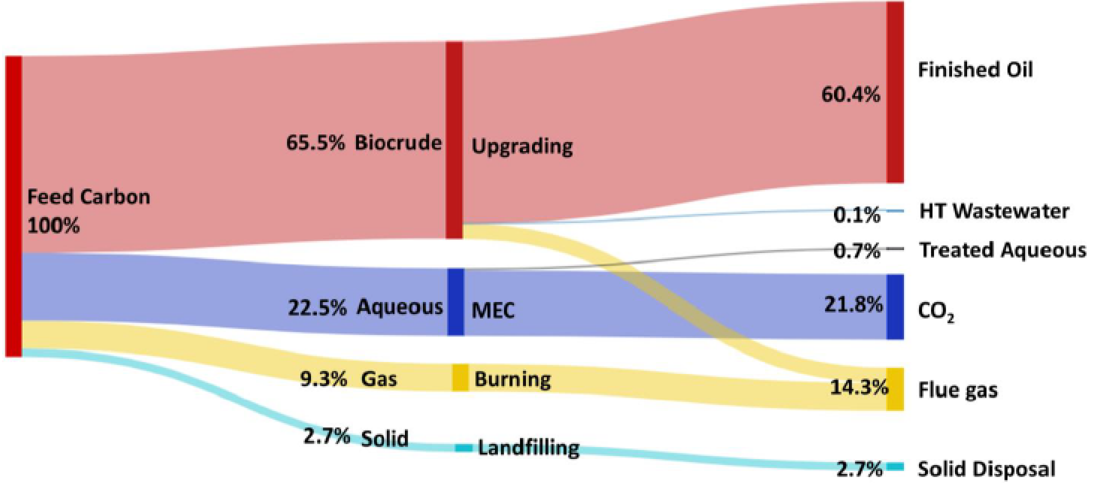


**MEC is >3 times more energy efficient than TEC to generate H_2 from wasted organic carbon in PHW.
MEC and TEC can be integrated to 1) provide a more flexible H_2 supply via water electrolysis and 2) decompose recalcitrant organic molecules (if any).**

2 – Progress and Outcomes – TEA

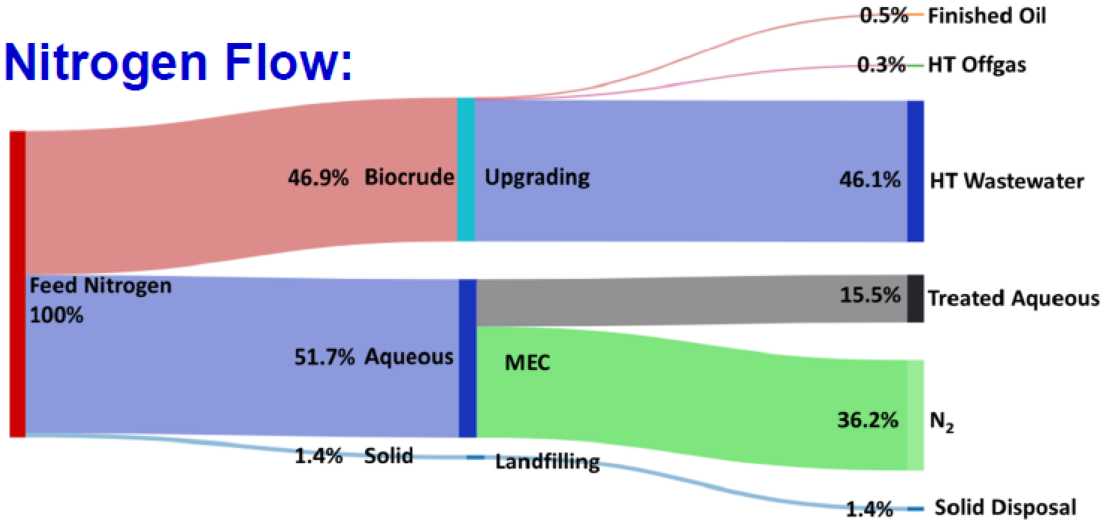
Carbon and Nitrogen Flows of Integrated HTL / MEC System

Carbon Flow:



- HTL can efficiently convert 60% of the feed carbon to finished oil (SAF, diesel, naphtha).
- MEC has the potential to efficiently decrease aqueous COD level by converting organics in aqueous to CO_2 .

Nitrogen Flow:

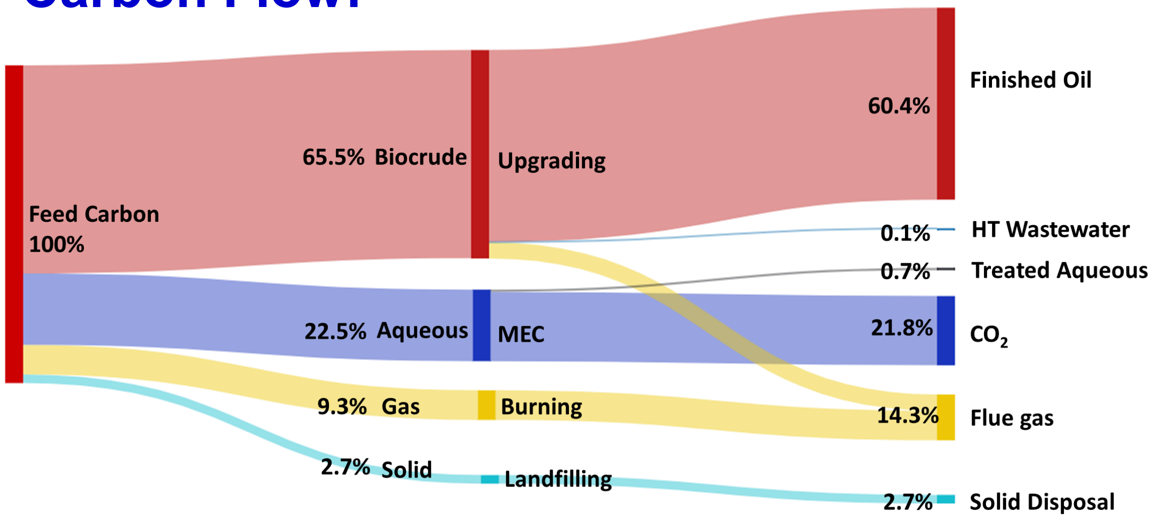


- HTL transfers the majority of N to HTL aqueous (PHW) and biocrude. N in aqueous mainly present in the form of **NH_3** and a small fraction in organic N.
- MEC can convert about **70% N** in aqueous to N_2.

2 – Progress and Outcomes – TEA

Carbon and Nitrogen Flows of Integrated HTL / MEC System

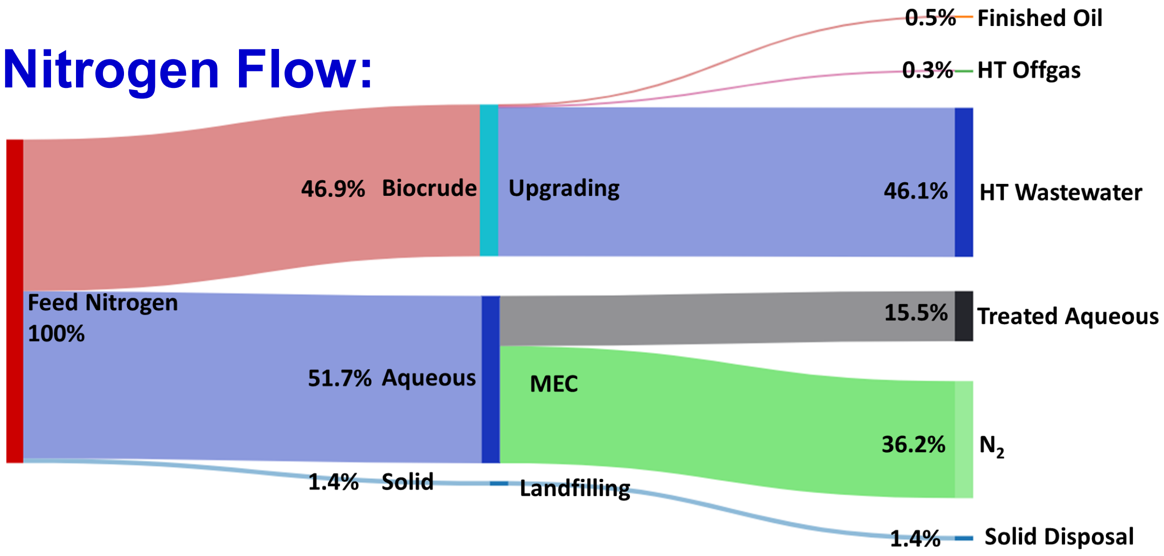
Carbon Flow:



- HTL can efficiently convert *60%* of the *feed C* to *finished oil (SAF, diesel, naphtha)* and *~23%* of the feed C in PHW.
- MEC has the potential to efficiently decrease aqueous COD level by converting organics in aqueous to CO_2 .

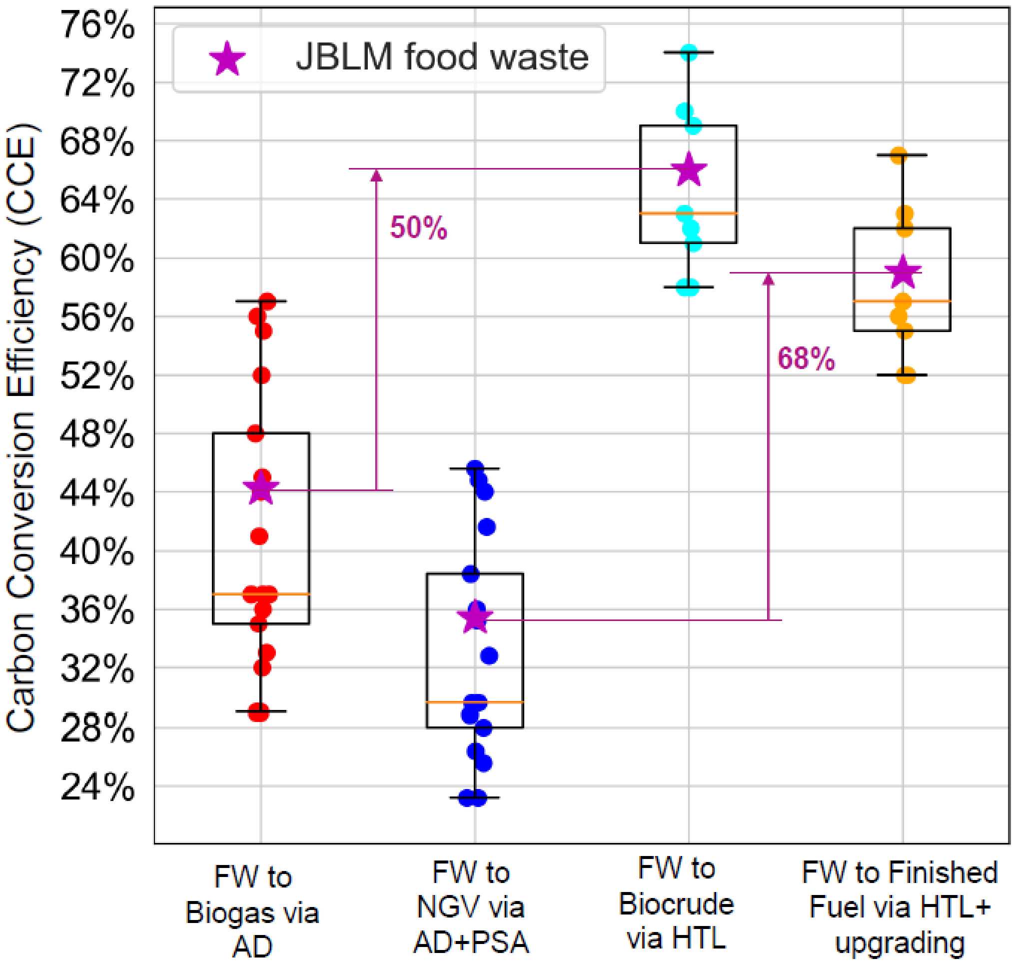
- HTL transfers *~52%* of *feed N* to HTL aqueous (PHW), mainly in the form of *NH_3 (~14% feed N)* and *organic N (~38% feed N),* such as *pyridine-, indole-like aromatics* and *short chain amines*.
- MEC can convert about **70% N** in aqueous to N_2.

Nitrogen Flow:



2 – Progress and Outcomes - TEA

Carbon Conversion Efficiency (CCE) for Integrated HTL vs. Benchmark AD



Food Waste to Natural Gas as Vehicle Fuel (NGV) via AD:

- Food waste to raw biogas CCE is **29%-57%** (average **41%**)
- Food waste to NGV CCE range is **23%-46%** (average **33%**)

Food Waste to Finished Fuel via HTL:

- Data source: 9 food waste or food waste/sludge co-feed PNNL's **bench HTL runs** and **continuous biocrude hydrotreater runs**
- Food waste to biocrude CCE range of **58%-74%** (average **65%**, JBLM to biocrude: **66%**)
- Food waste to finished oil CCE range of **52%-67%** (average of **58%**, JBLM to finished fuel: **59%**)

Carbon Conversion Efficiency (CCE)

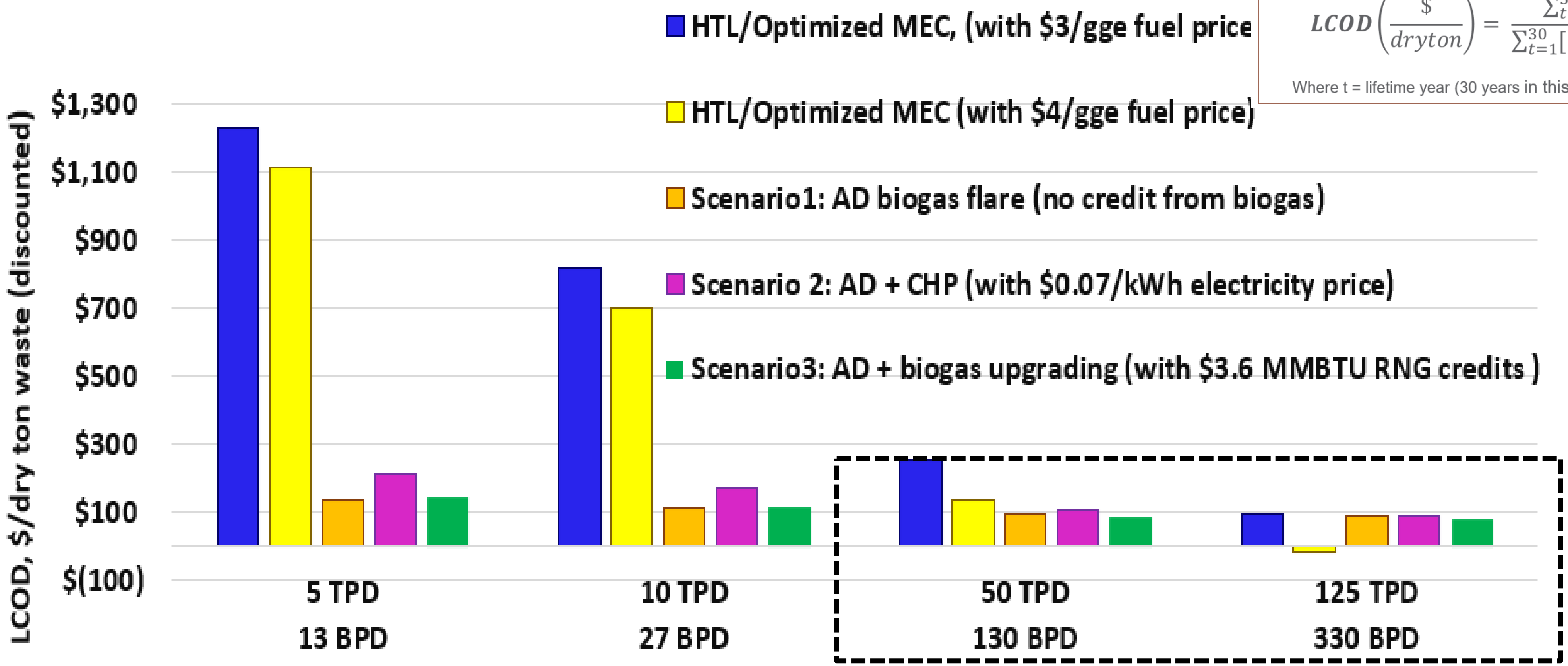
Feedstock	Product	AD	HTL/MEC	Change
Different FW (using the average CCE)	Intermediate (biogas/biocrude)	41%	65%	**+58%**
	Final fuel (NGV/ liquid fuel)	33%	58%	**+76%**
JBLM FW (using theoretical AD correlation)	Intermediate (biogas/biocrude)	44%	66%	**+50%**
	Final fuel (NGV/ liquid fuel)	35%	59%	**+68%**

2 – Progress and Outcomes - TEC

Levelized Cost of Disposal (LCOD) for Integrated HTL/MEC System vs. AD

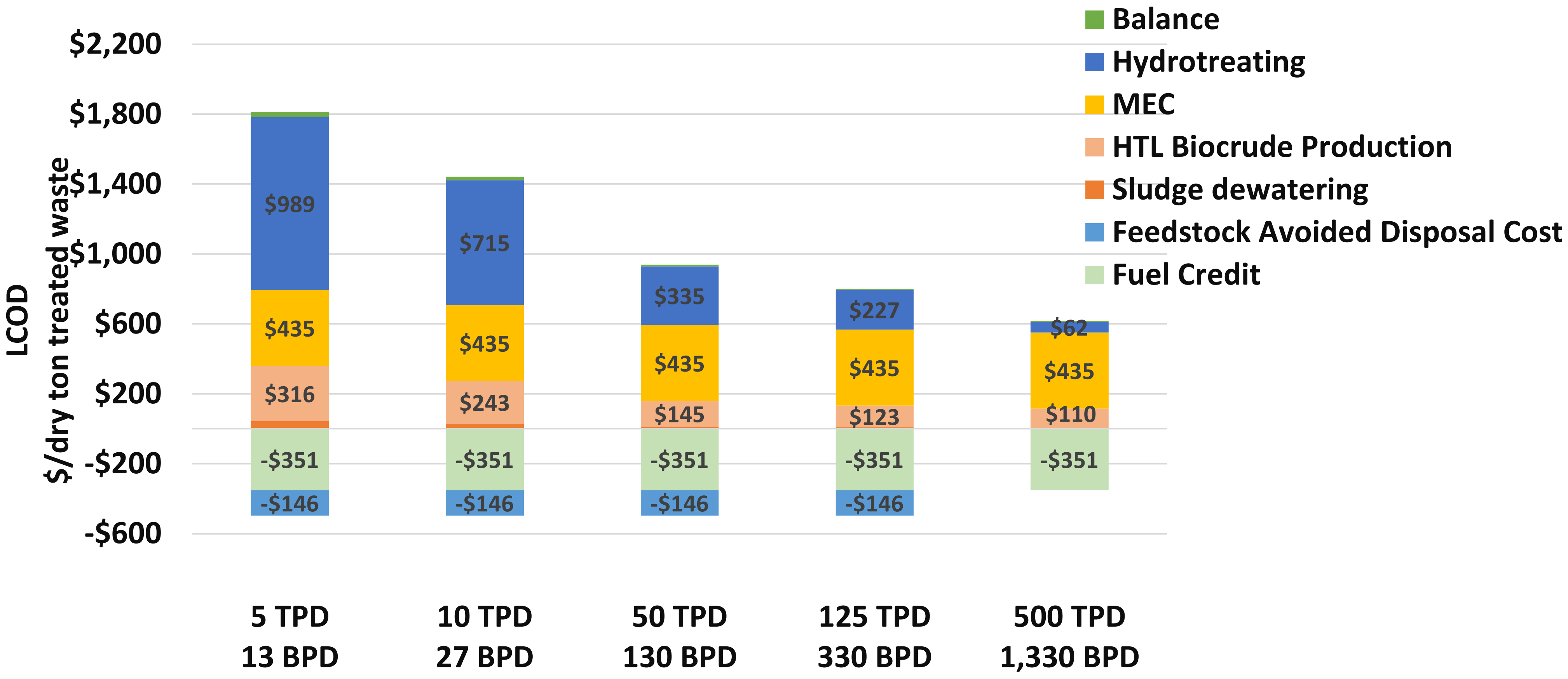
$$LCOD\left(\frac{\$}{dryton}\right) = \frac{\sum_{t=1}^{30}[(annual\ cash\ flow)_t\,/(1+r)^t]}{\sum_{t=1}^{30}[(annual\ waste\ feed\ flow)\,/(1+r)^t]}$$

Where t = lifetime year (30 years in this work) and r = discount rate (10% in this work)



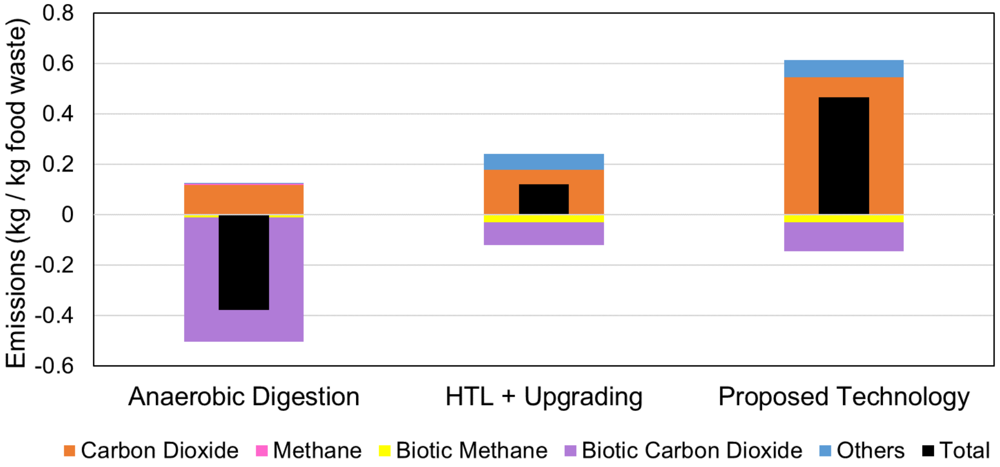
The optimized HTL/MEC system begins to compete with AD (to raw biogas) > 50 TPD scale

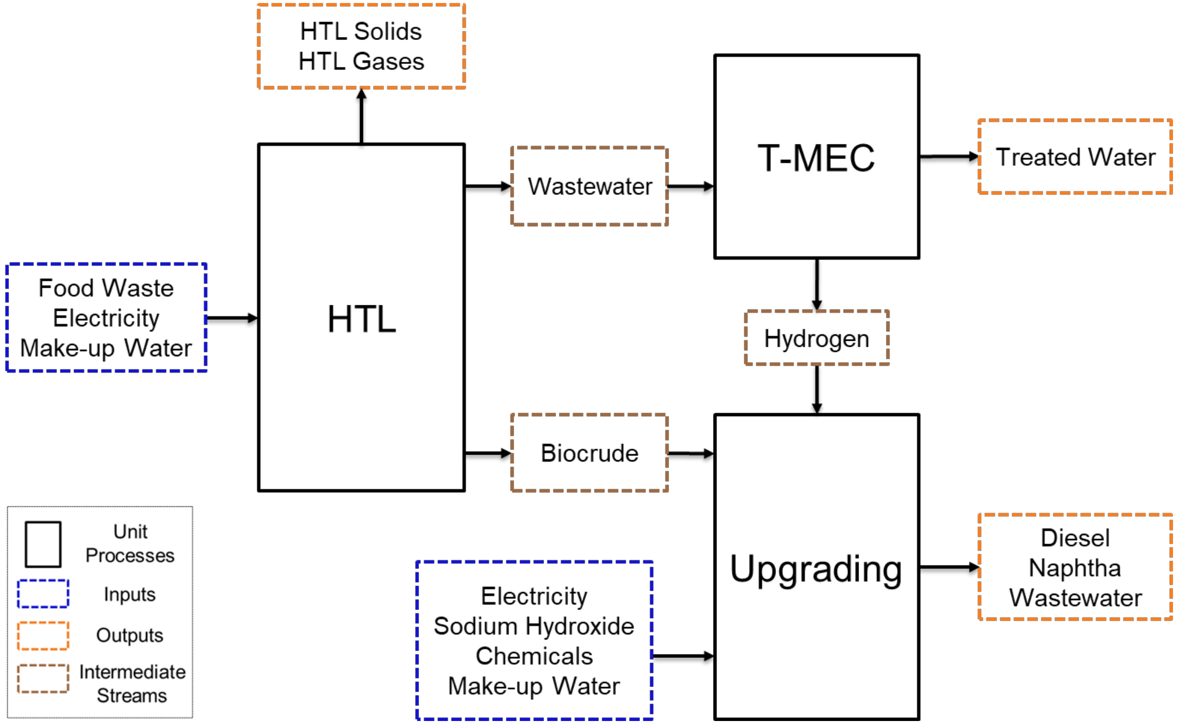
Levelized Cost of Disposal (LCOD) Breakdown for IntegratedHTL/MEC System



2 – Progress and Outcomes - LCA

- LCA models for three systems were developed:
  1. Anaerobic Digestion (AD)
  2. Hydrothermal Liquefaction (HTL) with Upgrading
  3. Hydrothermal Liquefaction, Upgrading, and T-MEC
- TRACI 2.1 quantifies the environmental impact of each system.




HTL Solids
HTL Gases

HTL

Food Waste
Electricity
Make-up Water

Wastewater

T-MEC

Treated Water

Hydrogen

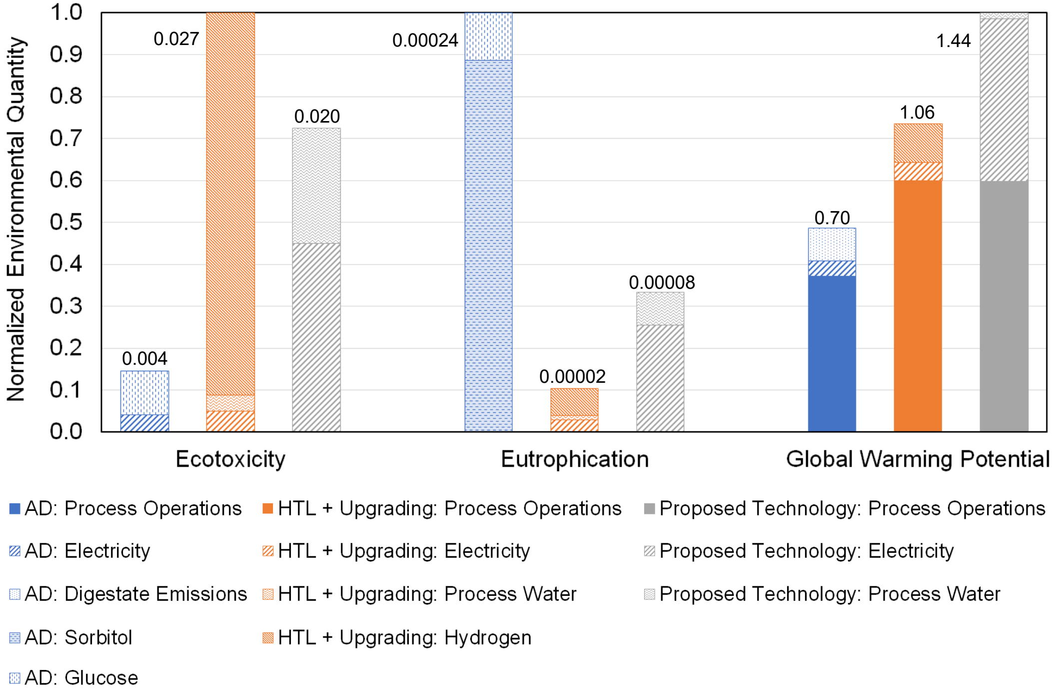
Biocrude

Upgrading

Electricity
Sodium Hydroxide
Chemicals
Make-up Water

Diesel
Naphtha
Wastewater

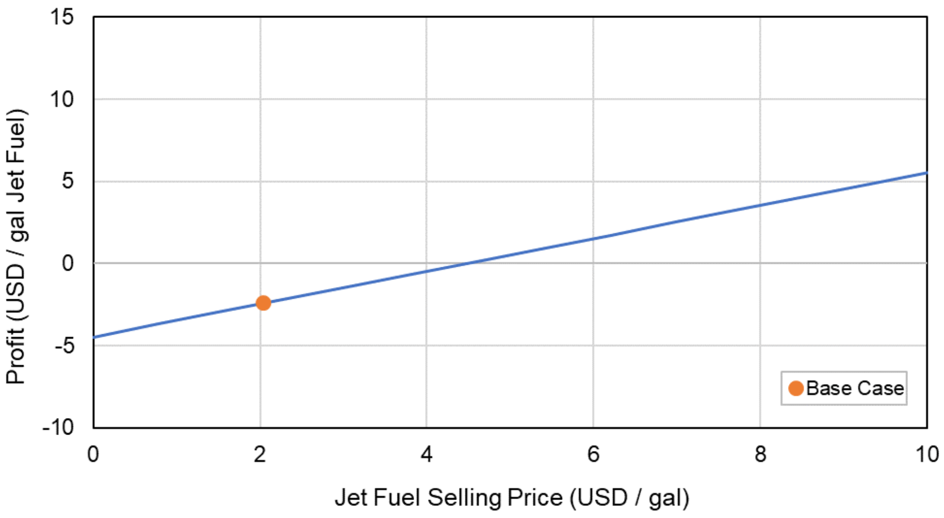
Unit Processes
Inputs
Outputs
Intermediate Streams

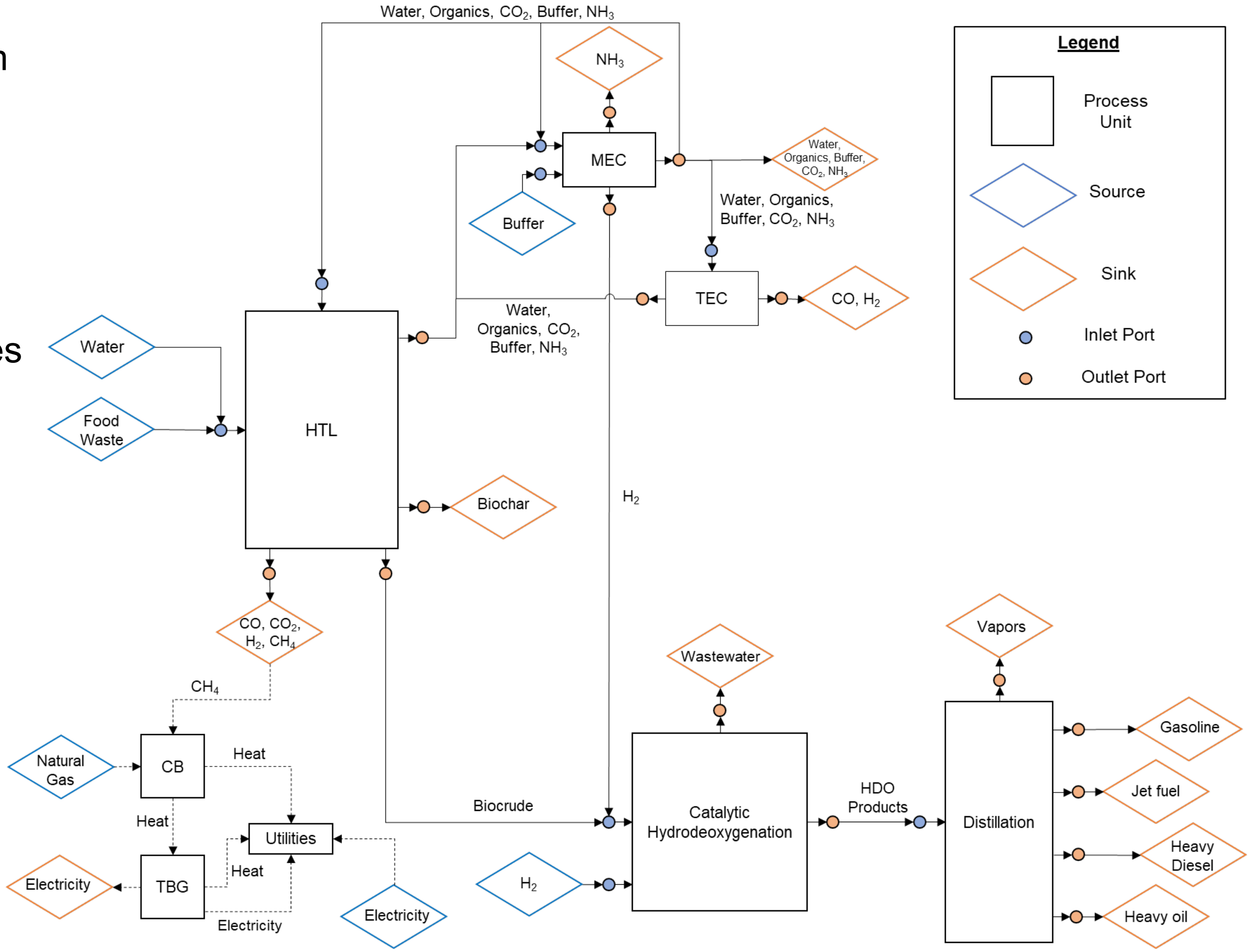


2 – Progress and Outcomes - System Level Analysis

- System level optimization model:
  - High level framework to evaluate distinct system configurations
  - Accounts for material and energy balances
  - Considers different requirements

- System level analysis:
  - Calculate key economic/environmental outcomes
  - Identify operational and economic drivers
  - Perform sensitivity analyses





3 – Impact

- The carbon conversion efficiency (CCE) of food waste to HTL biocrude is ~50% higher than the CCE of food waste to biogas via AD.
- The CCE of integrated HTL and upgrading to produce finished fuel is ~68% higher than AD and gas cleaning to produce natural gas for vehicle fuel.
- The MEC can provide the required hydrogen for biocrude upgrading with a COD removal efficiency >90%.
- The integrated HTL/MEC process with optimization is cost-competitive with AD above about 50 TPD scale.
- When demonstrated successful, this project will provide an integrated approach to advance DOE’s goal of scaling up new technologies to produce sustainable aviation fuels (SAF).

Summary

- We have successfully met the milestones of the project, passed the intermediate review, and now we focus on system analysis, pilot system development and integration.
- Pilot HTL systems were built and operated, converted two types of food wastes to biocrude. Hydrotreating is underway to produce jet fuel.
- Both MEC and TEC can produce H_2 from the PHW and meet H_2 demand for bio-crude upgrading.
- The integrated HTL/MEC process with optimization can be cost-competitive with AD above about 50 TPD scale.

Quad Chart Overview

Timeline

- *Oct. 1, 2020 (contract signed April, 2021)*
- *Sept. 30, 2024*

	FY22 Costed	Total Award
DOE Funding	*637,372 (PU+UIUC)* *433,567 (PNNL)*	*2,499,732*
Project Cost Share *	624,933	

TRL at Project Start: 2-3
TRL at Project End: 4-5

Project Goal

Integrated food waste to biofuel pathway with synergistic aqueous waste valorization.

End of Project Milestone

Aim to improve carbon conversion efficiency by > 50% or reduce disposal costs of the food waste by > 25%.

Funding Mechanism

FOA- DE-EE0009269

Project Partners*

- UIUC
- PNNL

*Only fill out if applicable.

Publications, Patents, Presentations, Awards, and Commercialization

1. Summers, Sabrina, Amanda Valentine, Zixin Wang, Yuanhui Zhang. 2023. Pilot-Scale Continuous Plug-Flow Hydrothermal Liquefaction of Food Waste for Biocrude Production. Fuel: Under review.
2. Summers, Sabrina, Siyu Yang, Jamison Watson, Yuanhui Zhang. 2022. Diesel blends produced via emulsification of hydrothermal liquefaction biocrude from food waste. Fuel: https://doi.org/10.1016/j.fuel.2022.124817
3. Zhang, Y. 2022. Toward a Circular Bioeconomy: Environment-Enhancing Food, Energy, and Water Systems (EE-FEWS). Resource Magazine 29 (3):11-15.
4. Jiang, J., et al., Scale-Up and Techno-Economic Analysis of Microbial Electrolysis Cells for Hydrogen Production from Wastewater, Water Research, in review

Publications, Patents, Presentations, Awards, and Commercialization

1. Summers, Sabrina. 2023. Pilot-scale hydrothermal liquefaction of wet biowaste. American Chemical Society. Energy and Fuels Division, Presidential Symposium: Biorefinery at the Crossroads, Sci-Mix
2. Jiang, J., et al., Molecular Transformation and Metabolic Insights during MEC treatment of post-hydrothermal liquefaction wastewater (PHW), 2022 AEESP Conference
3. Oral presentation at Organic Reactions Catalysis Society. Developing Electrocatalytic Processes for the Conversion of Biomass-Derived Molecules into Fuels and Chemicals at Normal Temperature and Pressure, PNNL
4. Presentation. Organic Reactions Catalysis Society Meeting. Jacksonville, FL. October 2022. “Developing Electrocatalytic Processes for the Conversion of Biomass-Derived Molecules into Fuels and Chemicals at Normal Temperature and Pressure”
5. Presentation*. 241st Electrochemical Society Meeting. May 2022.“Electrocatalytic Oxidation of Biomass-Derived Carboxylic Acids into Fuels and Chemicals”
6. Presentation*. TC Biomass 2022, April 2022. “Renewable Fuel Production via Electrocatalytic Co-processing of Biomass-Derived Aqueous Waste and Bio-oils at Normal Temperature and Pressure”
7. Winner of National Lab Accelerator Pitch Event. Palo Alto, CA. November 2022 with the pitched titled, “Cleaning Wastewater for Energy Production and a Sustainable Future.”
8. Seminar at Iowa State University titled “Developing electrocatalytic processes for the conversion of biomass-derived feedstocks into renewable fuels and chemicals”
9. “Electrocatalytic bio-oil and wastewater treatment” with IPID 31994-E has been licensed to CogniTek Management Systems, Inc. (“CogniTek”)

Publications, Patents, Presentations, Awards, and Commercialization

- Joint invention disclosure with Princeton University titled “Integrated microbial and electrocatalytic process to generate H2 from wastewater at 100% energy efficiency (iEdison No. 0685901-22-0216)”

1. Lopez-Ruiz won an award for Basic Energy Sciences – Reaching a New Energy Sciences Workforce (BES-RENEW) Program to increase participation of underrepresented groups in clean energy research. The topic is “Controlling reaction pathways under the non-ideal conditions of seawater electrolysis”
2. Lopez-Ruiz won the “National Lab Accelerator Pitch Event - November 16 in Palo Alto, CA” with the pitched titled, “Cleaning Wastewater for Energy Production and a Sustainable Future.”
3. Lopez-Ruiz was nominated for “2022 EP&M Innovation in Research Team” and “2022 EP&M Operational Excellence” awards
4. Jerry Jiang won the best poster award in the 2022 AEESP Conference.

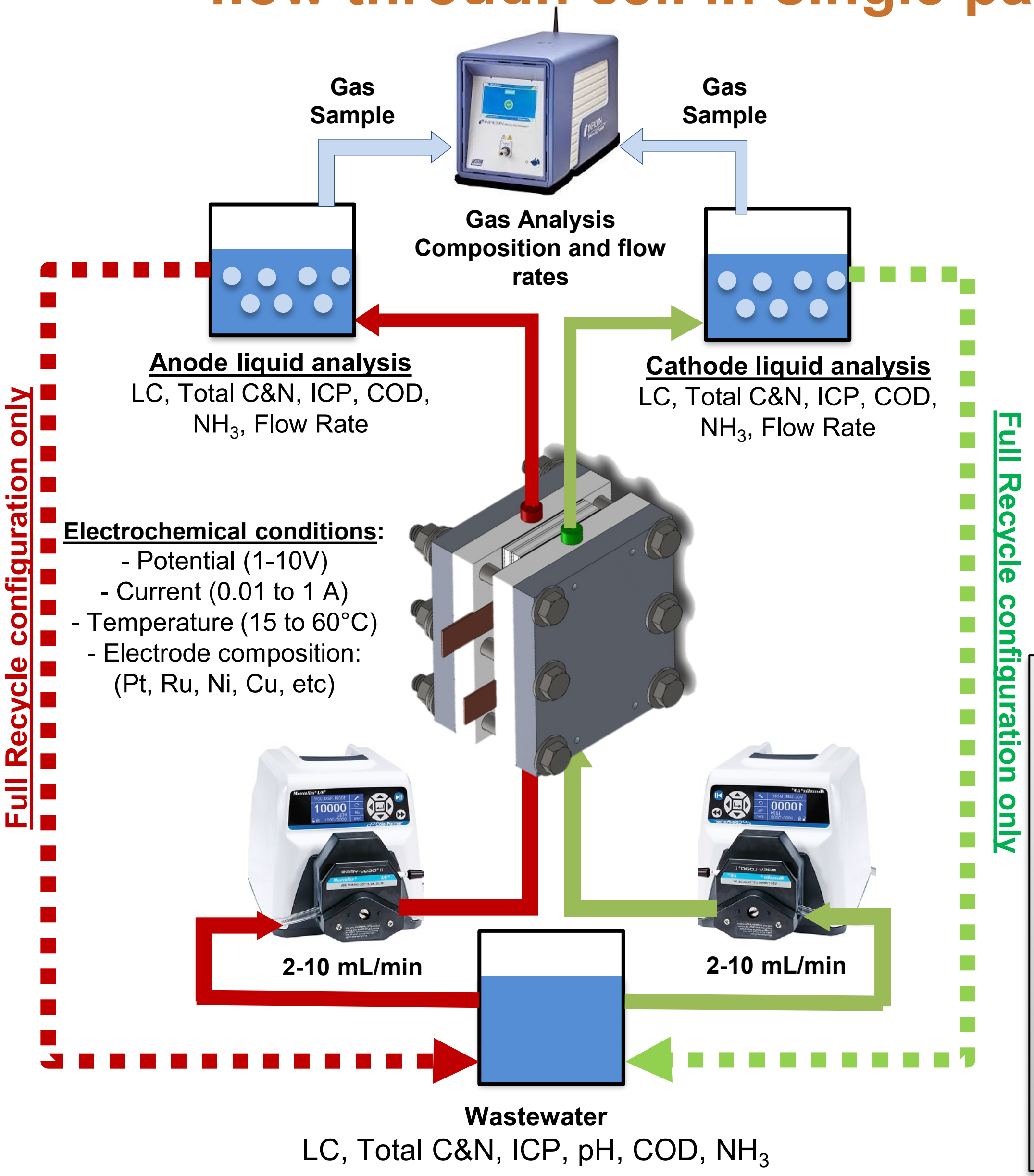
Additional Slides

(Not a template slide – for information purposes only)

- *The following slides are to be included in your submission for evaluation purposes, but will* ***not*** *be part of your oral presentation –*
- *You may refer to them during the Q&A period if they are helpful to you in explaining certain points.*

2 – Progress and Outcomes

We evaluate the performance of different electrocatalysts in a continuous-flow through cell in single pass and full recycle configuration



Gas Sample

Gas Sample

Gas Analysis Composition and flow rates

Anode liquid analysis
LC, Total C&N, ICP, COD, NH_3, Flow Rate

Cathode liquid analysis
LC, Total C&N, ICP, COD, NH_3, Flow Rate

Electrochemical conditions:
- Potential (1-10V)
- Current (0.01 to 1 A)
- Temperature (15 to 60°C)
- Electrode composition: (Pt, Ru, Ni, Cu, etc)

Full Recycle configuration only

Full Recycle configuration only

2-10 mL/min

2-10 mL/min

Wastewater
LC, Total C&N, ICP, pH, COD, NH_3

Anode reactions:

Oxygen evolution: $H_2O \rightarrow {}^1/_2\,O_2 \boxed{+ 2H^+ + 2e^-}$

Organic oxidation: $2C_xH_yO_z \rightarrow C_{2(x-1)}H_{2(y-2)}O_{2(z-2)} + CO_2 \boxed{+ 2H^+ + 2e^-}$
(via decarboxylation)
$e.g., 2C_2H_4O_2 \rightarrow C_2H_6 + 2CO_2 + 2H^+ + 2e^-$

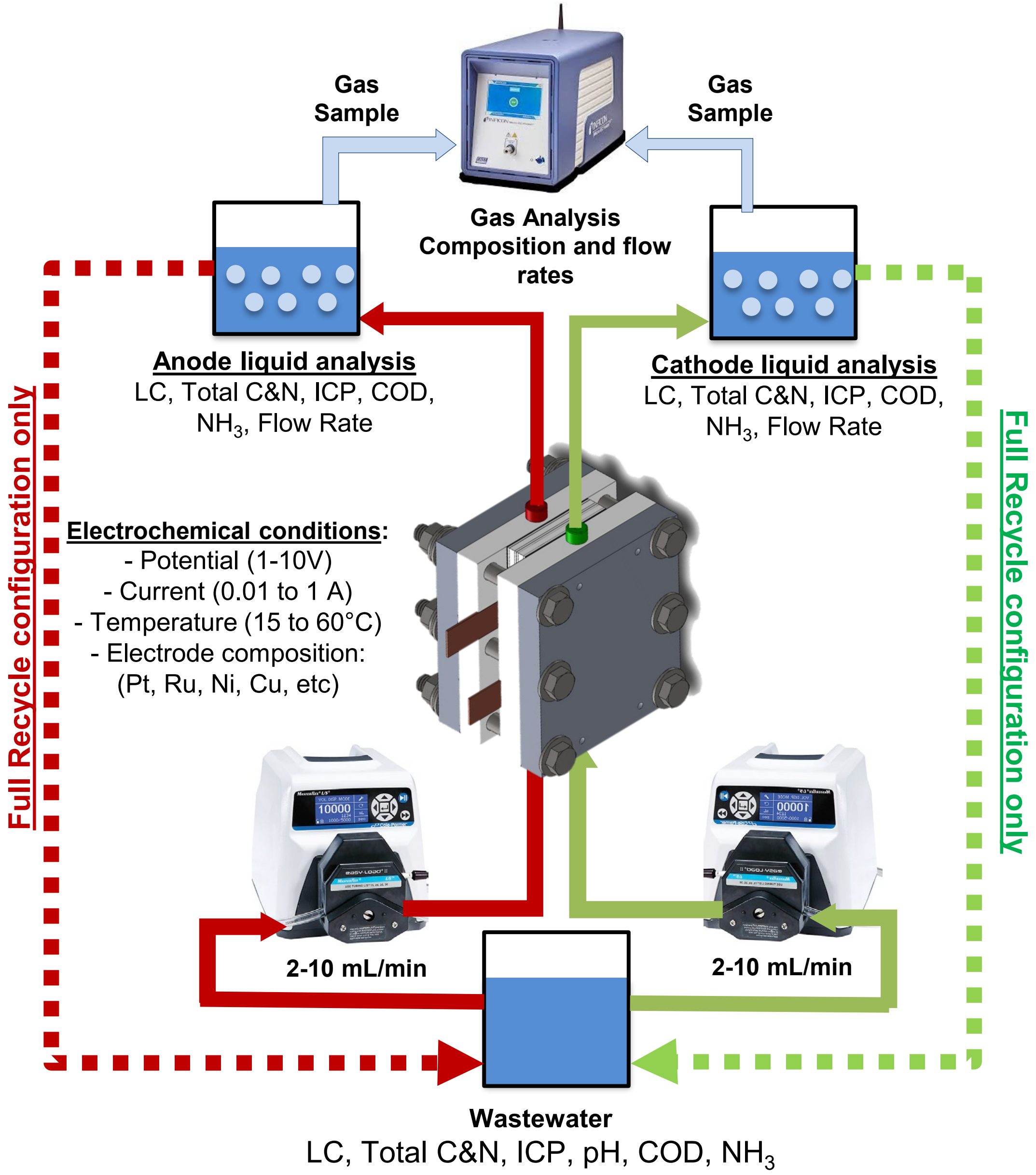
Ammonia oxidation: $2NH_3 \rightarrow N_2 \boxed{+ 6H^+ + 6e^-}$

Cathode reaction:

H_2 evolution (HER): $\boxed{2H^+ + 2e^-} \rightarrow H_2$

The TEC can produce H_2 from organics as well as water; hence, it can be used to close the gap between H_2 gen from organic molecules and H_2 needed in upgrading.

We evaluate the performance of different electrocatalysts in a continuous-flow through cell in single pass and full recycle configuration



Gas Sample

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Electrochemical conditions:
- Potential (1-10V)
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- Electrode composition: (Pt, Ru, Ni, Cu, etc)

2-10 mL/min

2-10 mL/min

Wastewater
LC, Total C&N, ICP, pH, COD, NH_3

- **We evaluate the electrocatalytic cell performance as a function of electrochemical conditions:**
  - **Metals**
  - **Morphology/ particle size**
  - **Electrolyte compositions (pH, species)**
  - **Electrochemical reaction conditions (A, V)**

$$\boldsymbol{H_2\ Production\ Rates}\left(\frac{kWh \cdot g_{metal}}{kgH_2}\right) = \frac{V \cdot i_T}{kgH_2/(g_{metal} \cdot h)}$$

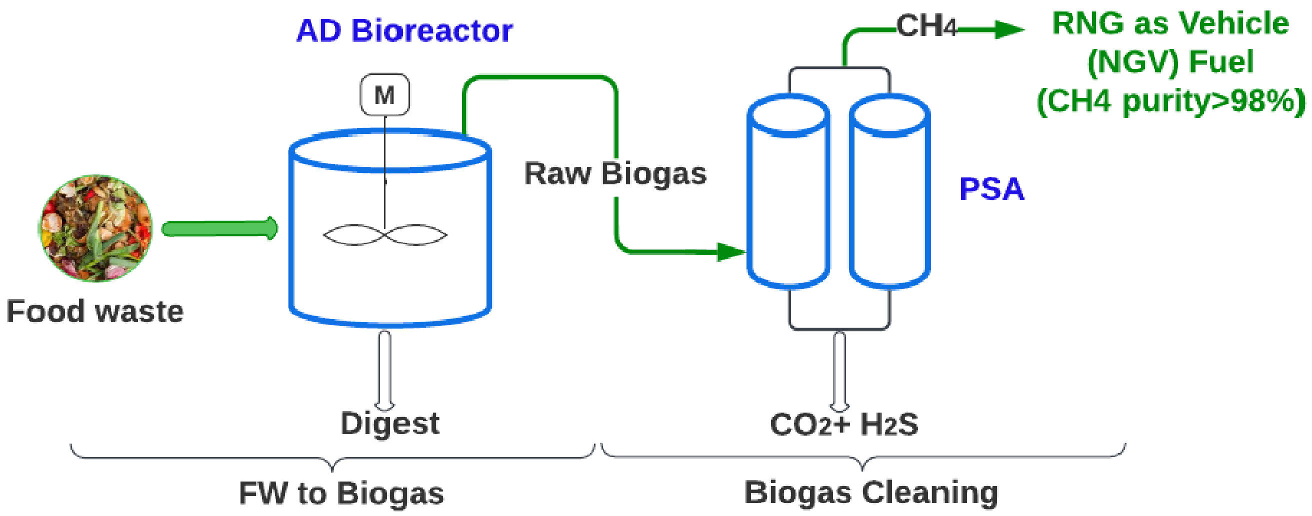
$$\boldsymbol{Energy\ Efficiency}\ (FE,\%) = \frac{H_2\ High\ Heating\ Value}{V \cdot i_T \cdot h} \times 100$$

V: Full cell voltage; i_T: total cell current; h: operation time

We will compare H_2 production rates and energy efficiencies to that of competitive technologies

2 – Progress and Outcomes

Results: Carbon Conversion Estimation for Benchmark Anaerobic Digestion System



- Food waste to biogas process data is collected from literature
- Food wastes are collected from **university canteens/cafeteria** or **local community**; **batch or semi-continuous** mesophilic AD process
- Methane recovery rate of **80%** is assumed for purifying raw biogas to NGV based on literature
- The theoretical carbon efficiency of JBLM to biogas is **52%** using the Buswell equation[1]

	Carbon Conversion Efficiency	**Assumption**
JBLM food waste to Biogas	**44%**	**85% theoretical biomethane yield** [1]
JBLM food waste to RNGV	**35%**	**80% methane recovery rate in gas cleaning** [2]

(1) Browne, et al. Applied Energy (2013).
(2) Byun, et al. Energy (2021).

Baseline AD LCOD Assumptions

Economic Assumptions for LCOD calculation

Variables	Values	Ref
Discounted rate	10%	User defined
Loan interest rate	5%	User defined
Tax rate	21%	User defined
Capital cost financed percent	90%	User defined
Project lifetime, year	30	User defined
Electricity Price, $/kWh	0.07	EIA historic data (4)
biogas yield, m3/metric ton	200	EPA AD model (5)
calorific value of biogas, kWh/m3	6.5	EPA AD model (5)
CHP efficiency	35%	EPA AD model (5)
surplus electricity for sell	80%	Ullah (2017) (6)
CAPEX	$CAPEX = 5.5519(Capacity)0.4642$ (1) $CAPEX = 0.01(capacity)^{0.6}$ (2)	
OPEX	$OPEX = 0.094\ Capacity$ (1) $OPEX = 0.0015(capacity)^{0.6}$ (2)	

Ref:
(1) Khan, et al. Waste Management 48: 548–64.
(2) Murphy, et al. Renewable Energy 29(7): 1043–57.
(3) all price in 2019 dollars.
(4) https://www.eia.gov/electricity/annual/
(5) https://www.epa.gov/anaerobic-digestion/anaerobic-digestion-tools-and-resources
(6) Ullah. Master Thesis. University of Alberta.

Responses to Previous Reviewers' Comments

- If your project has been peer reviewed previously, address 1-3 significant questions/criticisms from the previous reviewers' comments which you have since addressed
- Also provide highlights from any Go/No-Go Reviews

Note: This slide is for the use of the Peer Reviewers only – it is not to be presented as part of your oral presentation. These Additional Slides will be included in the copy of your presentation that will be made available to the Reviewers.