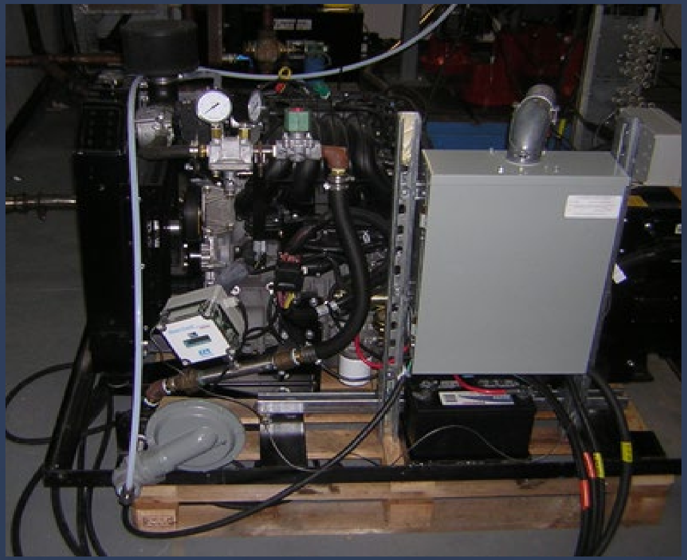
DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

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

WBS: 5.1.3.201
Organic Waste Review Panel



April 2023

I ILLINOIS

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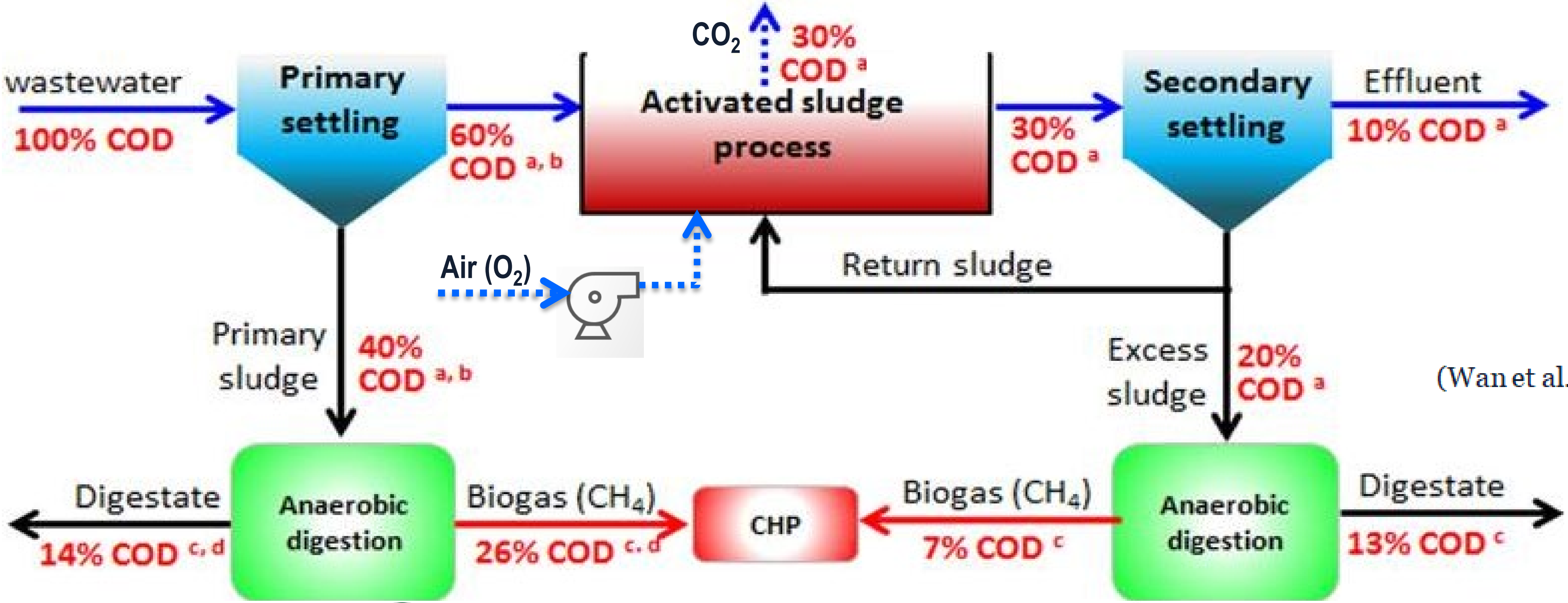
Project Overview- Background: *Current Wastewater (WW) Plants*

Most current WW Plants recover <33% of incoming energy & have a negative energy balance

- Conv. Activated Sludge (CAS) + Sidestream Anaerobic Digestion (AD) + Combined Heat/Power (CHP)
- 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



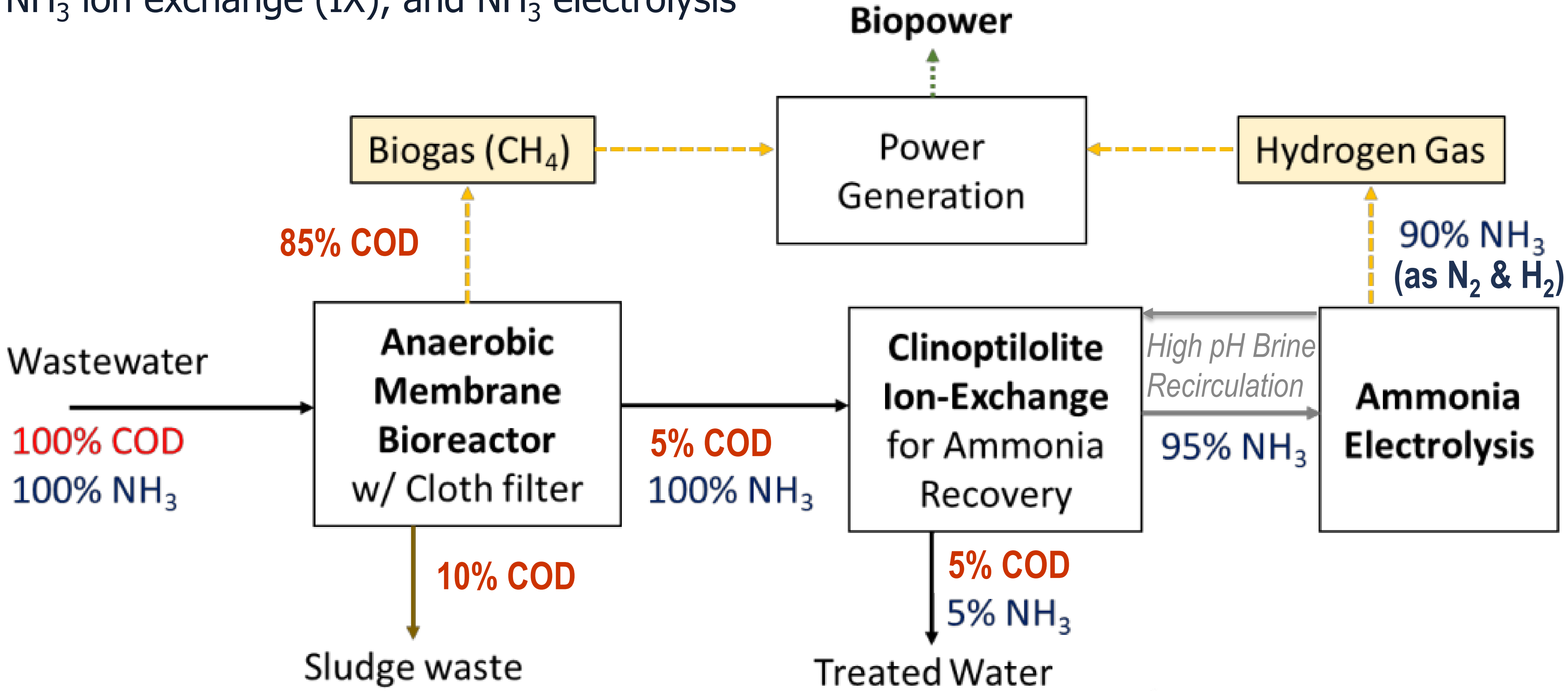
(Wan et al., 2016)

Project Overview- Goals and Importance

1) Increase net energy yield from municipal wastewater treatment
    - Mainstream anaerobic digestion of organics & electrolysis of ammonia to hydrogen
    - Decrease or eliminate energy demand for aerobic digestion (aeration)
2) Anaerobic membrane bioreactors (AnMBRs) facilitate mainstream anaerobic digestion but previous AnMBRs suffer from:
    - High costs due to low flux membranes
    - High energy inputs for membrane fouling control
3) This project resolves key limitations of AnMBRs and adds conversion of ammonia to hydrogen gas by electrolysis
4) Municipal WW treatment consumes ~1-3% of US electricity:
    - Proposed system changes the paradigm of WW treatment from being a net energy consumer to being a net energy producer

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

- 4,300 gpd pilot-scale system at a local wastewater treatment plant (Urbana, IL)
- Integrates three subsystems : novel cloth filter anaerobic membrane bioreactor (CFAnMBR), NH_3 ion exchange (IX), and NH_3 electrolysis



Illinois Sustainable Technology Center

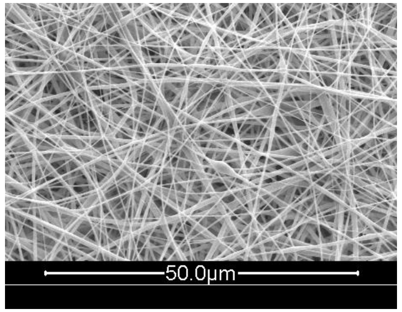
TEXAS TECH UNIVERSITY

MAINSTREAM ENGINEERING

50th Anniversary AQUA-AEROBIC SYSTEMS, INC. A Metawater Company 1969 – 2019

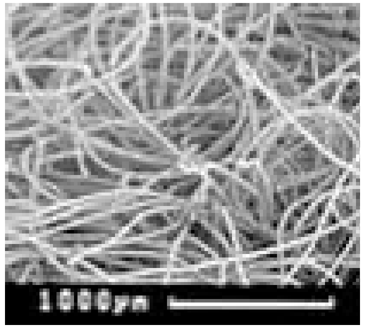
Anaerobic Membrane Bioreactors (AnMBR) increase WW net energy yield

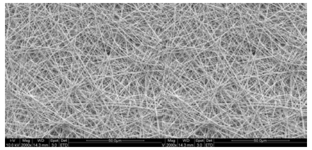
- Key Advantages of AnMBRs
  - Avoids significant energy input for aeration in CAS
  - Avoids energy loss for conversion of organics to CO_2
  - Higher effluent water quality via membrane filtration
  - Can operate at w/o heating to enable mainstream treatment
- Key Disadvantages of Previous AnMBRs and 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 (MF) membrane ~2000x magnification

Cloth filter ~100x magnification





Microfiltration ~100x magnification

Approach- Project Management

Monthly conference calls with all project collaborators

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

Project updates with partner treatment facility

Dissemination of results with stakeholders (wastewater/anaerobic digestion conferences, regional wastewater facilities

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

Diversity in background of project partners and in hiring practices

Project Partners

- Texas Tech University- NH_3 Electrolysis
- Mainstream Engineering- Biogas Engine Tests
- Colorado State University- TEA/LCA
- Aqua-Aerobic Systems- Cloth Filter (AnMBR)
- Urbana-Champaign Sanitary Dist.- Host Site

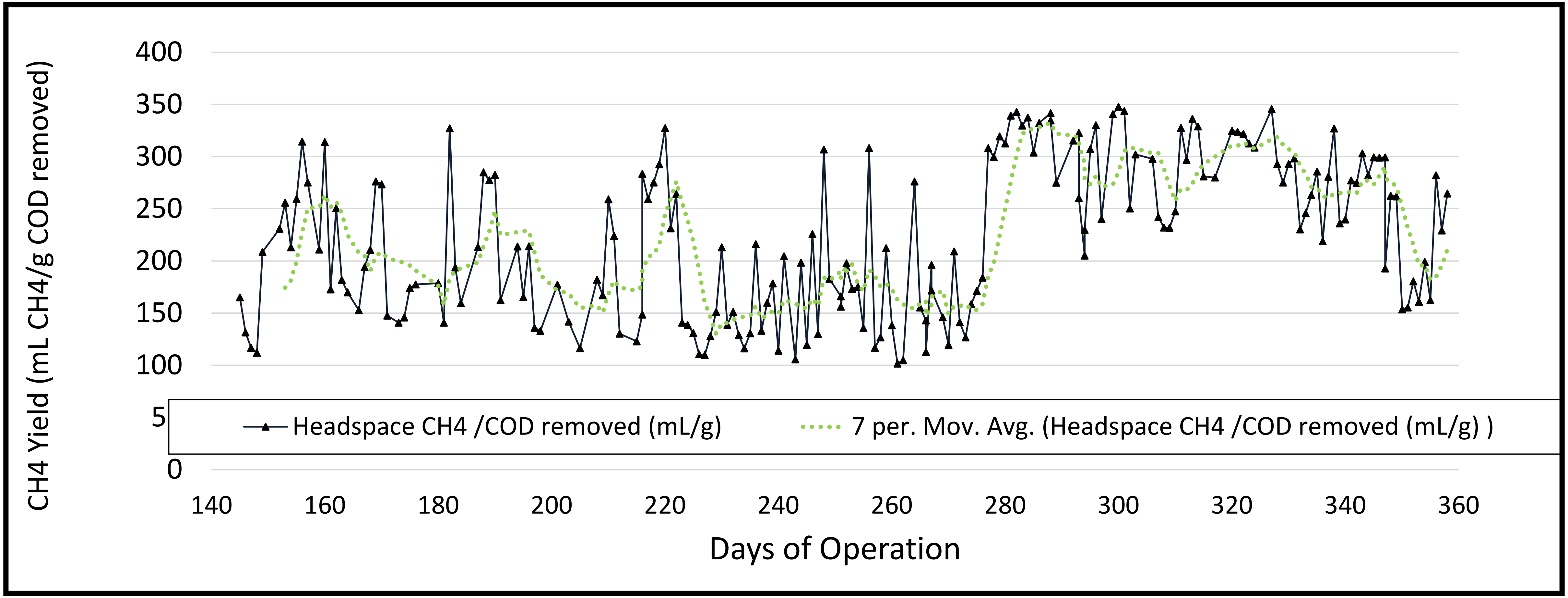
Approach- Project Risks and Mitigation Strategies

Risks	Mitigation Strategies
Anaerobic membrane bioreactor • High fouling of cloth filter • Low organics removal • Electrical/mechanical issues from corrosive biogas	• Biofilm support media to reduce solids loading on filter • Add coagulants or adsorbents to AnMBR • Improved ventilation of cloth filter unit
NH3 Ion-exchange • Materials procurement- supply chain issues • NH3 removal < 95% • High chemical use (NaOH)	• Use previously fabricated pilot system and retrofit for this project • Test alternative ion-exchange resins • Reduce regeneration frequency
NH3 electrolysis • Hydrogen purity < 90% • Low energy conversion efficiency	• Improved separator material • Increase brine pH/NH3 concentration
Biogas + H2 combustion • Engine corrosion from biogas • H2 burn rate different than CH4	• Aluminum parts for reduced corrosion • Explore alternate uses for high-purity H2

2 – Progress and Outcomes

Robust biogas production achieved with cloth filter AnMBR in all seasons

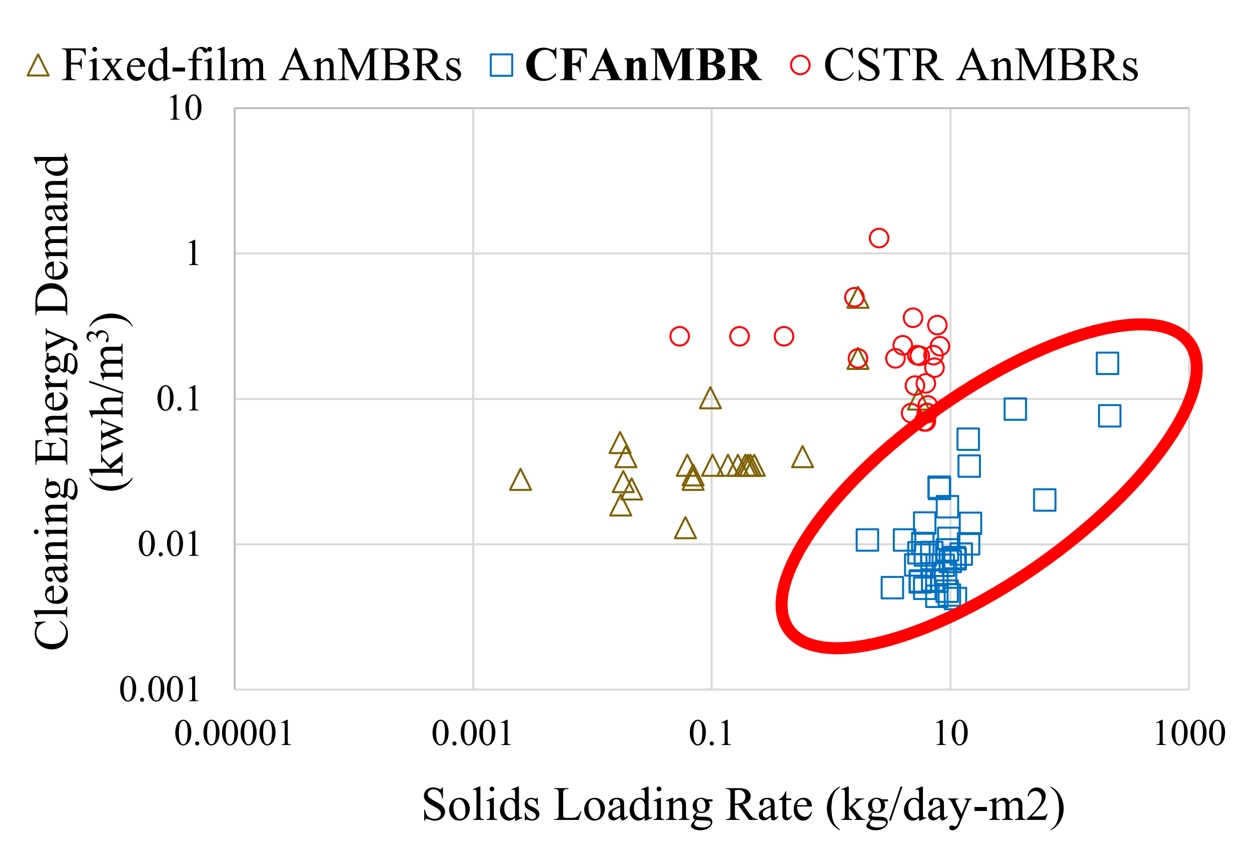
- Headspace methane averaged ~235 mL CH_4/g $COD_{removed}$ (67% of maximum CH_4 yield)
- Achieved 80-90% removal of COD (Typical AD COD removal = 40-60%)
- AnMBR operated at ambient temperature year round (Typical AD operates at 37^{o}C w/heating)
- Dissolved methane losses averaged 10 – 35% of COD removed (higher in winter)

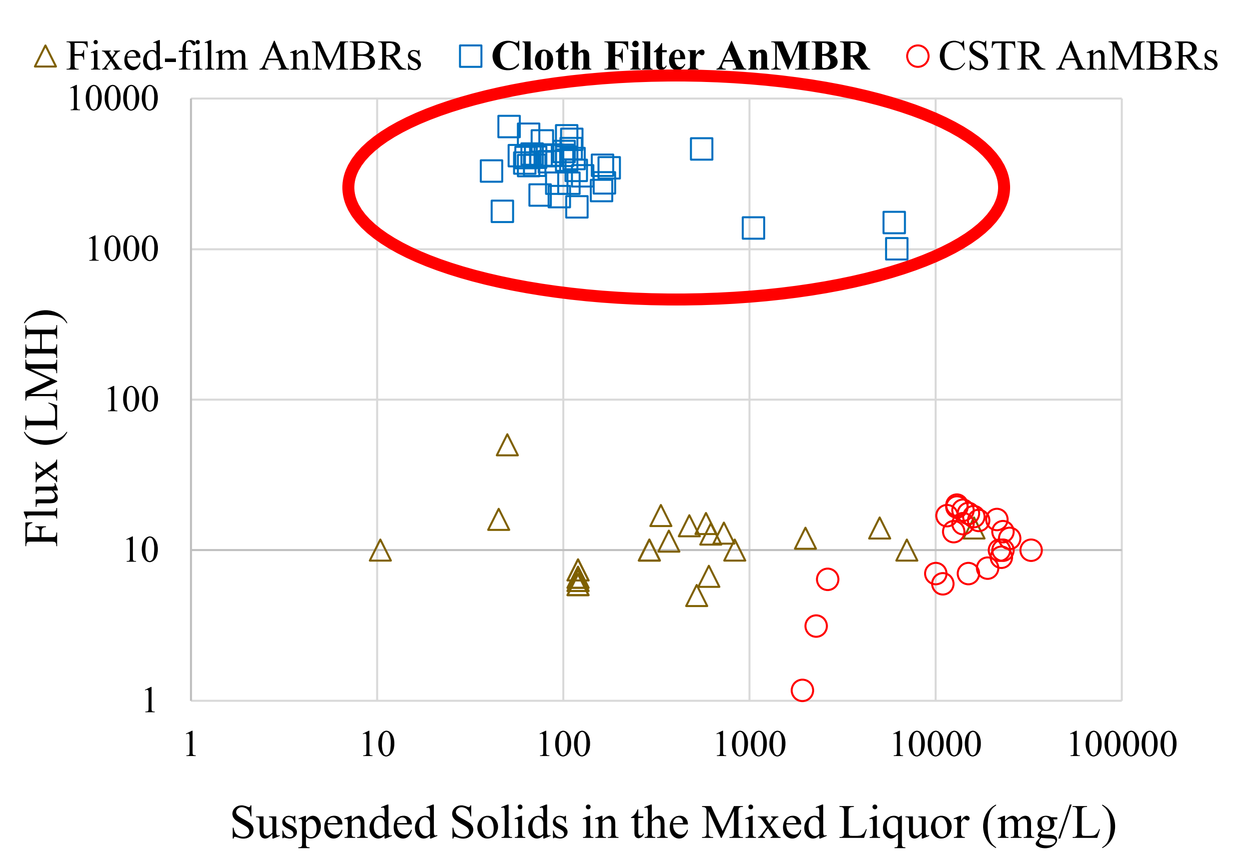


Progress and Outcomes

Cloth filter membrane reduces cleaning energy and increases flux

- Increased flux by 100x (lower CAPEX for membrane)
- Cleaning energy <0.01 kWh/m3 (project target 0.1 kWh/m3)
- Achieved 90% COD removal with coagulant dosing (FeCl3 + starch polymer)

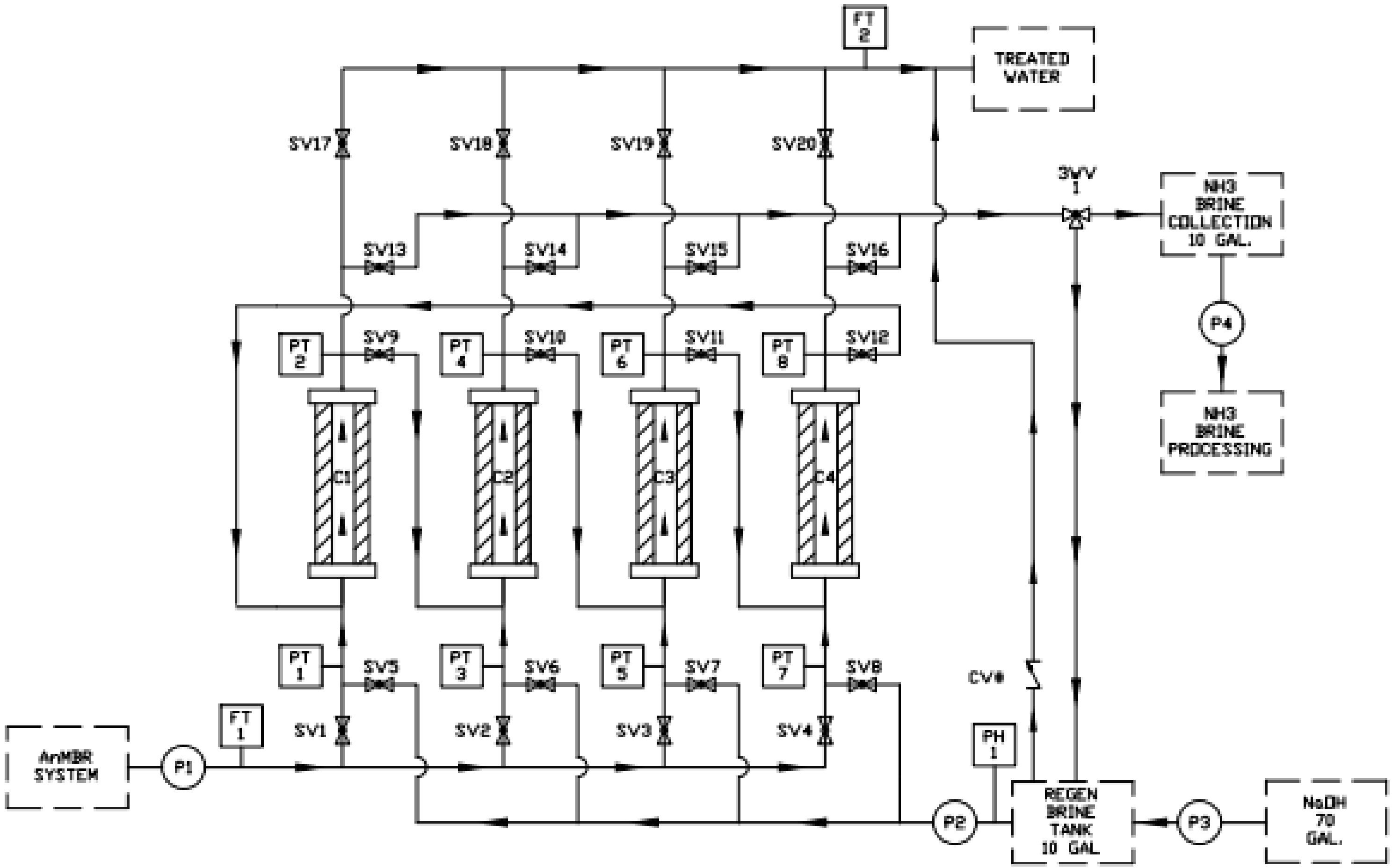




Progress and Outcomes

NH3 ion-exchange (IX)system

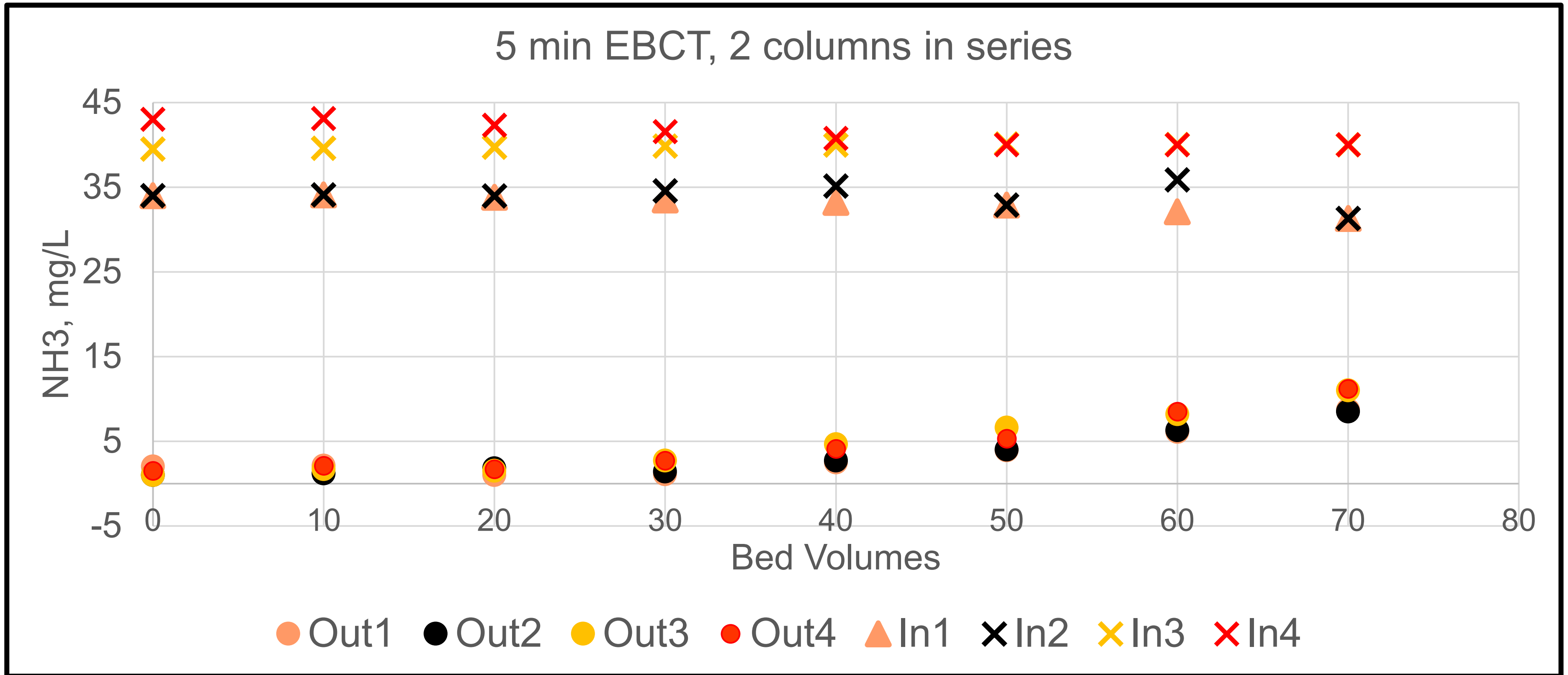
- Avoided supply-chain related delays by refurbishing an existing ion-exchange system
- Changing wastewater paradigm by converting waste NH_3 to valuable product (H_2)



Progress and Outcomes

NH3 removal using clinoptilolite media

- 90% NH3 removal up to 70 bed volumes in consecutive regeneration cycles
  - Avg effluent NH3 over capture cycle :
- Avg NH3 concentration 1,100 mg/L in regenerant brine
- Frequent regeneration cycles (~5.8 h) could increase NaOH consumption

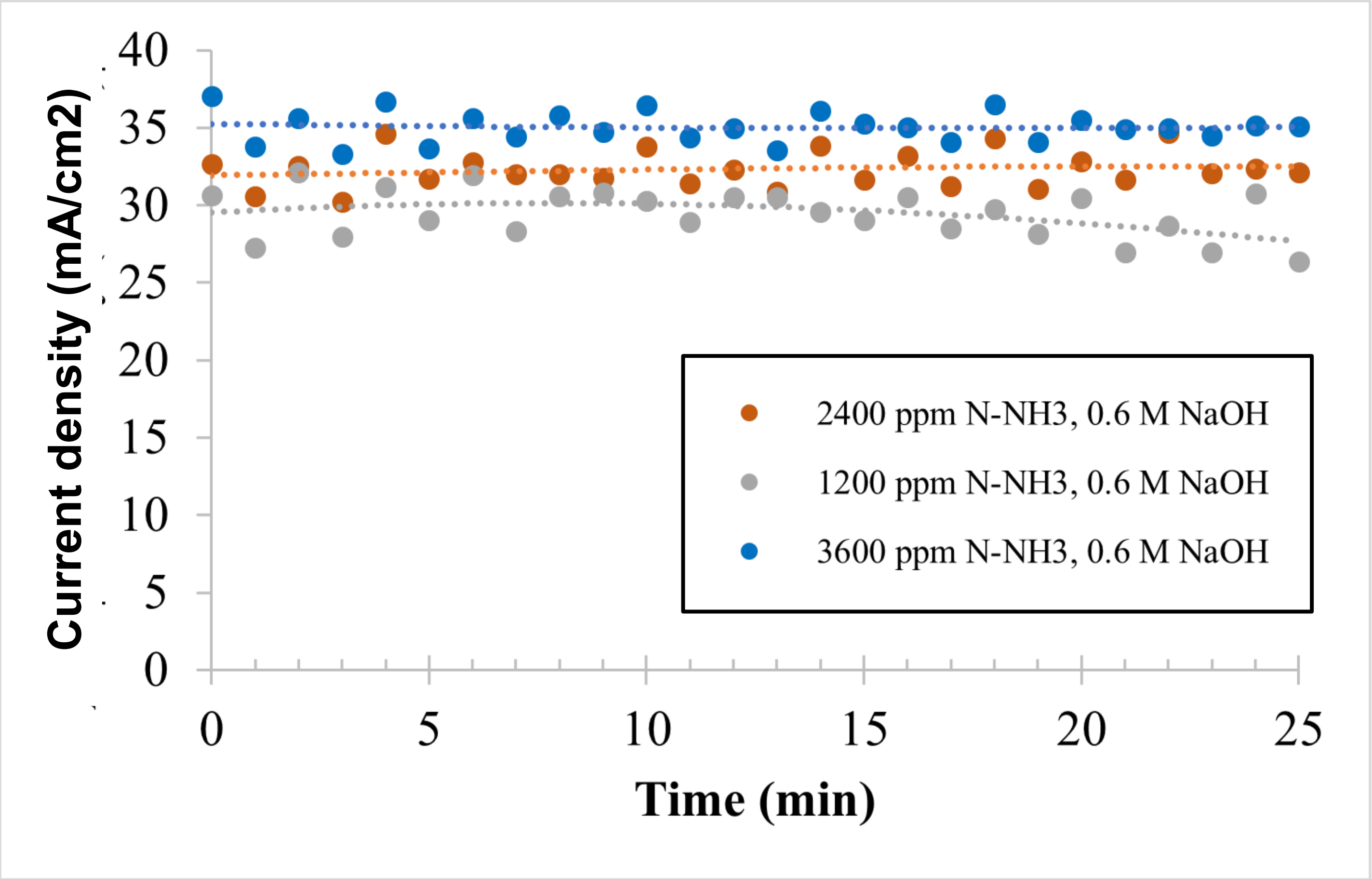


Progress and Outcomes

NH3 conversion to H2 using electrolysis

- Previously measured >93% H_2 purity in bench-scale system
  - Demonstrated increased current density at higher pH (~13.5) and higher brine NH_3 concentration
- Recently completed pilot-scale, skid-mounted electrolysis unit for integration with AnMBR and I-X pilots
- Supply-chain manufacturing delays for control panel and Zirfon separator material (higher H_2 purity)

Pilot-scale NH3 electrolysis skid



Progress and Outcomes

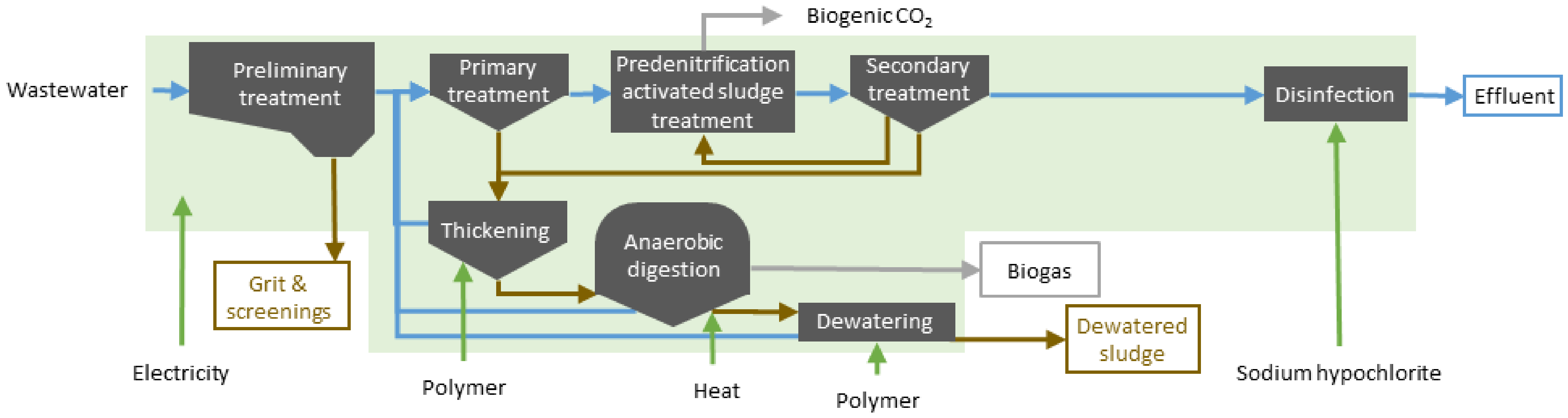
Co-combustion H_2 with biogas

- Tested with biogas tolerant engine (e.g., aluminum vs iron components)
- Hydrogen production increases fuel energy output by 22%
  - Improves economies of scale for smaller treatment plants
- Did not achieve project goal of 1% increase in brake thermal efficiency
  - Thermal losses due to aluminum components selected for corrosion resistance
  - Evaluate alternate H_2 uses (bottle gas, hydrogen fuel cell, biomethanation)

CH_4/CO_2 (% v/v)	Biogas/H_2 (% v/v)	P_e (kW)	MBT (deg BTDC)	Fuel Flow (slpm)	ϕ	Thermal efficiency (%)
70/30	0	10.2	50	101.4	1.01	27.1
70/30	95/5	10.4	50	106.7	1.00	27.0
70/30	85/15	10.4	50	117.0	1.00	25.7
70/30	81/19	10.3	50	120.9	1.01	25.3

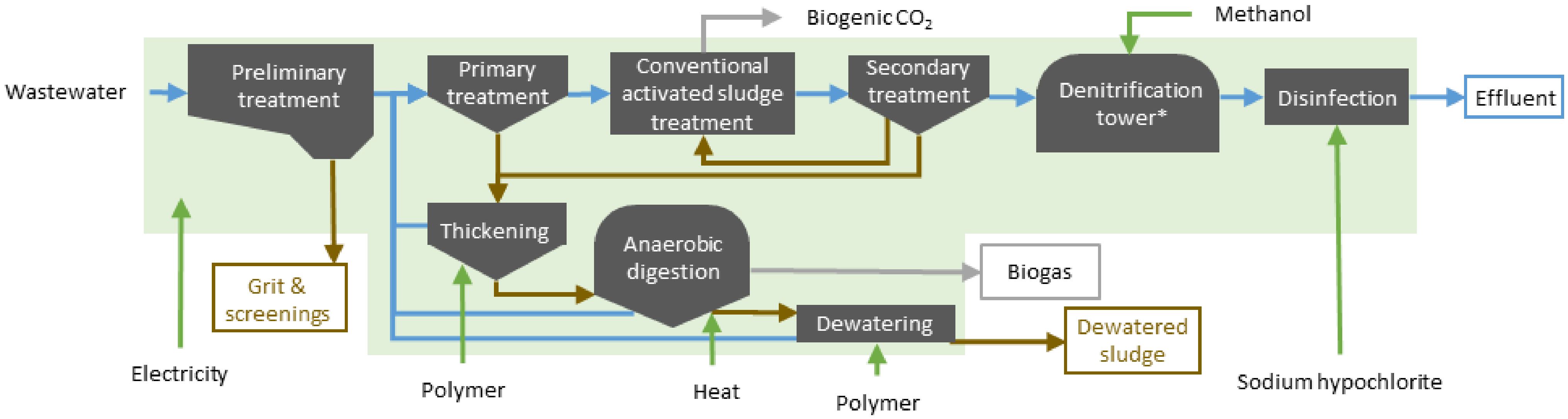
TEA/LCA Process Flow Diagrams

Conventional activated sludge w/ nutrient removal (CAS) (Lower Cost Industry Standard Process)



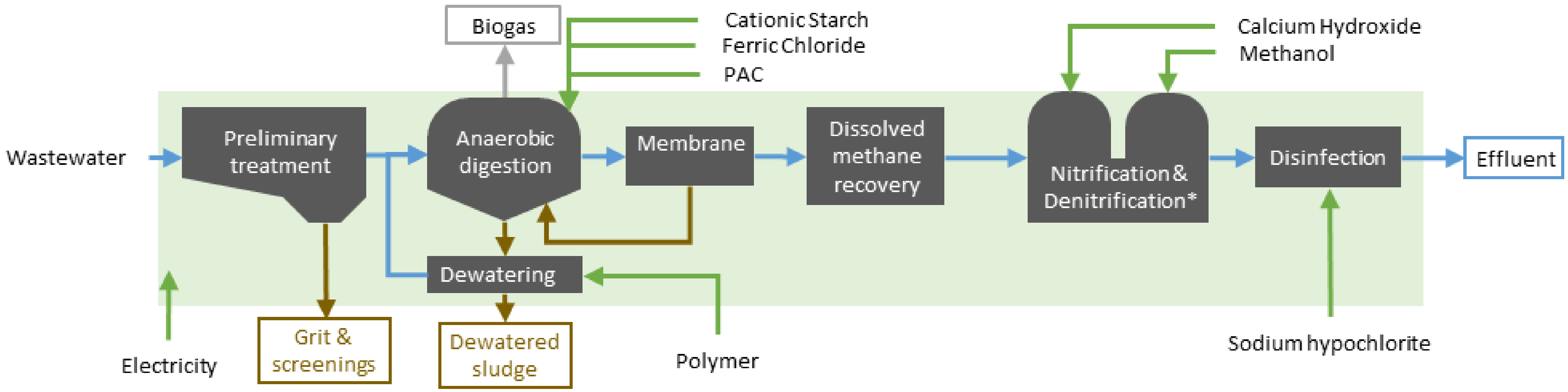
TEA/LCA Process Flow Diagrams

CAS w/ Tertiary nutrient removal (Higher Cost Industry Standard Process)



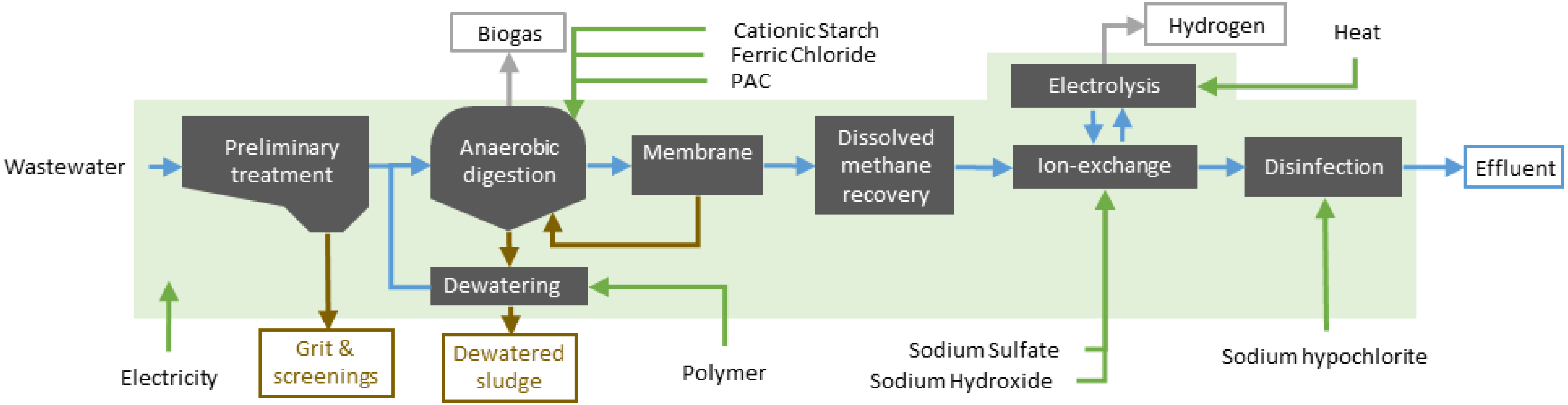
TEA/LCA Process Flow Diagrams

Previous AnMBR + Tertiary Denitrification (Start of Project Technology Baseline)



TEA/LCA Process Flow Diagrams

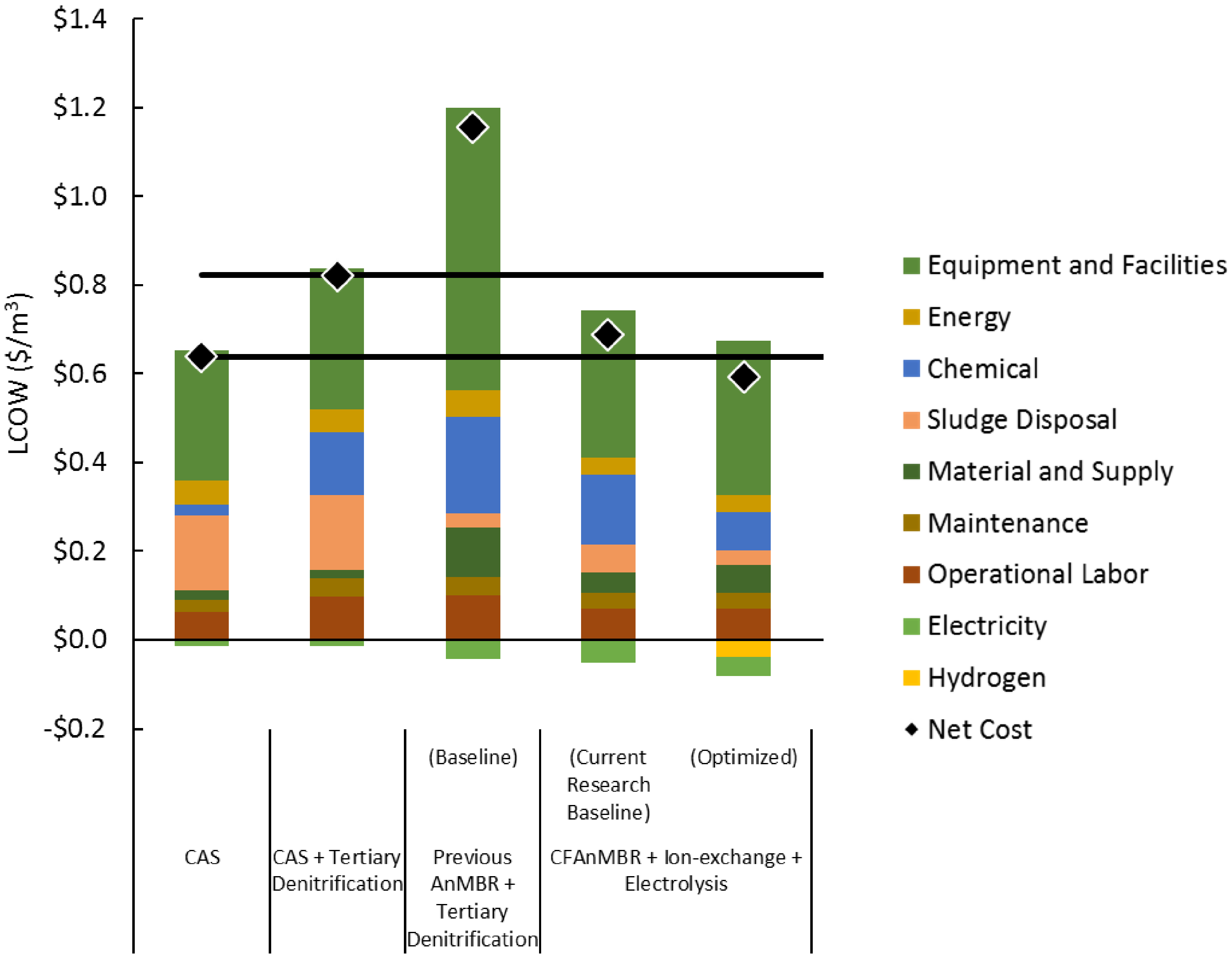
Proposed D-LEWT Process: CFAnMBR + Ion-exchange + Electrolysis



Progress and Outcomes

Treatment costs competitive with industry standards

- D-LEWT process significantly lowered treatment cost relative to traditional AnMBR Baseline
- Current and Optimized D-LEWT process can compete with conventional activated sludge (CAS) treatment processes
  - Optimized process includes reduced chemical doses & selling H2 as bottle gas

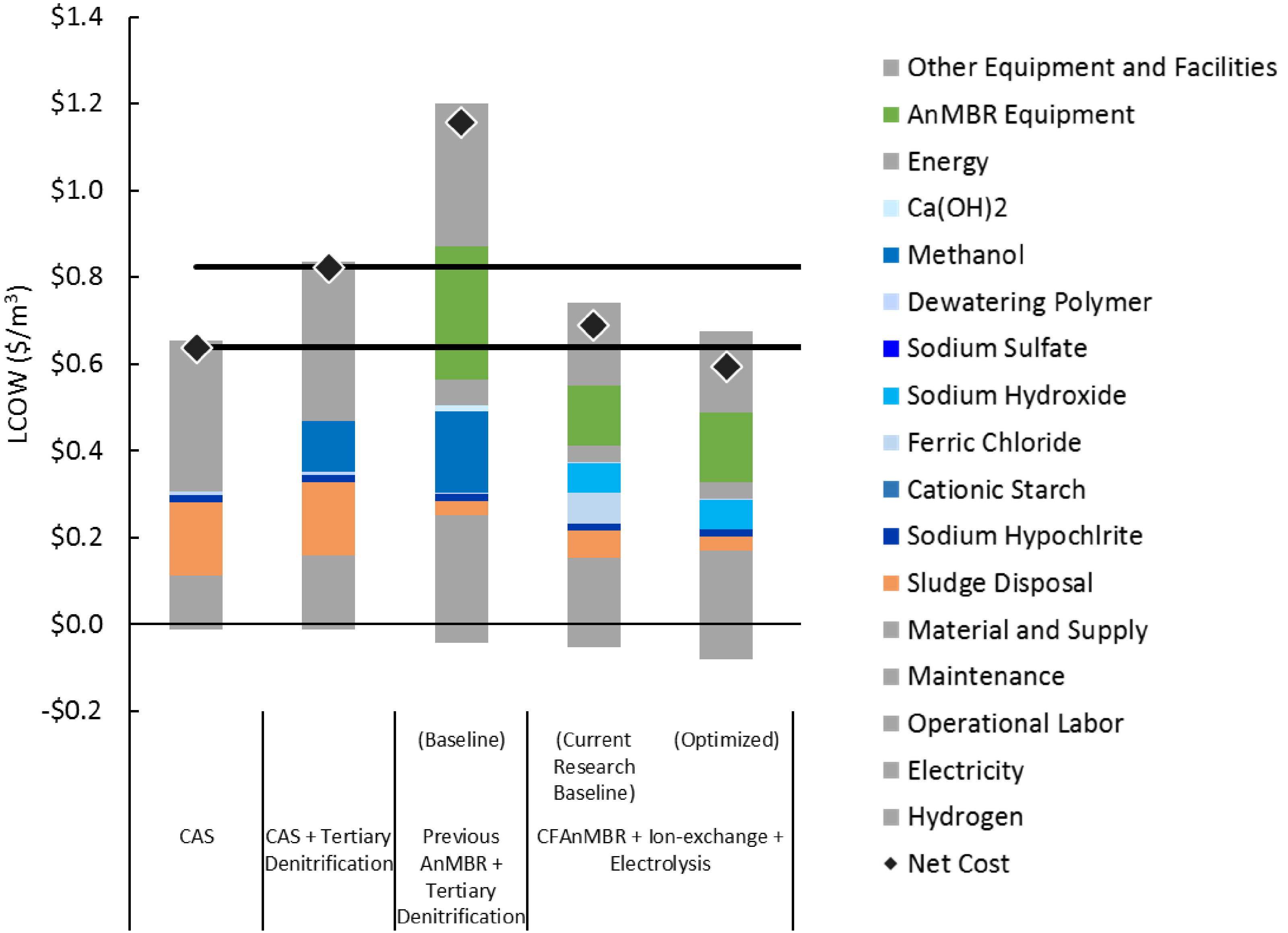


Progress and Outcomes

Treatment costs competitive with industry standards

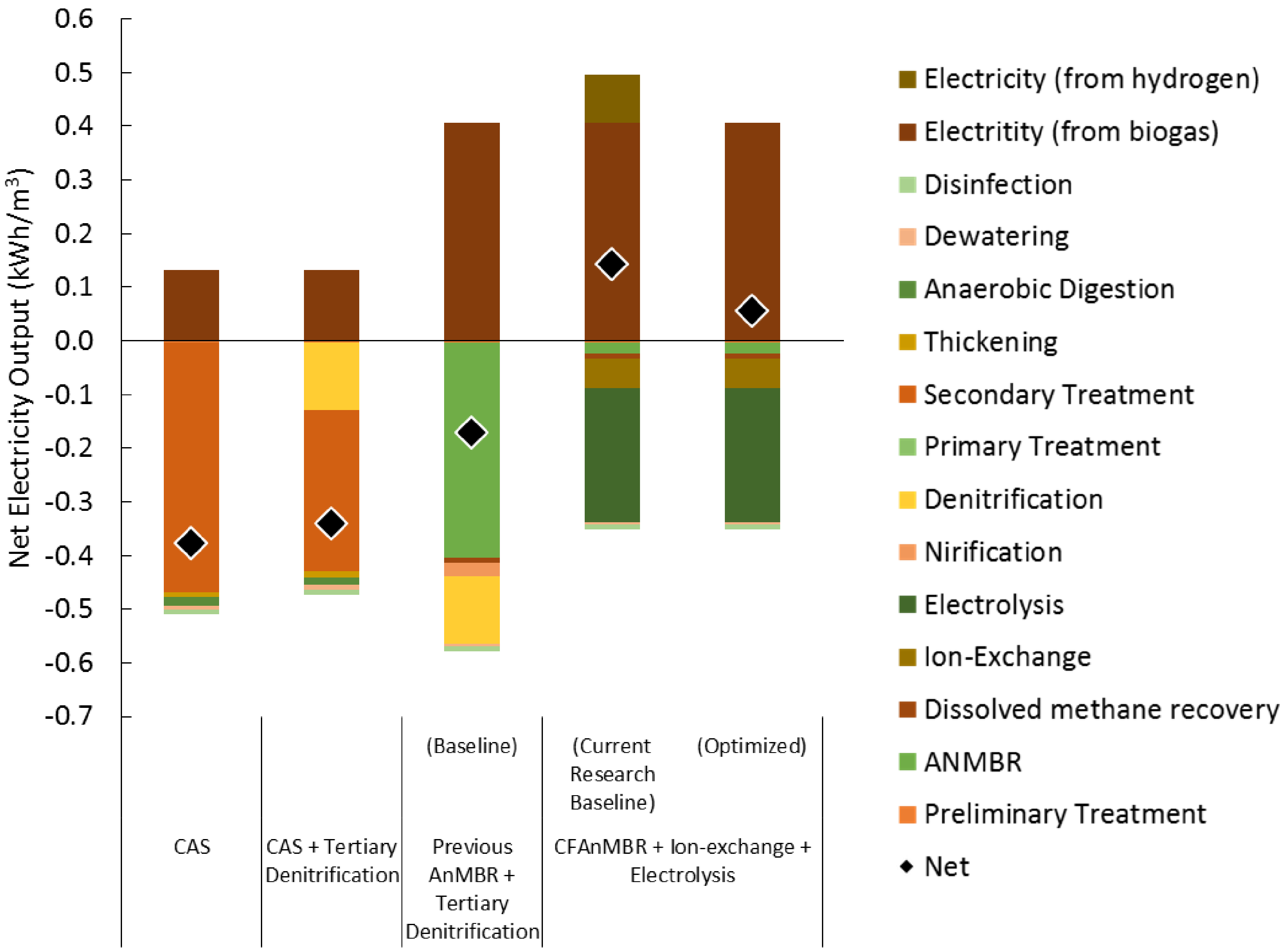
Primary process differences highlighted by different colors

- Sludge disposal cost reduction relative to CAS
- Greater increase in chemical costs (NaOH + coagulants)
- Lower membrane costs relative to conv. AnMBR



Progress and Outcomes

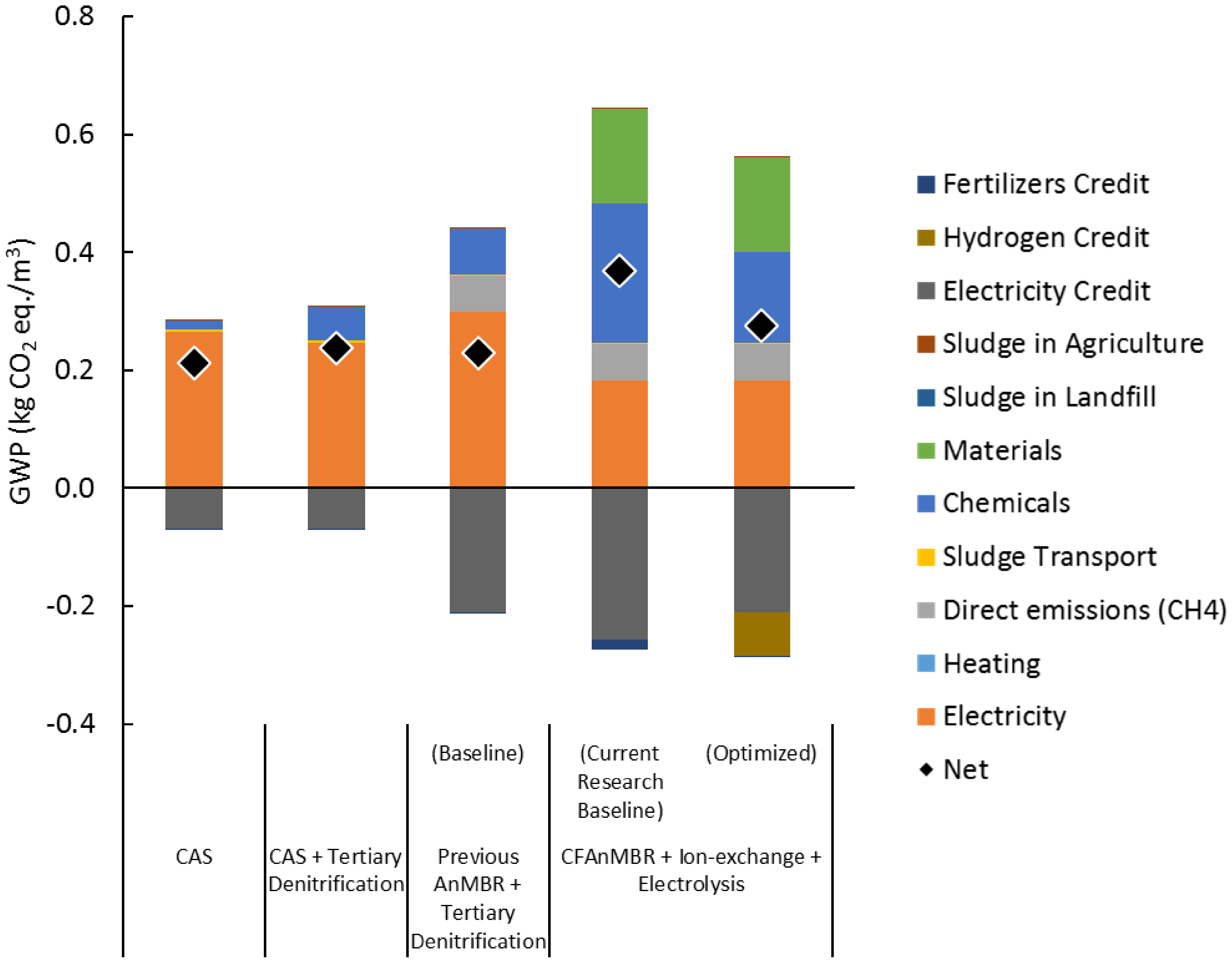
Net energy positive wastewater treatment



- Overall D-LEWT process is net energy positive
- Hydrogen production is net energy negative, but lower energy than current denitrification processes
- Cost Optimized D-LEWT process produces less energy because H2 not burned for electricity

Progress and Outcomes

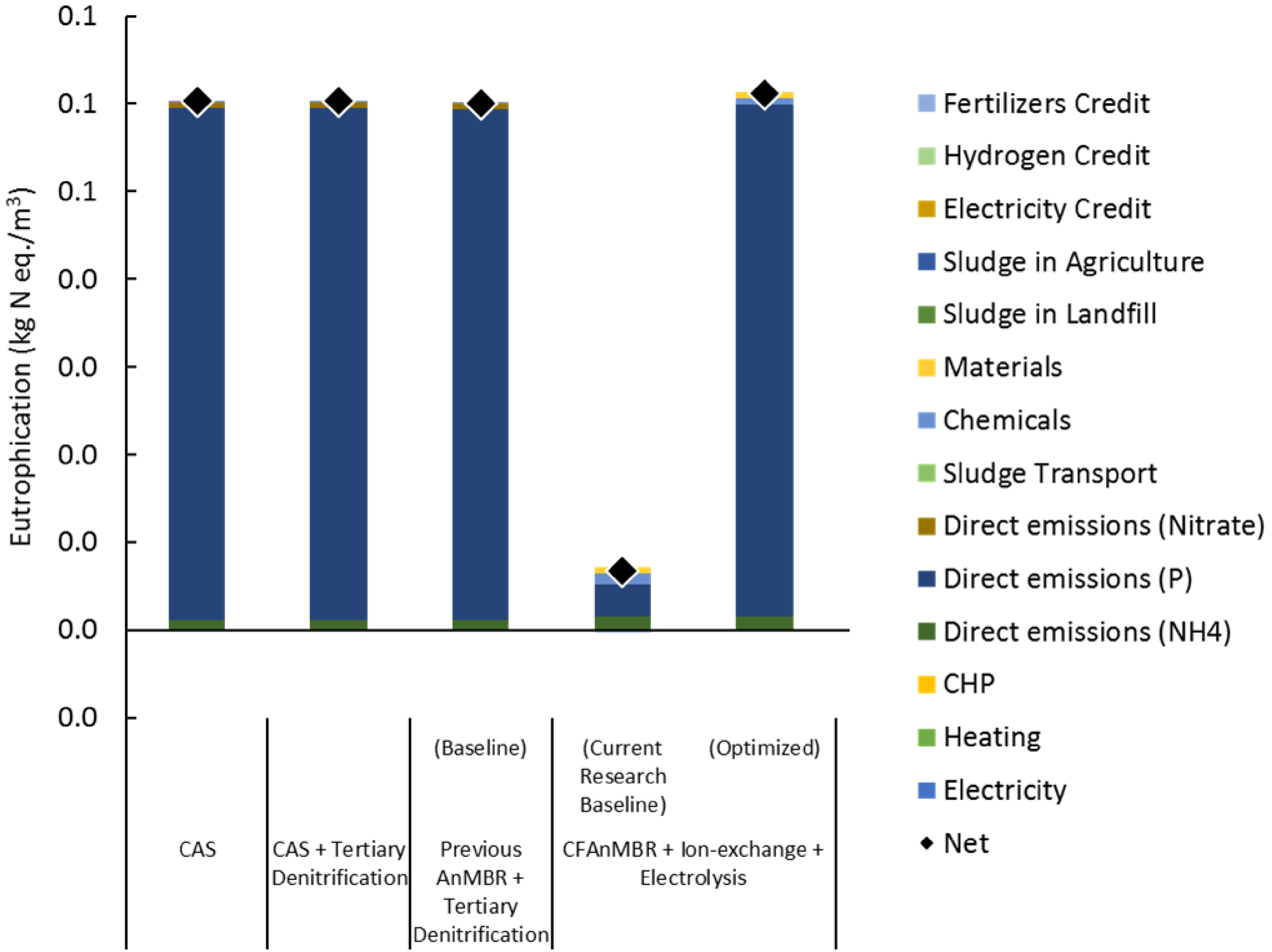
Chemical and material consumption increase climate impacts



- Electricity consumption is lowered
- Chemicals have a high impact
- Ion exchange resin has a high impact.
- Dissolved methane emissions must be minimized.

Progress and Outcomes

Lower eutrophication potential when coagulants used



- All scenarios have reduced eutrophication potential b/c of including denitrification processes
- Current research baseline also removes phosphorus b/c of iron coagulant used with AnMBR
- Cost optimized D-LEWT replaces coagulant w/ activated carbon
  - Iron doped activated carbon may provide partial phosphorus removal

3 – Impact

- Project demonstrates an integrated process at TRL-6 to achieve net energy positive WW treatment that is cost competitive with current WW process
- CFAnMBR uses two commercially available technologies (anaerobic digester and cloth filter)
  - Accelerate industry acceptance and deployment
- Use of plastic growth media in digester to lower solids loading on membrane and enhance flux in AnMBR proceses
- Dissemination of results via industry conferences
  - WEFTEC national wastewater industry exhibition
  - Regional wastewater plant operator conference
  - IWA anaerobic digestion specialty conference
  - A&WMA national conference

Summary

- High flux, low cleaning energy cloth filter membrane bioreactors (CFAnMBR) resolves major limitations of mainstream anaerobic digestion
  - >100x increase in flux, >97% lower cleaning energy relative to conventional AnMBR
- Net energy production (+0.2 kWh/m3) for municipal wastewater treatment, versus energy consumption (-0.4 kWh/m3) for conventional activated sludge
  - Eliminates aeration needs, need to optimize coagulant use
  - Need to resolve issue of dissolved methane in effluent (20 – 50% biogas)
- >90% NH_3 removal in ion-exchange subsystem
  - Need to reduce chemical and energy inputs
  - Explore alternative ammonia capture/removal methods

Quad Chart Overview

Timeline
- *Project start date : October 2018*
- *Project end date : June 2023*

	FY22 Costed	Total Award
DOE Funding	*$327,888*	*$1,585,115*
Project Cost Share *	20%	

TRL at Project Start: 3
TRL at Project End: 6

Project Goal
Maximize net power generation from municipal wastewater treatment by reducing energy inputs and increasing energy outputs

End of Project Milestone
Demonstrate integrated field pilot achieving:
- *>90% COD removal with cleaning energy <0.1 kWh/m3*
- *>90% NH3 capture using ion exchange*
- *>90% H2 purity using electrolysis*

Funding Mechanism
DE- FOA-0001926

Topic Area 3: Biomass, Biosolids, and Municipal Solid Waste to Energy

Project Partners
- Colorado State University, Texas Tech University, Mainstream Engineering, Aqua-Aerobic Systems, Urbana-Champaign Sanitary District

Responses to Previous Reviewers' Comments

- Given the high chemical and energy inputs of the NH3 electrolysis step, alternative NH3 management methods were explored in TEA/LCA. Project partners are helping evaluate alternative uses for high-purity H2 gas
- Dissolved methane in effluent remains a limitation for mainstream anaerobic digestion. Future work will investigate adding a process for energy efficient methane degassing.

Publications, Patents, Presentations, Awards, and Commercialization

- Cole, G.M., Schideman, L., Gerardine, B., Quinn, J.C, 2022, Addressing outstanding obstacles to the adoption of anaerobic membrane bioreactors through techno-economic analysis and life cycle assessment [Invited Speaker], Energy and Environment Seminar Series presented by The Energy Institute, Fort Collins, Colorado, United States
- “Low energy wastewater treatment using novel cloth filter anaerobic membrane design.” IWA AD17 Anerobic Digestor conference. June 2022. Ann Arbor, Michigan
- “Maximizing Bio-renewable Energy from Wet Wastes.” Oral Presentation of MBREWW Project to Illinois Association of Water Pollution Control Operators. 84th Annual Regional Conference. October 18, 2022. Urbana, Illinois
- “Low energy wastewater treatment using novel cloth filter anaerobic membrane design”. Oral Presentation. A&WMA’s 116th Annual Conference and Exhibition . June 5, 2023. Orlando, Florida.