DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

Maximizing Bio-Renewable Energy from Wet Wastes (M-BREWW)

WBS: 5.1.3.201
Organic Waste Review Panel

February 2021

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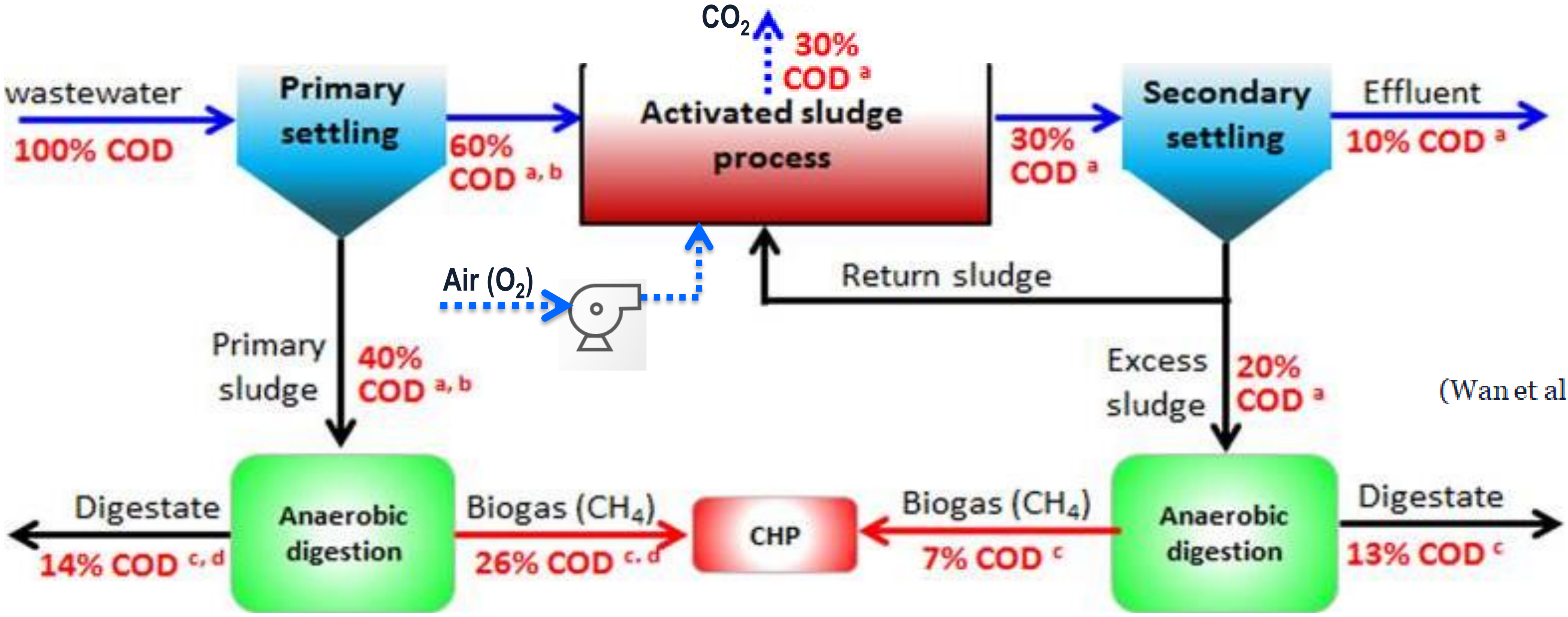
Project Overview & Background- *Current Wastewater (WW) Plants*

Conventional Activated Sludge (CAS) with Sidestream Anaerobic Digestion (AD) and Combined Heat/ Power (CHP) recovers <33% of WW organic energy content and has a poor net energy balance

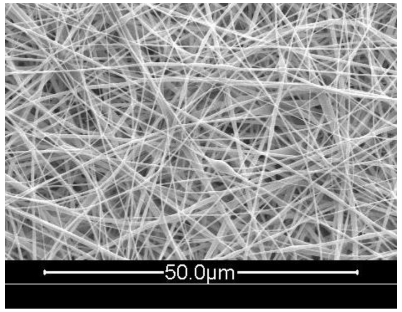


(Wan et al., 2016)

- Large aeration energy input to convert ~30% of WW organics (a.k.a, COD) to CO_2
- Typical AD requires heating and only converts ~30-60% of influent COD to biogas

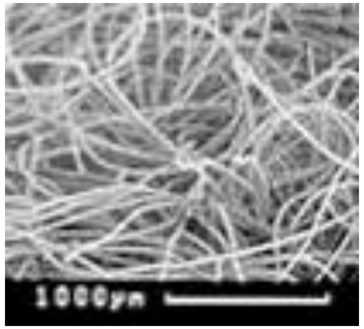
Anaerobic Membrane Bioreactors (AnMBR) increase WW net energy yield

- Key Advantages of AnMBRs
  - Avoids significant energy input for aeration in CAS
  - Avoids energy loss for conversion of organics to CO_2
  - Higher effluent water quality via membrane filtration
  - Can operate at w/o heating to enables mainstream treatment

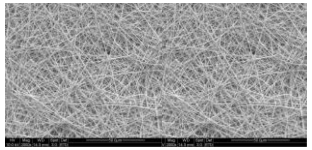


Microfiltration (MF) membrane ~2000x magnification

Cloth filter ~100x magnification



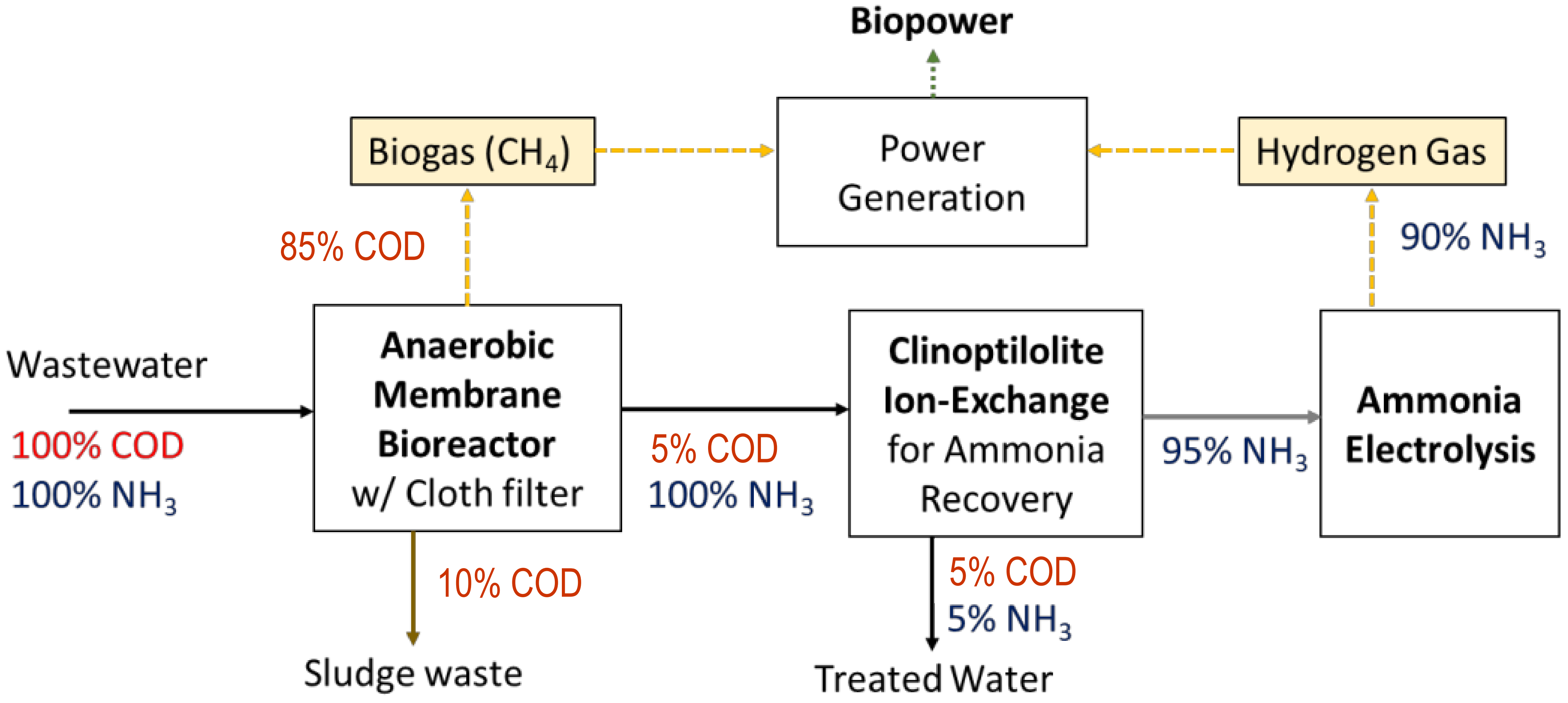
- Key Disadvantages of Previous AnMBRs and Mitigation Methods
  - Requires significant energy input for membrane fouling control
    - Replace MF membrane (<0.5 μm pores) with cloth filter (2-10 μm pores)
    - Include coagulants or adsorbents in AnMBR to improve cloth filter organics removal
  - Need post-treatment to remove ammonia (NH_3) from AnMBR effluent
    - Ammonia ion exchange and electrolysis to produce H_2 gas
  - Dissolved methane is an issue, especially at lower temperatures



Microfiltration ~100x magnification

Proposed D-LEWT System *(Distributed Low-Energy WW Treatment)*

Pilot-scale (3 gpm) integration at WW plant site incorporating an anaerobic membrane bioreactor (AnMBR), ion exchange NH_3 capture, and NH_3 electrolysis to maximize WW energy recovery.



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1. Management- *Project Team and Roles*

Prime Contractor: University of Illinois

Key Personnel:
- Dr. Lance Schideman (P.I.)
- Dr. Nandakishore Rajagopalan

Responsibilities
- Project Management
- Install/Optimize AnMBR
- Improve Ion Exchange efficiency
- Integration of NH_3 Electrolysis into field pilot
- Improve energy efficiency of integrated system

Industrial Advisory Board

Wastewater Industry Stakeholder Organizations:
- Urbana-Champaign Sanitary District
- US Army Corps of Engineer

Responsibilities
- Host site for testing with real WW influent
- Advise on current industry drivers
- Review and comment on project results

Aqua-Aerobic System, Inc
- Mark Hughes, P.E.

Responsibilities
- Provide and Install Pilot Scale Cloth Filter
- Advise on Optimizing Cloth Filter Performance

Texas Tech University
- Dr. Gerardine Botte

Responsibilities
- Improve NH_3 Electrolysis in Lab
- Upscale NH_3 Electrolysis to Pilot (w/Ambreon, llc)

Colorado State University
- Dr. Jason Quinn

Responsibilities
- Interim and Final Techno-Economic & Life-Cycle Analysis

MainStream Eng. Corp.
- Michael Cutbirth

Responsibilities
- Characterize & optimize engine generator for H_2 enhanced biogas

1. Management – *Key Project Communication Links*

Monthly conference calls with all the project collaborators

Quarterly submission of project report

Individual communication with each technology working group to go over specific issues

Bimonthly conference call with DOE managers

All project files uploaded to a cloud-based file share on box.com for storage and later use by the project team

1. Management- *Key Risks and Mitigation Strategies*

Technical Risk	Mitigation Strategies	Likelihood	Impact
Cloth filter AnMBR fouling higher than expected. Effluent water quality below discharge standards.	• Use biofilm support media to reduce the suspended solids sent to the cloth-filter • Increase backwash frequency • Add coagulants or adsorbents to AnMBR • Add other post-treatment processes	🟨	🟨
Clinoptilolite Ion-Exchange system ammonia recovery from AnMBR effluents <95%	• Increase number of adsorption columns • Increase NaOH/NaCl concentration for more complete adsorbent regeneration	🟩	🟩
Low hydrogen gas (H_2) conversion efficiency of ammonia electrolysis cells	• Increase the pH of the ammonia brine • Increase ammonia concentration in brine • Periodically regenerate electrodes	🟩	🟩
Demonstrate the combined combustion of biogas and H_2 for biopower production	• Use biogas tolerant engine generator • Pre-treatment of biogas if needed	🟩	🟨

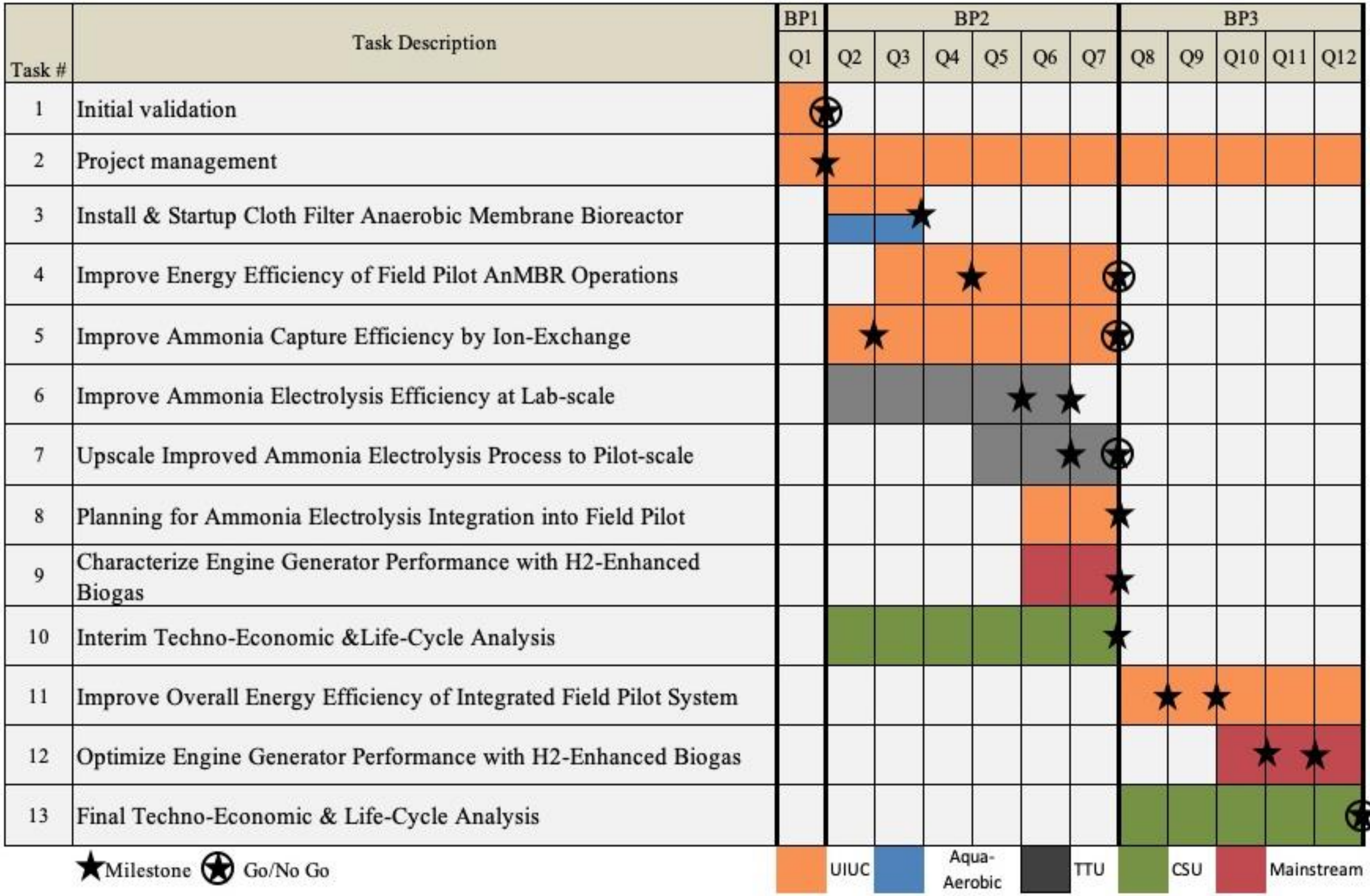
🟩 Low 🟨 Medium 🟥 High

2. Approach- *Project Objectives*

- **Development and integrated pilot demonstration of the D-LEWT WW system combining:**
  - **Cloth-filter anaerobic membrane bioreactor (AnMBR)**
    - Increase flux of the AnMBR by >10x compared to current micro-/ultra-filtration membranes
    - Reduce the energy requirements for AnMBR fouling control from 0.4 kWh/m3 to below 0.1 kWh/m3
    - Include coagulants and/or adsorbents to increase cloth filter effluent water quality
  - **Ammonia ion-exchange (I-X)**
    - Evaluate new adsorbents for improved efficiency over baseline clinoptilolite I-X media
  - **Ammonia electrolysis**
    - Improve hydrogen gas purity from 75% to greater than 93% v/v
    - Improve ammonia electrolysis cell reactor design for scale-up from 300 cm^2 to 3,000 cm^2 (10x)
  - **Combined Heat and Power**
    - Engine generator optimization to use both CH_4 and H_2 bio-derived fuels
    - Confirm engine tolerance for common biogas contaminants (H_2S)
- **Techno-economic & Life-cycle analysis to quantify cost & environmental impacts**

2. Approach- *Project Schedule*

- **BP2- Lab-Scale Development**
  - NH_3 I-X (UIUC)
  - NH_3 Electrlys. (TTU)
- **BP2- Pilot Demo at Separate Sites**
  - AnMBR (UIUC)
  - Biogas tolerant engine (Mainstream)
- **BP 3- Integrated Field Pilot**
  - AnMBR + NH_3 I-X + NH_3 Electrolysis
- **BP2&3- System Analysis Feedback**
  - TEA and LCA (CSU)
  - Industrial Advisors



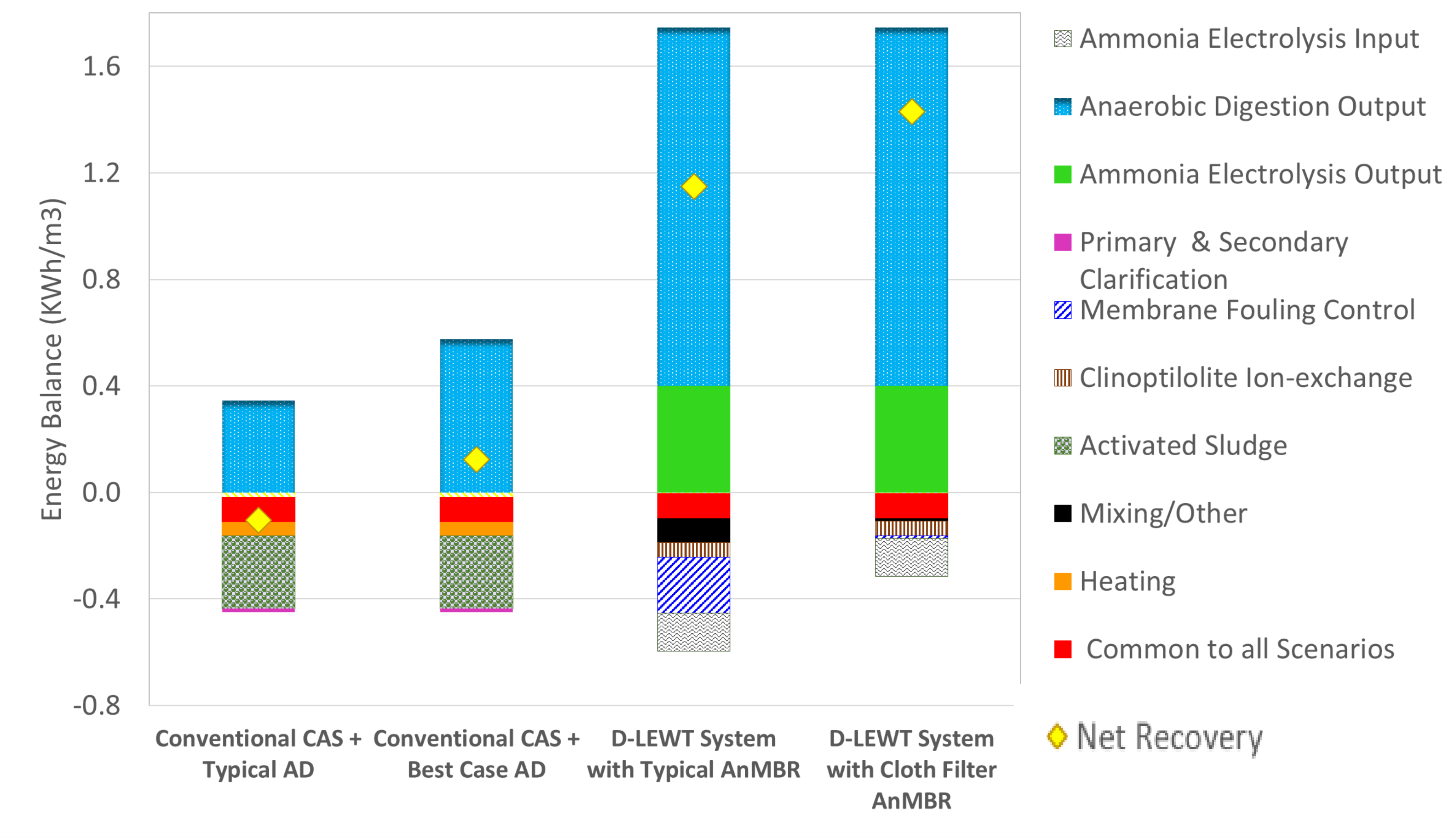
Task #	Task Description	BP1	BP2						BP3				
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
1	Initial validation	🟧 ✪											
2	Project management	🟧 ★	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
3	Install & Startup Cloth Filter Anaerobic Membrane Bioreactor		🟧 🟦	🟧 🟦 ★									
4	Improve Energy Efficiency of Field Pilot AnMBR Operations			🟧	🟧 ★	🟧	🟧	🟧 ✪					
5	Improve Ammonia Capture Efficiency by Ion-Exchange		🟧 ★	🟧	🟧	🟧	🟧	🟧 ✪					
6	Improve Ammonia Electrolysis Efficiency at Lab-scale		⬛	⬛	⬛	⬛ ★	⬛ ★						
7	Upscale Improved Ammonia Electrolysis Process to Pilot-scale					⬛	⬛ ★	⬛ ✪					
8	Planning for Ammonia Electrolysis Integration into Field Pilot						🟧	🟧 ★					
9	Characterize Engine Generator Performance with H2-Enhanced Biogas						🟥	🟥 ★					
10	Interim Techno-Economic &Life-Cycle Analysis		🟩	🟩	🟩	🟩	🟩	🟩 ★					
11	Improve Overall Energy Efficiency of Integrated Field Pilot System								🟧 ★	🟧 ★	🟧	🟧	🟧
12	Optimize Engine Generator Performance with H2-Enhanced Biogas										🟥 ★	🟥 ★	🟥
13	Final Techno-Economic & Life-Cycle Analysis								🟩	🟩	🟩	🟩	🟩 ✪

★Milestone ✪ Go/No Go

🟧 UIUC 🟦 Aqua-Aerobic ⬛ TTU 🟩 CSU 🟥 Mainstream

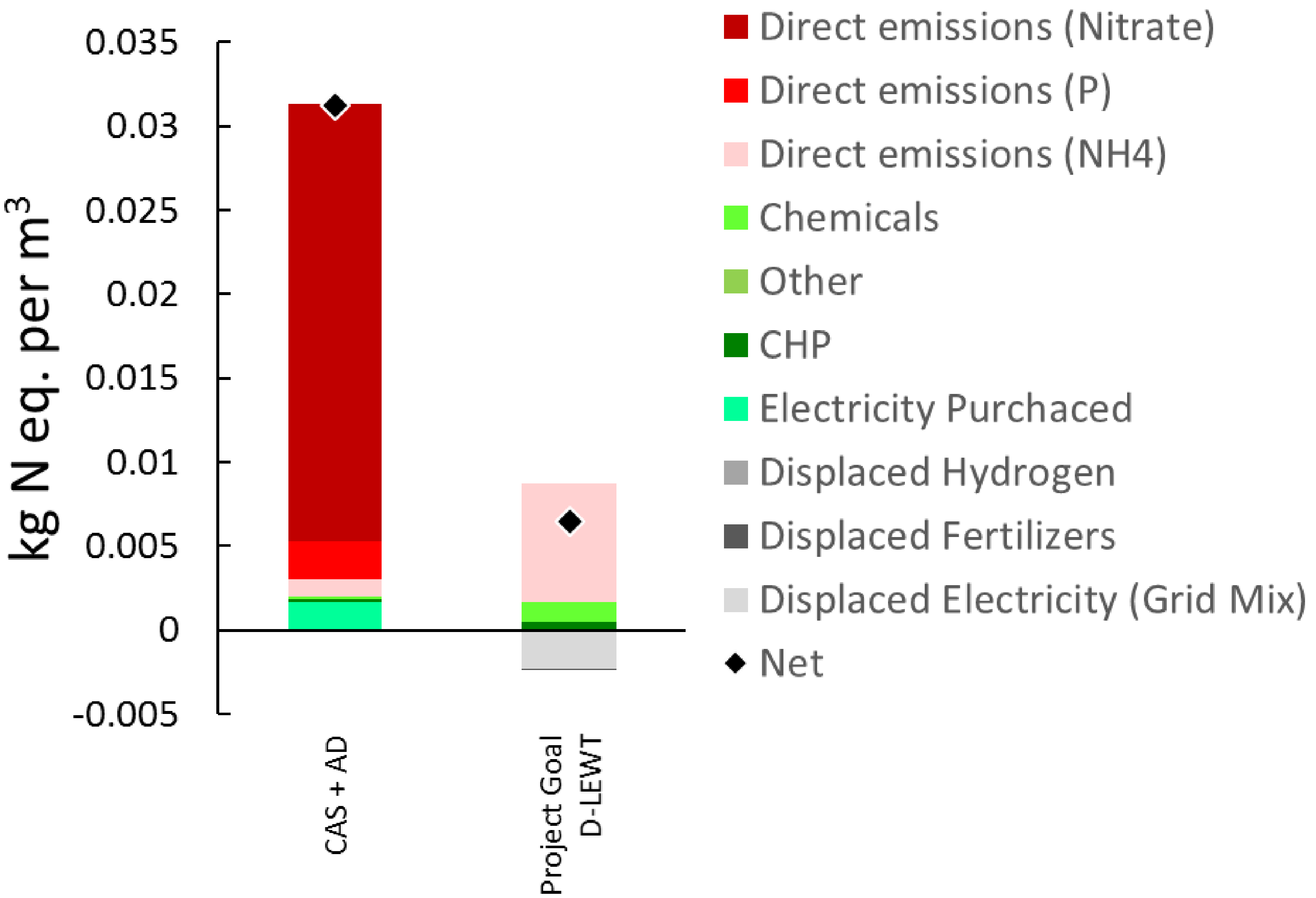
3. Impact- *Improved WW Net Energy Balance*

- Most WW plants are net energy negative
  - Consumes ~1-3% of total US electrical supply
- Best-case current WW processes have a small positive net energy yield
- Proposed D-LEWT approach increases WW net energy yield >10x
  - Eliminates activated sludge aeration energy
  - Increases biogas >2x
  - New H_2 gas product
  - Reduces net GHGs



3. Impact- *Reduced Effluent Nutrients and Industry Outreach*

- D-LEWT converts $NH_4^+ \rightarrow N_2$ gas & thus reduces eutrophication
  - Current WW plants convert most $NH_4^+ \rightarrow NO_3^-$ & discharge it
- Industry Outreach
  - WEFTEC 2020 presentation to US WW industry
  - 2021 National Meeting of the Electrochemical Society
- Commercialization via project partner marketing channels
  - *Aqua Aerobics* markets cloth filters to WW industry
  - *Ambreon* developing up-scaled ammonia electrolysis systems



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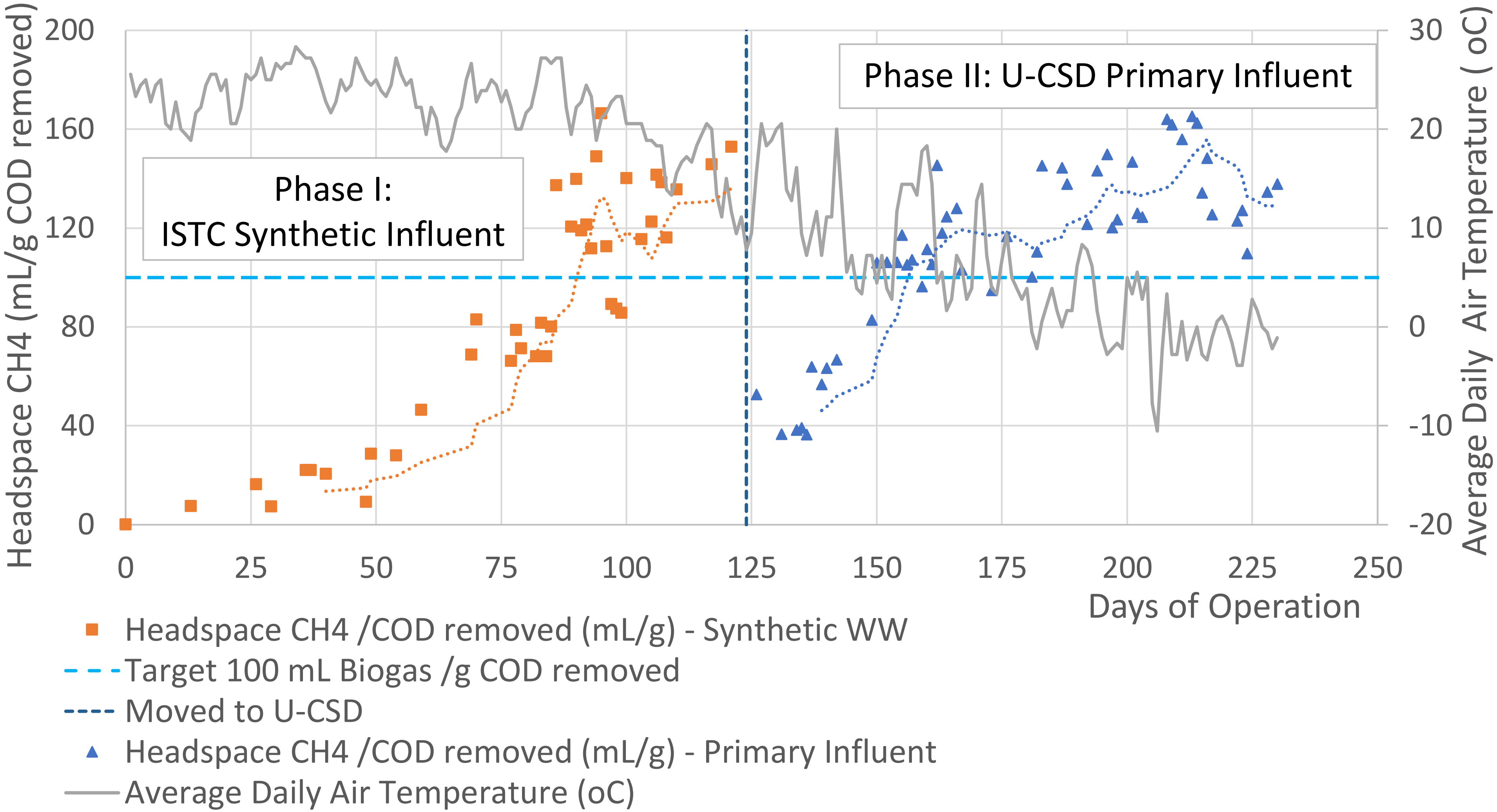
4. Progress and Outcomes- *Cloth-filter AnMBR*

Milestone T3.1 – Field Pilot cloth-filter AnMBR biogas production > 100 mL/g $COD_{removed}$



Pilot cloth-filter AnMBR maintained headspace methane yields above 130 mL CH_4/g $COD_{removed}$ even during winter without process heating

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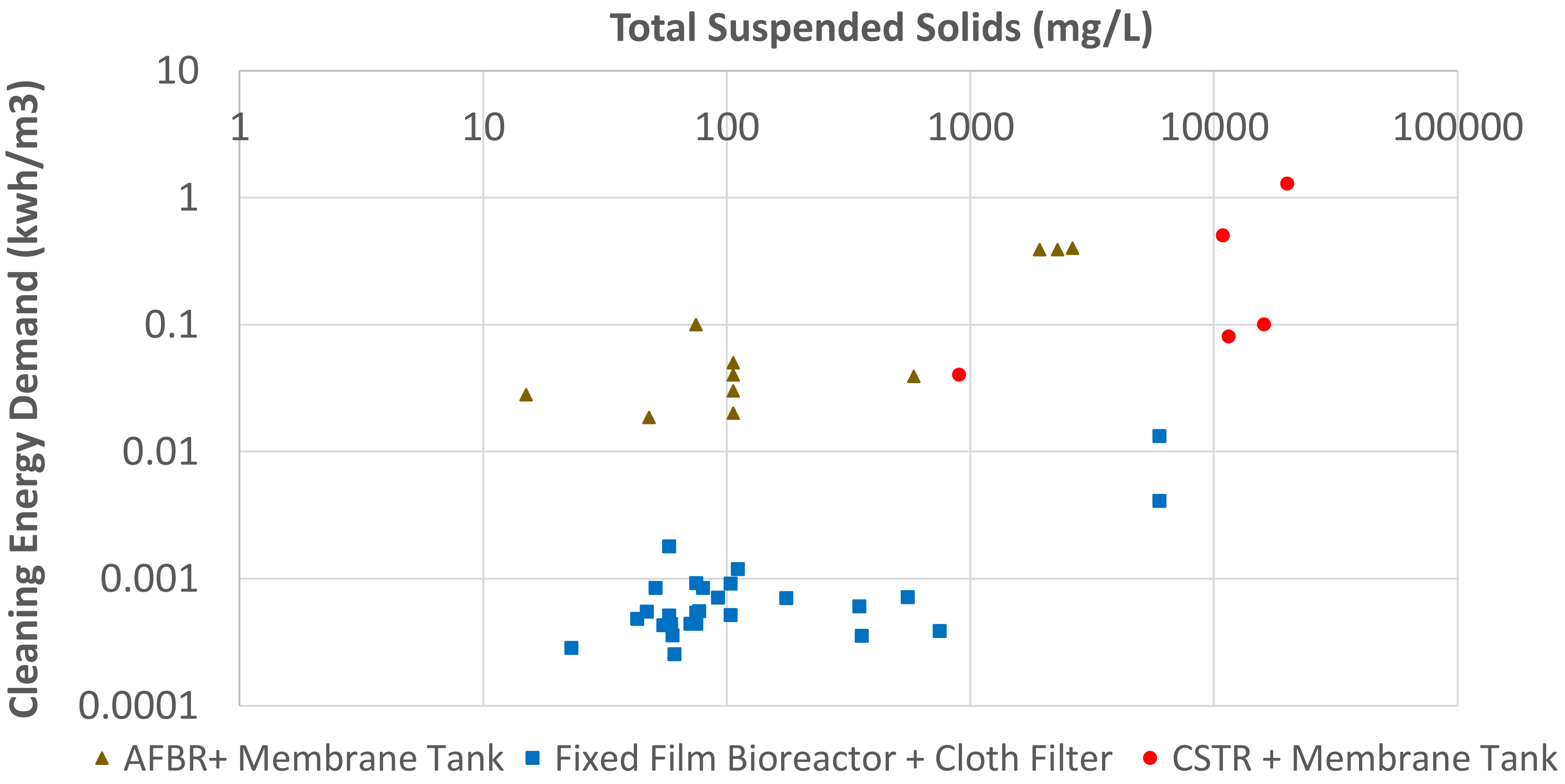
4. Progress and Outcomes- *Cloth-filter AnMBR*

Milestone T4.1 - Projected membrane cleaning energy below 0.1 kWh/m^3 target

Cloth-filter AnMBR cleaning energy demand was at least 10 times lower than the cleaning energy for all previous AnMBR configurations operated with similar suspended solids loading.



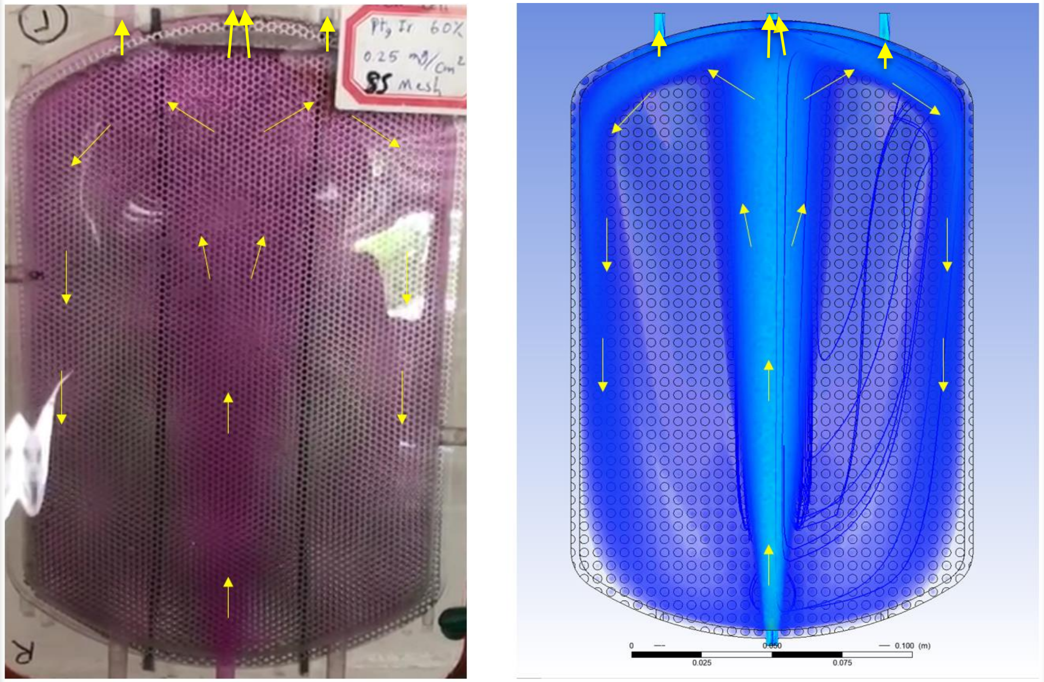
Cleaning energy demand of different AnMBR systems at various solid loading levels

4. Progress and Outcomes- *Ammonia Electrolysis*

Flow Optimization in the Ammonia Electrolysis Cell via Computational Fluid Dynamics (CFD)

- Important to avoid flow recirculation to minimize the N_2 and H_2 getting mixed after the polarity is switched

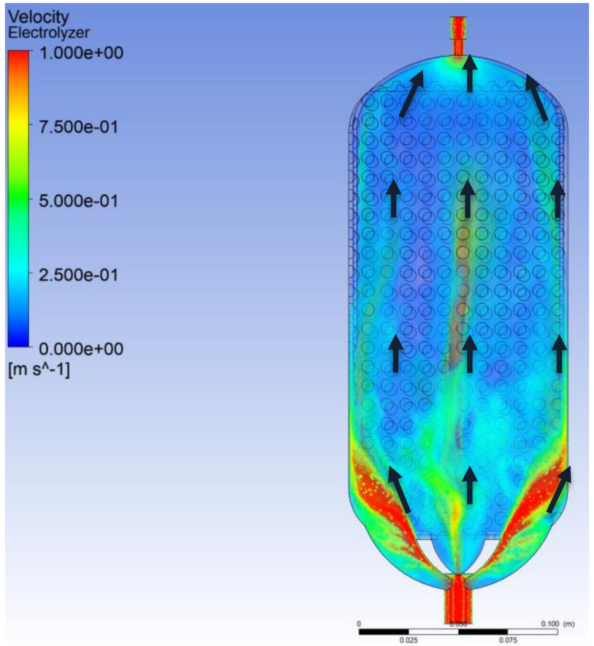
Previous Cell



(a) (b)

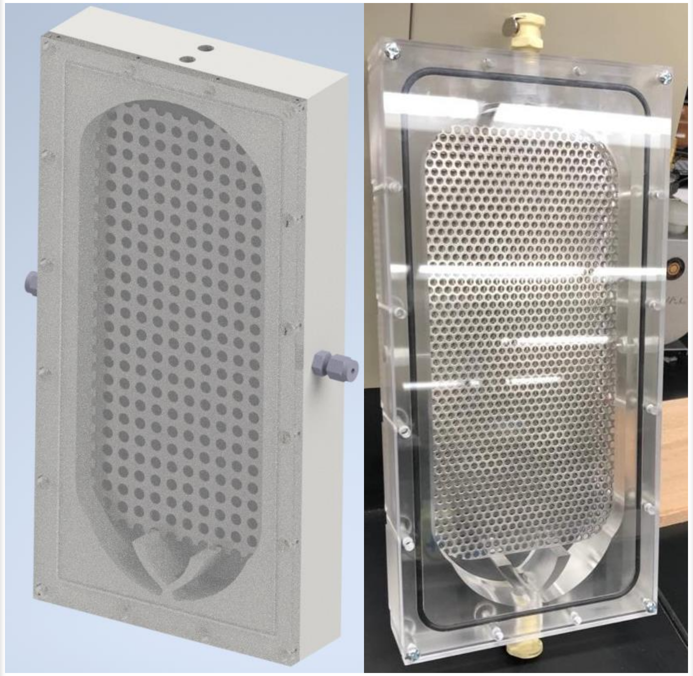
- Flow was recirculating through the cell

CFD Improved Cell Design



- Flow diffuser was added
- Fluid flow optimized

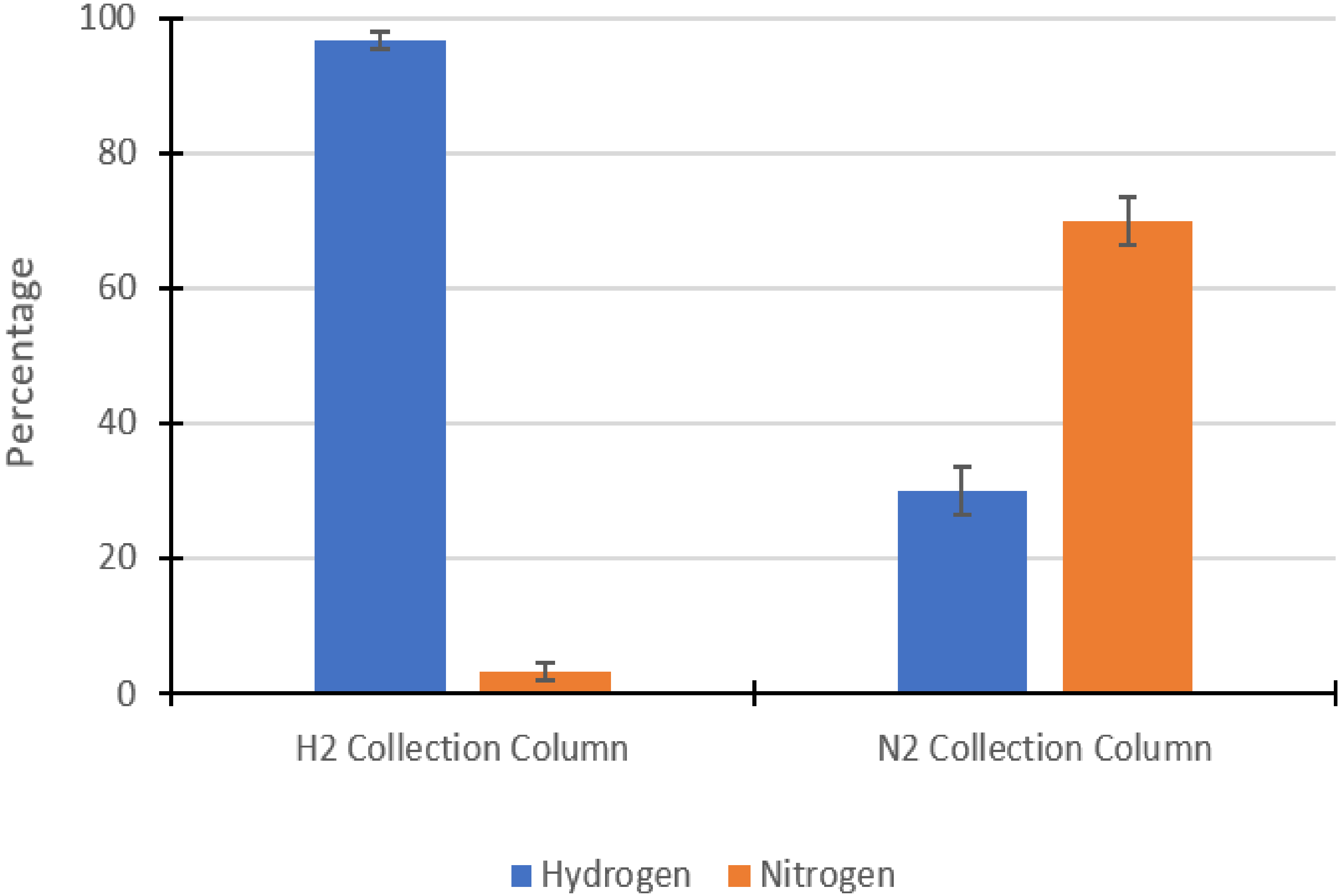
Manufactured Cell



- Cell design optimized with feedback from CFD and manufacturing

4. Progress and Outcomes- *Ammonia Electrolysis*

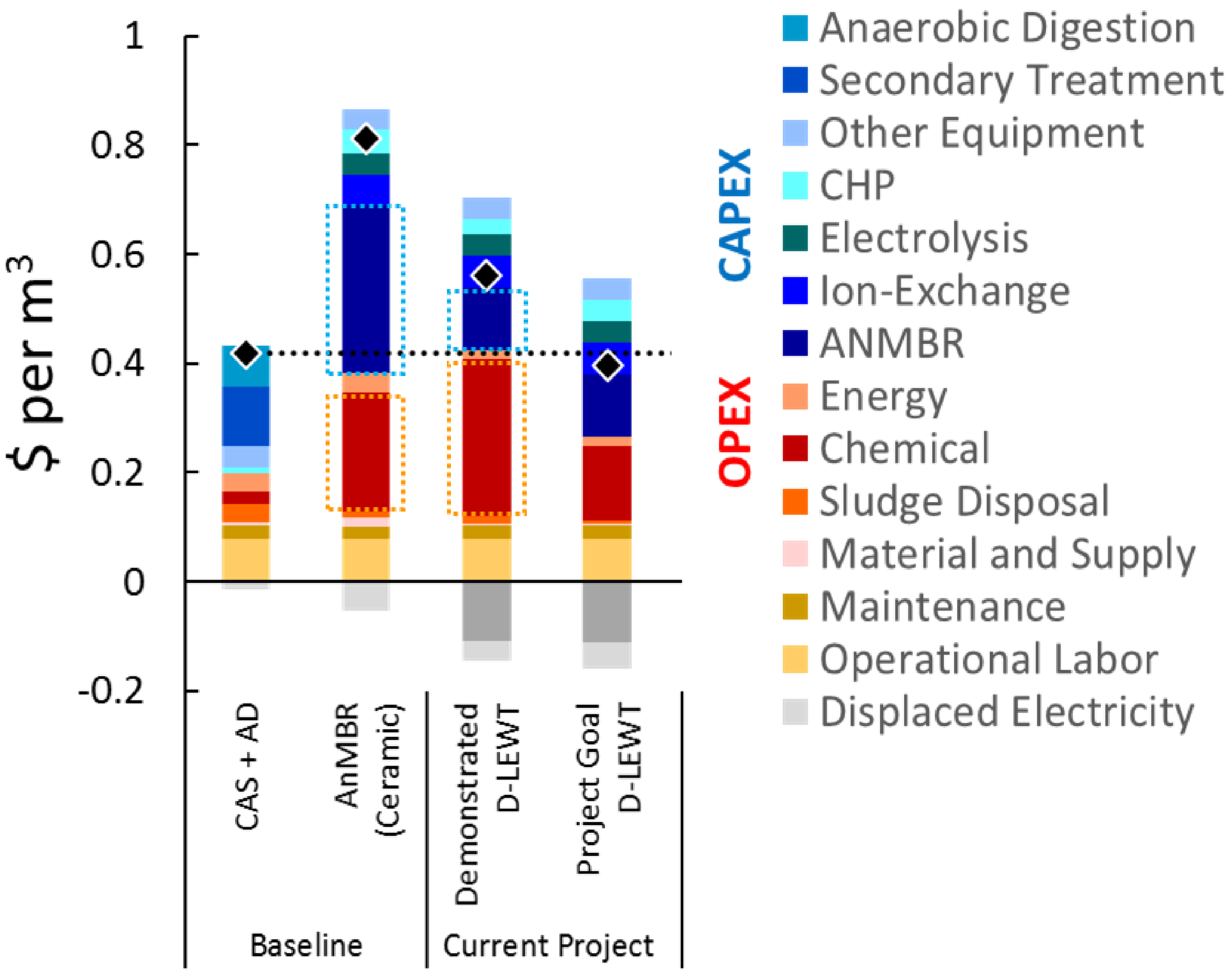
Milestone: T6.1 - Validate NH_3 electrolysis product separation at bench scale w/ H_2 purity >93% v/v



- 96.8% H_2 purity was achieved
- Cell design and fluid flow was optimized using CFD
- Inexpensive nylon mesh between electrodes to decrease the cost
- Catalyst loading decreased from 5mg/cm^2 to 0.3mg/cm^2
- Demonstrated anode/cathode polarity switching to maintain current density
  - Valve switching needs to be refined to reduce H_2 gas crossover

4. Progress and Outcomes- *Techno-Economic Analysis*

- **Initial project baseline cost for D-LEWT system was ~2x reference cost for CAS**
  - Largest CAPEX for AnMBR
  - Largest OPEX for chemicals
- **Current D-LEWT system costs are 30% lower than initial baseline cost**
  - Cloth filter AnMBR flux >100x higher
  - Cloth filter cleaning energy >10x lower
- **Future work focus on reducing chemicals**
  - NaOH used for ammonia electrolysis
  - Coagulants used for AnMBR
  - Project end goal is to match CAS + AD costs
- **Cloth filter AnMBR tradeoff is reduced effluent water quality**
  - COD removal reduced from ~95% to 80%
  - Future work to assess adding adsorbents



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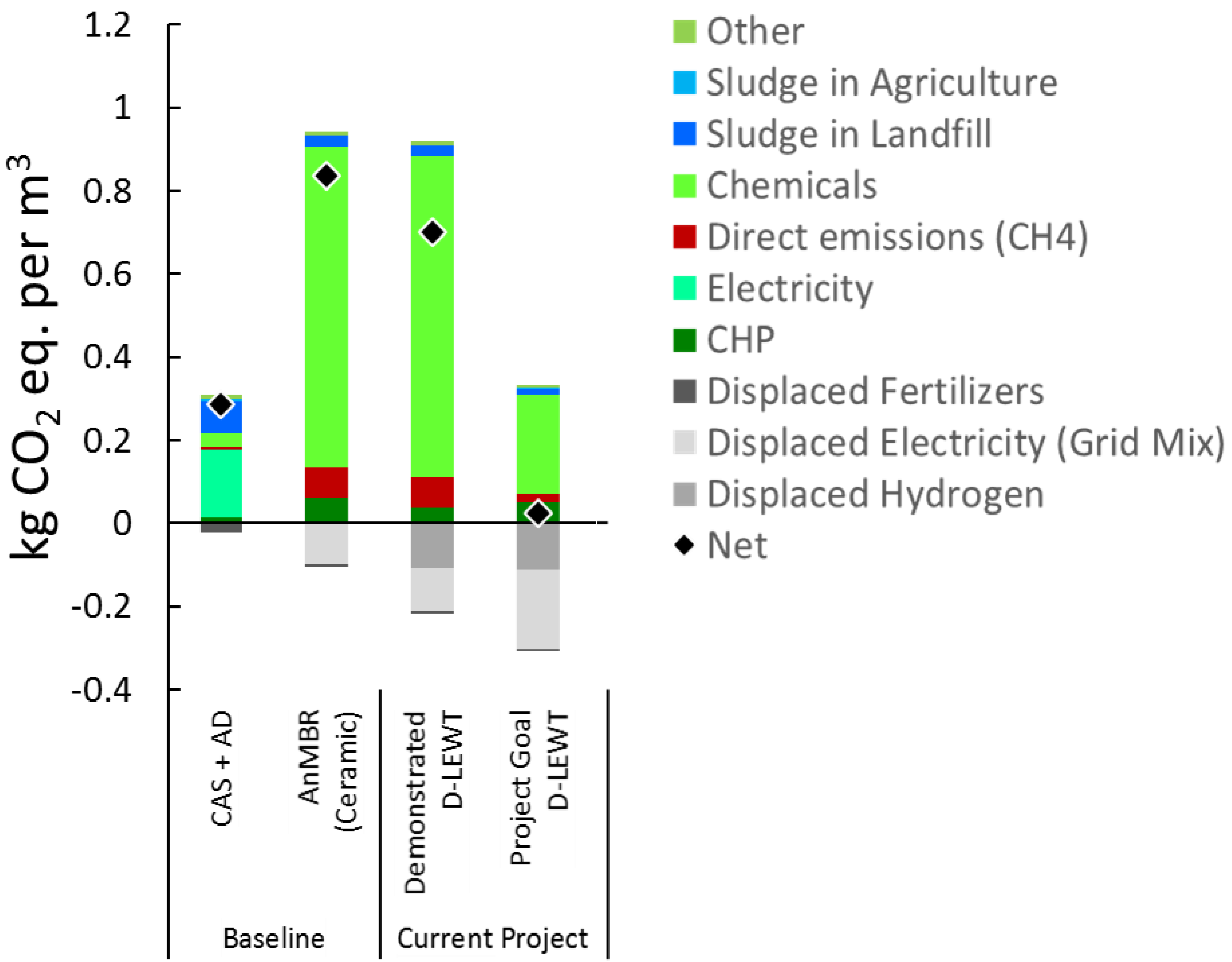
4. Progress and Outcomes- *Life-Cycle Analysis*

- **Initial project baseline GHGs for D-LEWT system was 3x reference cost for CAS**
  - NaOH for electrolysis primary GHG source
- **Current D-LEWT system GHGs 15% lower than initial project baseline**
  - Main GHG savings for H_2 production
- **Future work focus on reducing chemicals and increasing biogas production**
  - Minimize NaOH used for raising pH in ammonia electrolysis
  - Reduced efficiency of NH_3 electrolysis for lower pH is justified based on GHGs & cost
  - Substitute NaCl for NaOH in ammonium ion exchange cation balance
  - Project end goal is to be ~ carbon neutral



Summary

- **Project plots course for WW treatment to be a significant net energy producer**
  - Current activated sludge WW treatment consumes 1-3% of total US electrical demand
  - Novel D-LEWT process = anaerobic membrane bioreactor + NH3 ion-exchange & electrolysis
  - Eliminates major energy input for conventional activated sludge (CAS) aeration
  - Net WW energy yield increased 10x with energy savings, more CH_4 and new H_2 source
- **Project addresses key limitations on D-LEWT process implementation**
  - Costs for microfiltration membrane system and energy usage for membrane cleaning
  - Cost and imbedded greenhouse gas emissions for electrolysis chemicals (NaOH)
  - Scaling of individual processes from bench scale and process integration
- **Primary project progress during Year 1 (Budget Period 2)**
  - Lowered membrane costs by 30% and cleaning energy by 10x using a commercial cloth filter system in a field pilot operating at the local WWTP
  - Demonstrated new electrolysis cell for reduced cost and improved H_2 purity (96%)
  - TEA and LCA modeling identified technology pathway to lower costs and GHGs below the current activated sludge WW treatment paradigm

Additional Slides