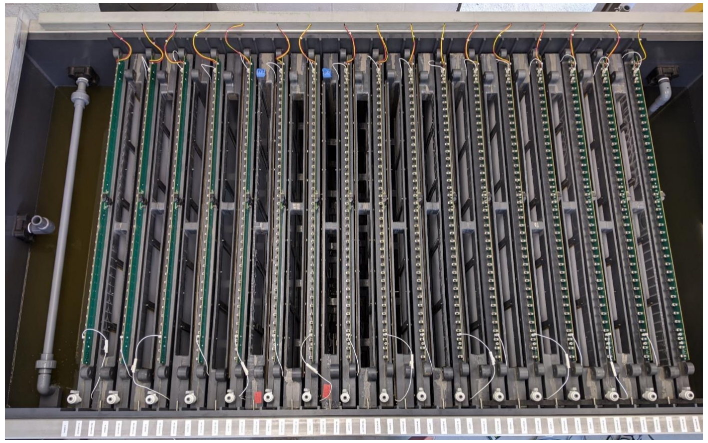
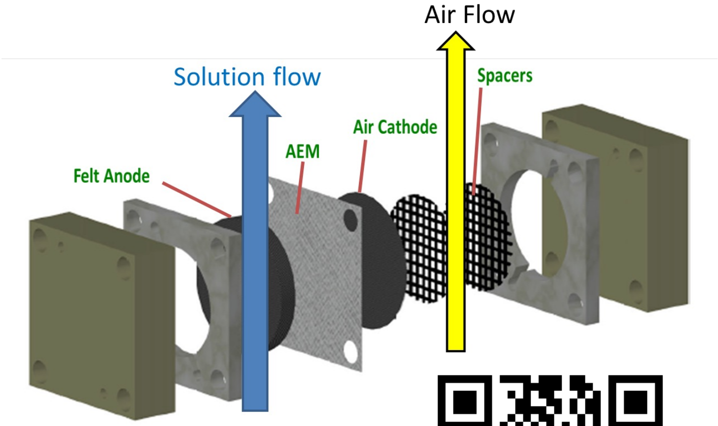
Microbial Electrotechnologies for Converting CO_2 into Natural Gas and Chemicals

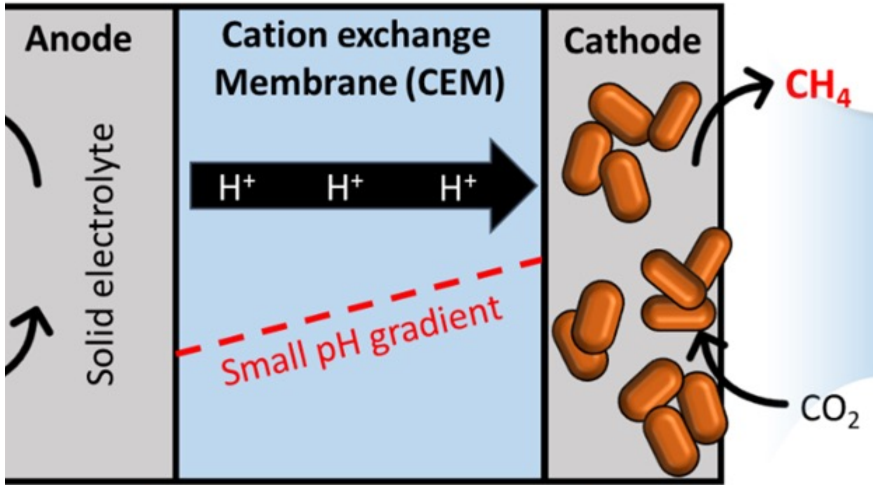
Bruce E. Logan

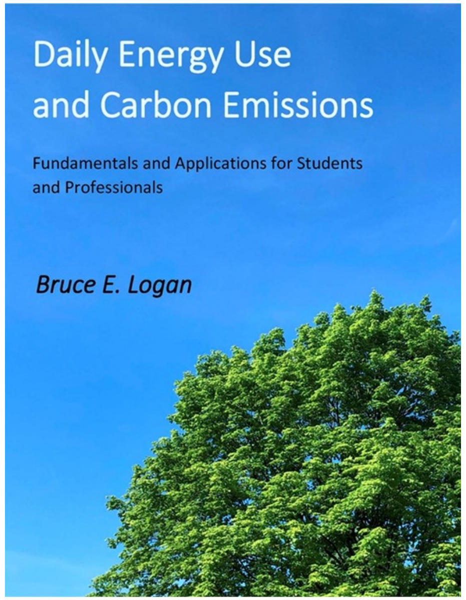
Penn State University, blogan@psu.edu

CORC Carbon Forum
December 7, 2022



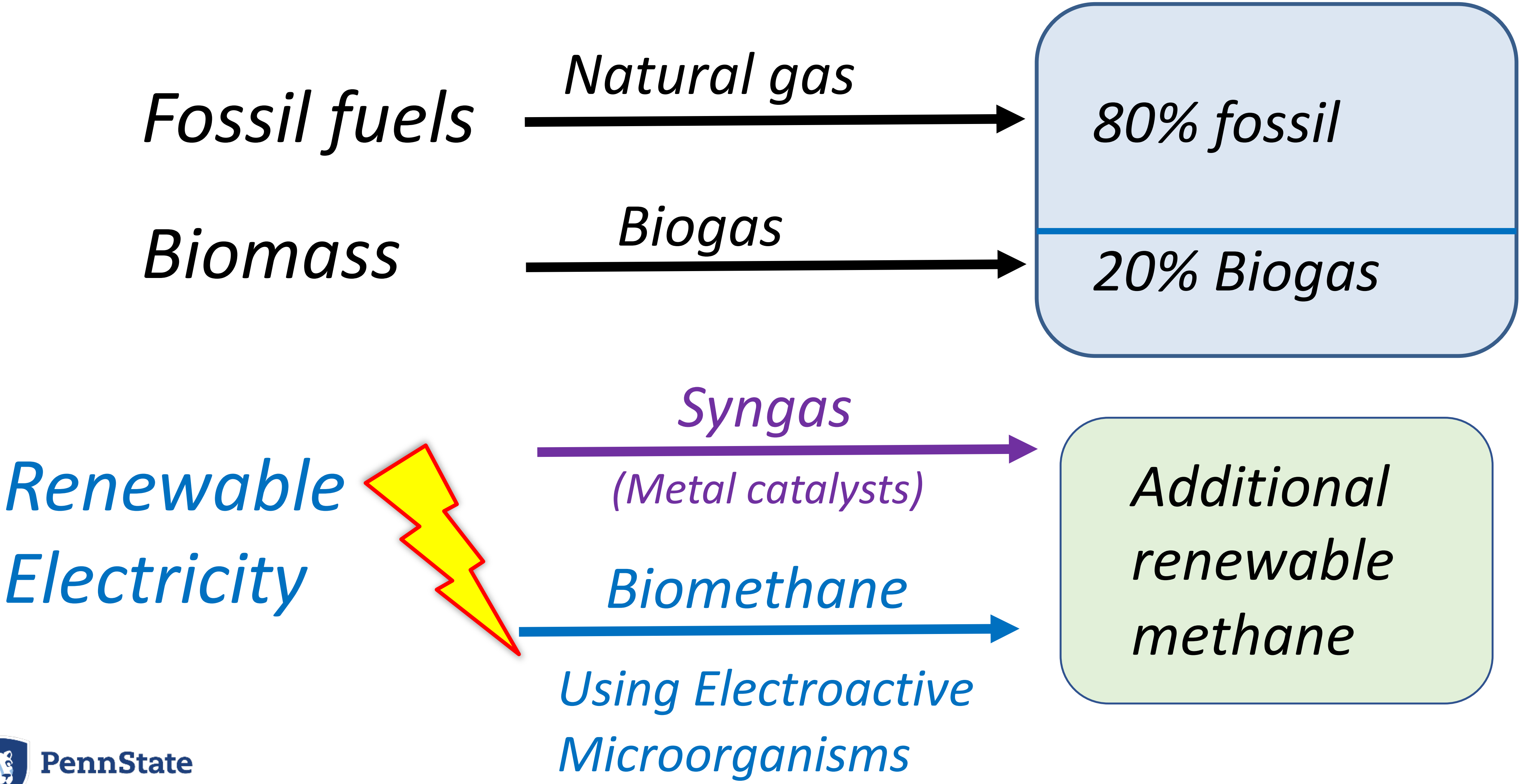






PennState

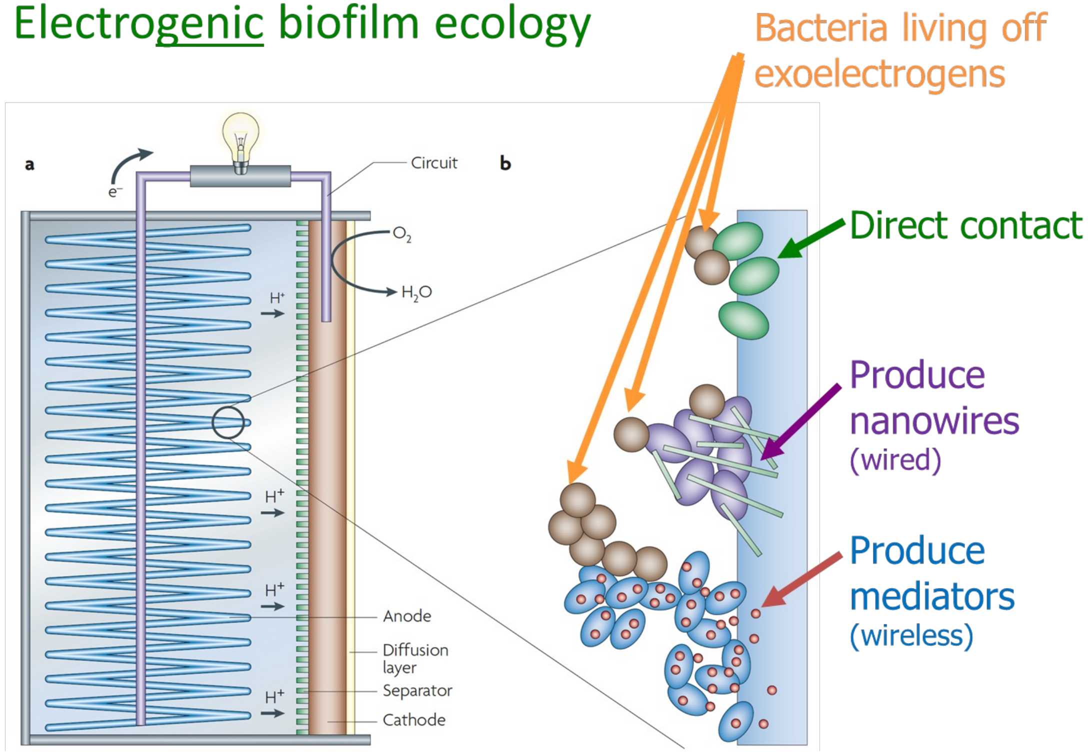
Gas (CH_4) is 16% of Energy use by Denmark



Electroactive microorganisms for Bioelectrochemical Systems

- Exoelectrogenic microorganisms
  - Generate electricity using inorganic (H_2) and simple organic molecules (e.g. acetate)
- Electrotrophic microorganisms
  - Accept electrons and reduce CO_2 to chemical products such as methane (CH_4) and simple organic molecules
- Interspecies electron transfer
  - Electron transfer between two microorganisms of different species
- Bioelectrochemical systems (BES)
  - Use electroactive (electrogenic or electrotrophic) microorganisms in systems with electrodes.

Electrogenic biofilm ecology

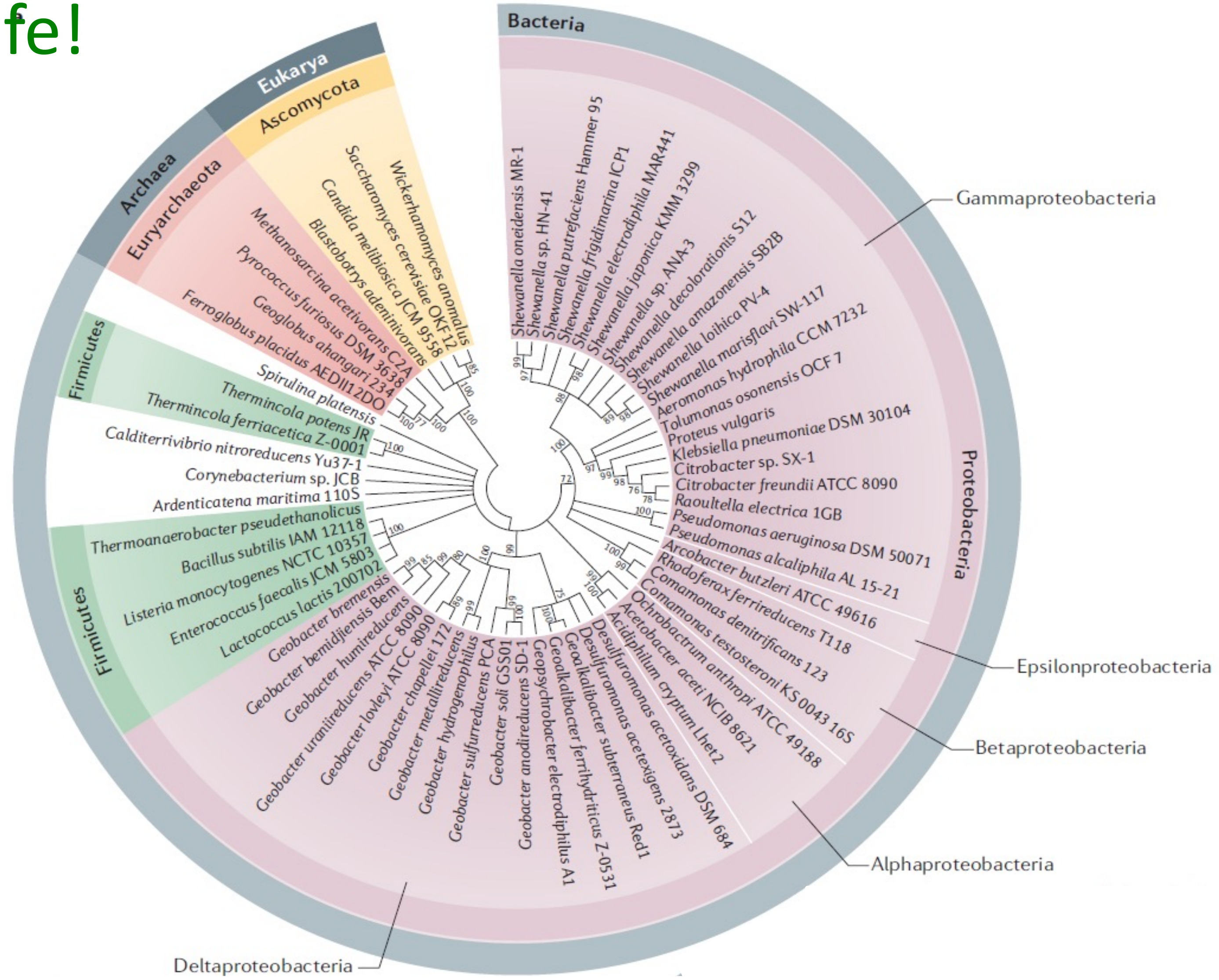


Logan, *Nature Rev. Microbiol.* (2009)

PennState

Exoelectrogenic microorganisms span all 3 domains of life!

- Bacteria
- Archaea
- Eukarya

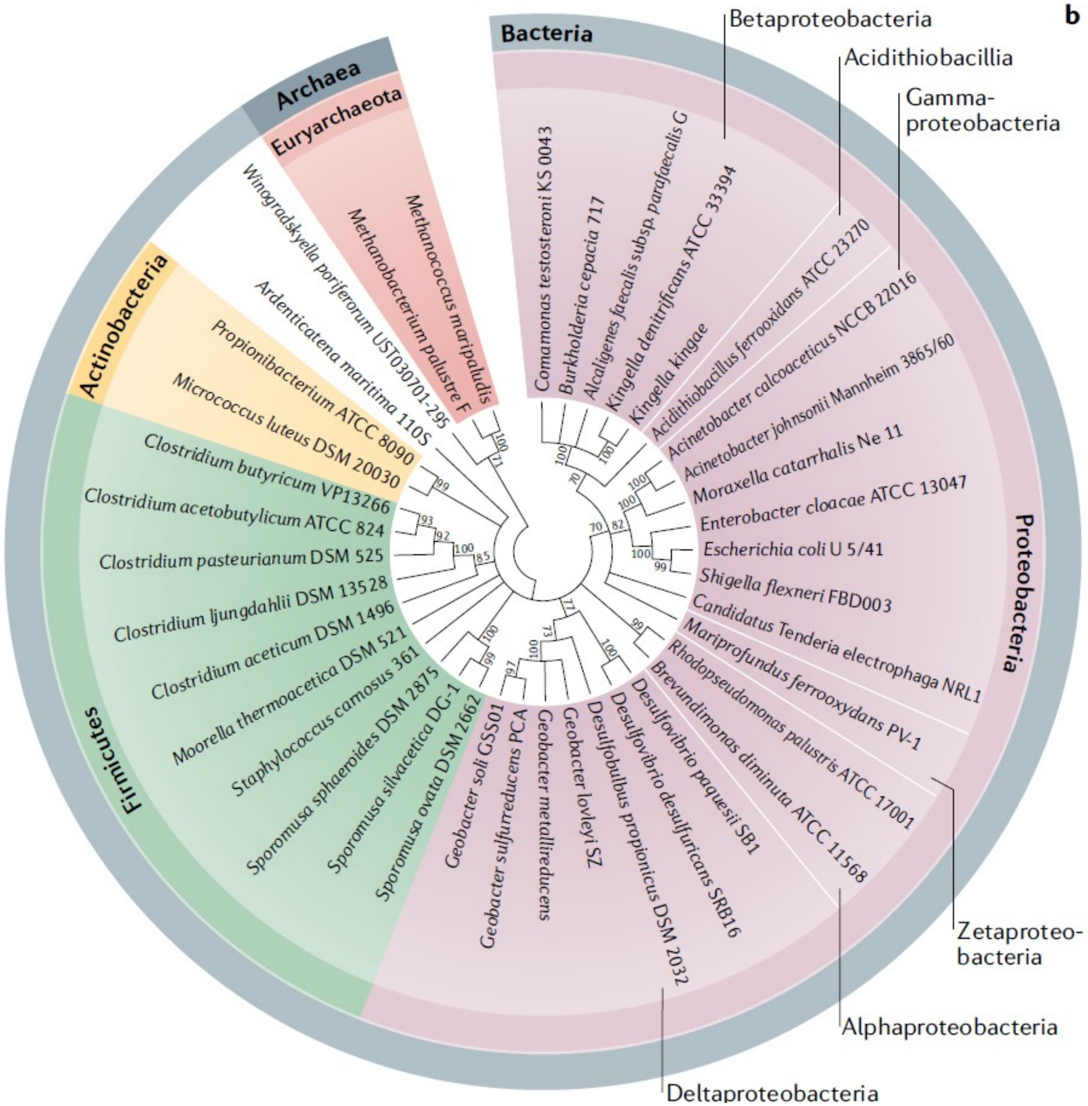


Logan, Rossi, Ragab, Saikaly (2019) *Nature Rev. Microbiol.*

Exoelectrotrophic microorganisms span 2 domains of life

- Bacteria
- Archaea

(no Eukarya)



Logan, Rossi, Ragab, Saikaly (2019) *Nature Rev. Microbiol.*

Bioelectrochemical Sysems (BES)

BES: Any reactor with microbes and electrical current

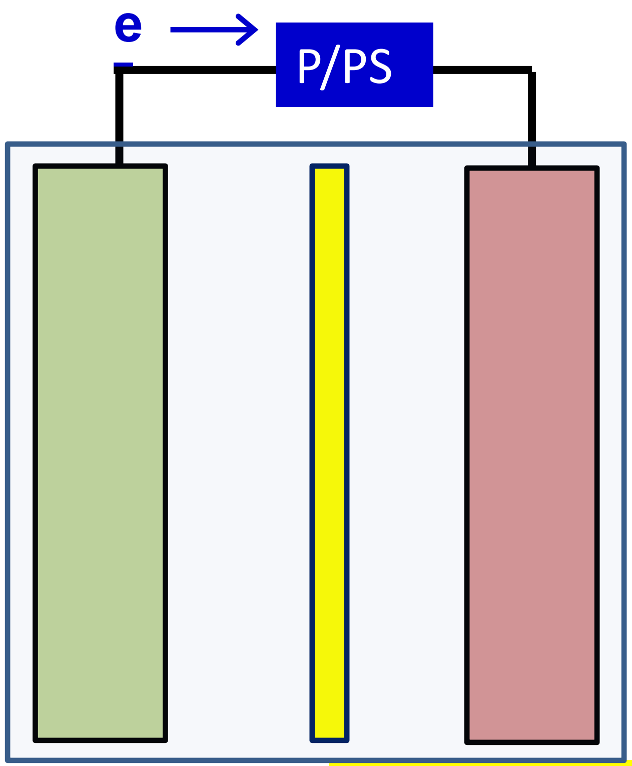
MET: Microbial Electrochemical Technologies (MFC, MEC, etc.)

Anode

- Exoelectrogenic Microbes (Bioanode)

or

- Abiotic (no microbes)



Cathode

- Electrotrophic Microbes (Biocathode)

or

- Abiotic (no microbes)

Power

- Generated (P) = Microbial fuel cell (MFC)
- Added (PS) → Microbial electrolysis cells (MEC) for H_2 or CH_4 generation at the cathode

Membrane

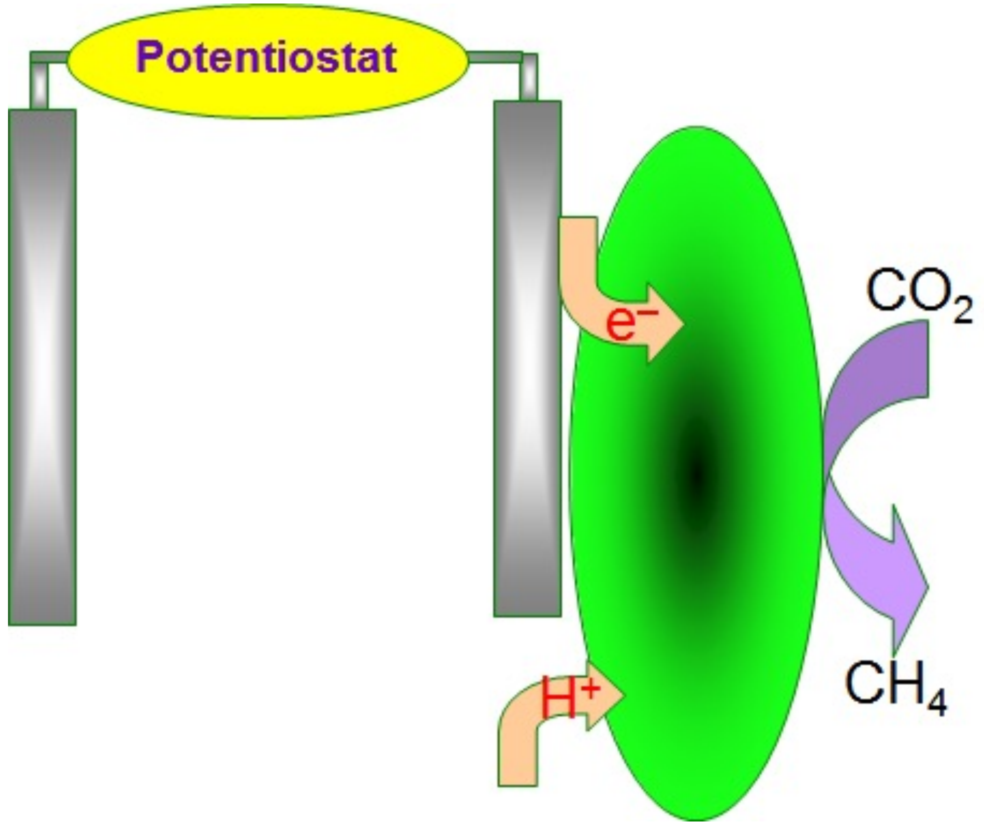
- None
- 1 or more

PennState

Many different chemicals can be used by electrotrophs to finally accept electrons from the cathode

Electron acceptors

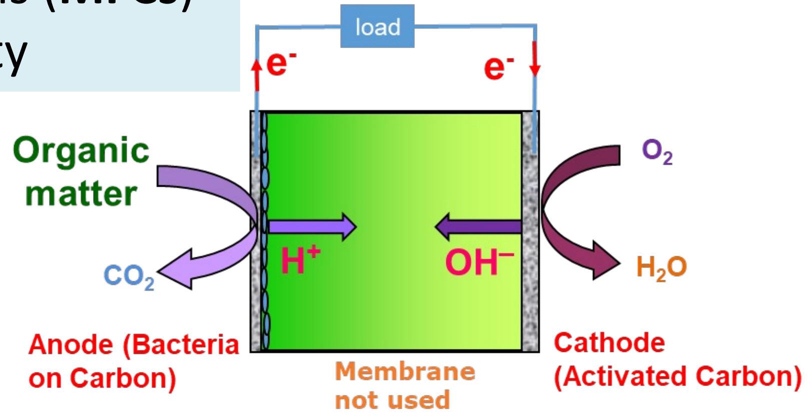
- Oxygen (makes electricity)
- Nitrate (denitrification)
- Metals (Copper plating)
- CO_2: reduction to produce organic compounds such as acetate
- CO_2: reduction by methanogens to make methane (CH_4)

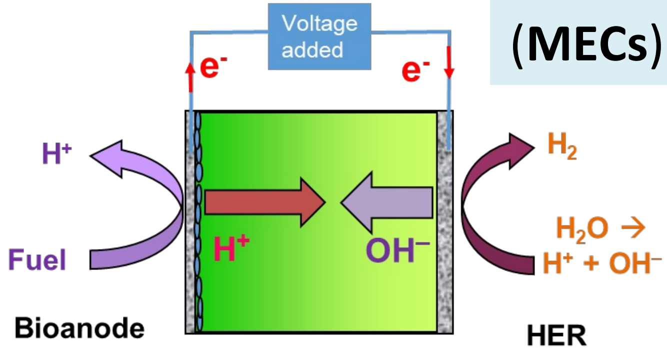


3 Main METs: MFCs, MECs, MMCs (MES)

Bacteria that generate electricity

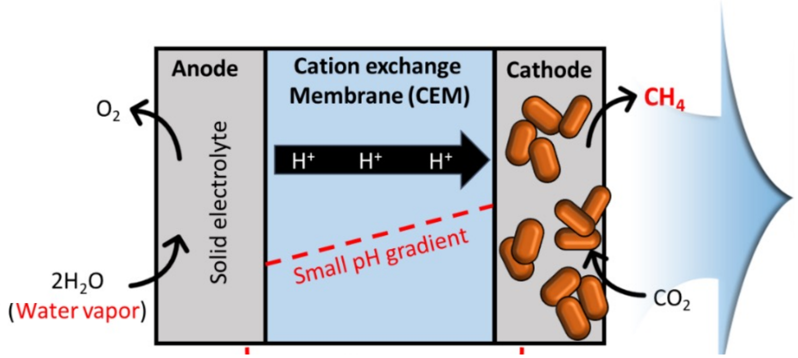
Microbial fuel cells (**MFCs**) produce electricity





Microbial electrolysis cells (**MECs**) produce H_2

Microorganisms that consume electricity (or H_2)



Microbial electrosynthesis cells (**MES**) produce chemicals

Microbial methanogenesis cells (**MMCs**) produce CH_4

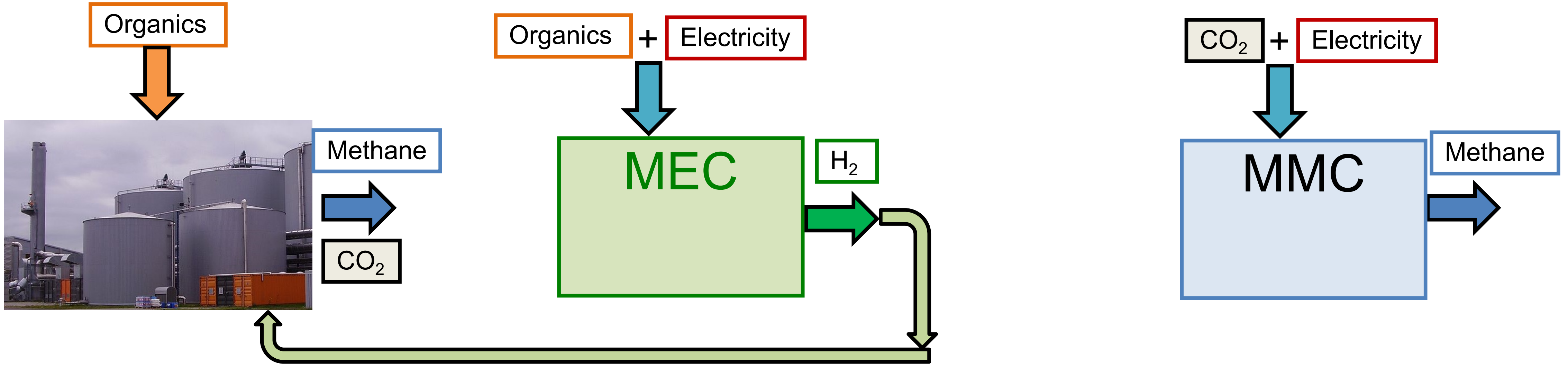
MES: Microbial ElectroSynthsis of chemicals

- BES → MES: Microbial electrosynthesis
- MET → MMC: microbial methanogensis cells

AD= anaerobic digestion

MECs can make H_2

MMCs can make methane from renewable electricity



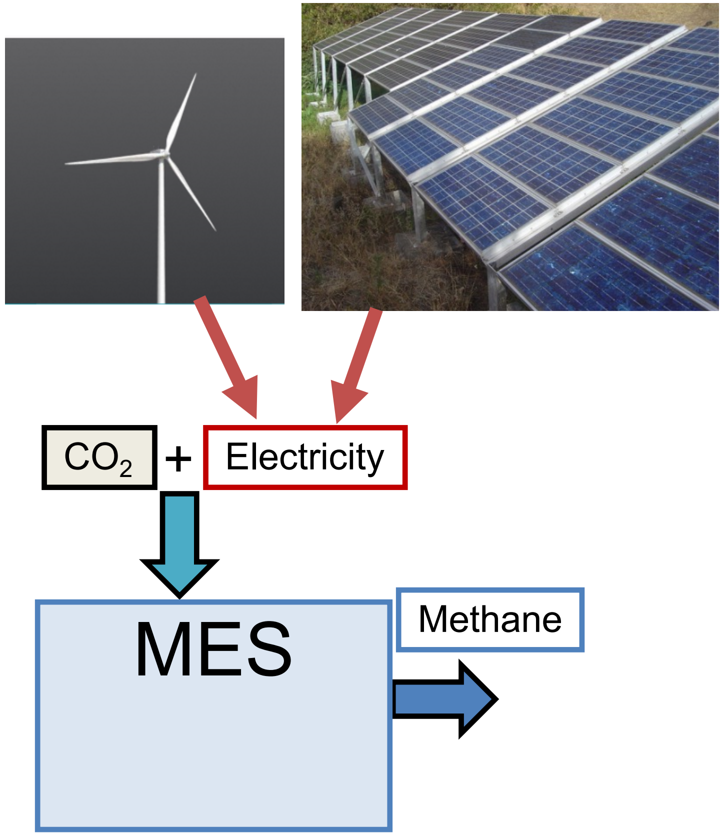
H_2 can be used to enhance methane concentrations and performance of anaerobic digesters (AD)

PennState

How can we move the MES technology forward?

1. Need to understand and optimize components
    a. Most effective microorganisms?
    b. How do methanogens get electrons?
    c. What are the best cathode materials?
2. How do we construct the reactor?
    a. MET: Different configurations
    b. MMC: New designs for methane generation
    c. Operation
    d. Materials
3. What next?

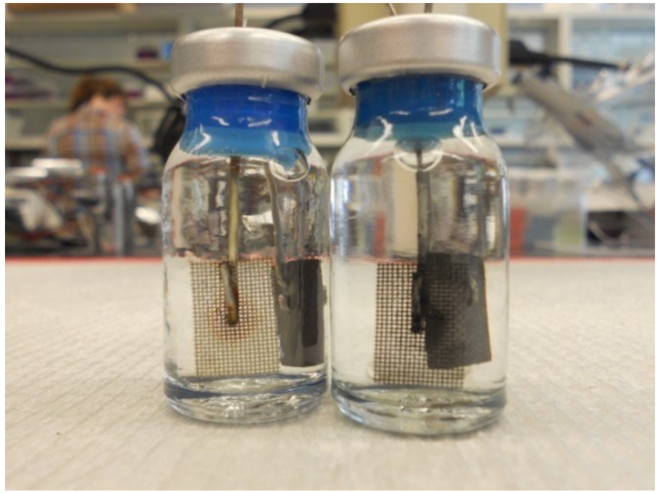
- BES → MES: Electromethanogensis
- MET → MMC: microbial methanogensis cells



1a. What **microbes** are on the cathodes to make methane?

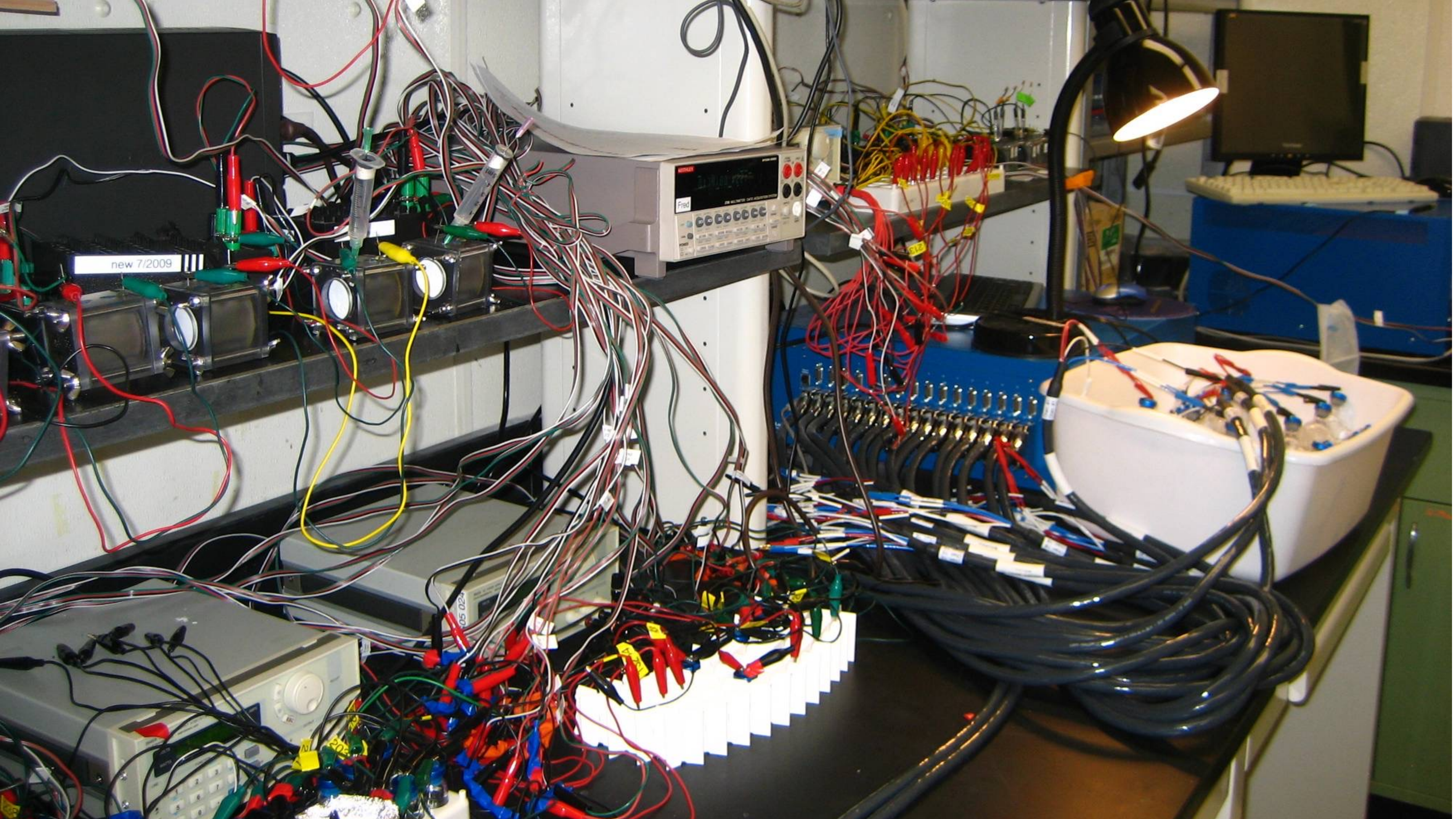
- Seek out diverse but rich sources of microorganisms
  - Anaerobic Digesters (AD), from the Penn State WWTP
  - Freshwater bog sediments (Bog)
- Examine in small reactors
  - Methane production with biotic anodes and cathodes
  - Amount of current
  - Microbial community

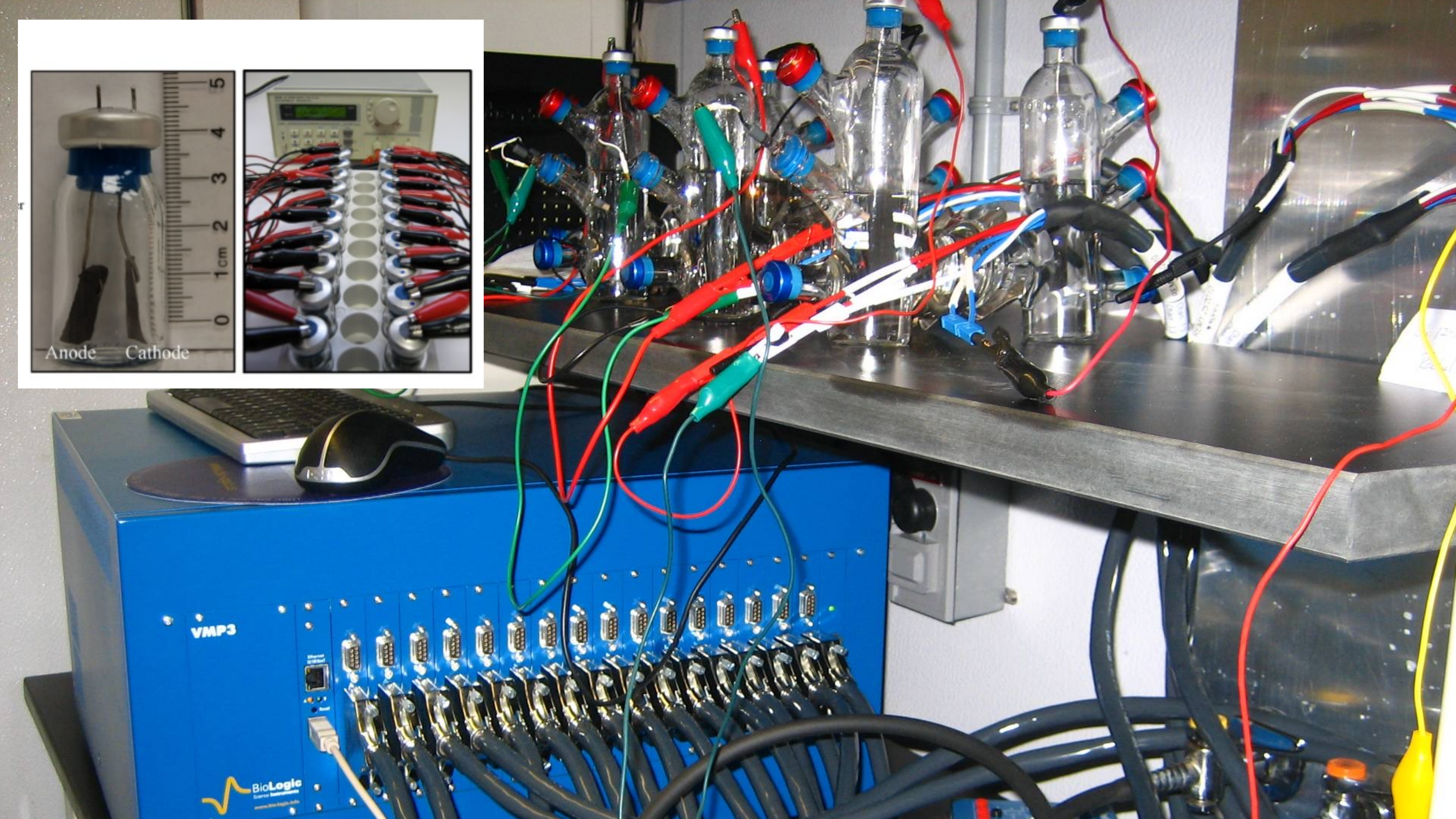
Call & Logan Biosens & Bioelectr 2011



Siegert, Li, Yates, Logan (2015) *Frontiers Microbiol.*

PennState

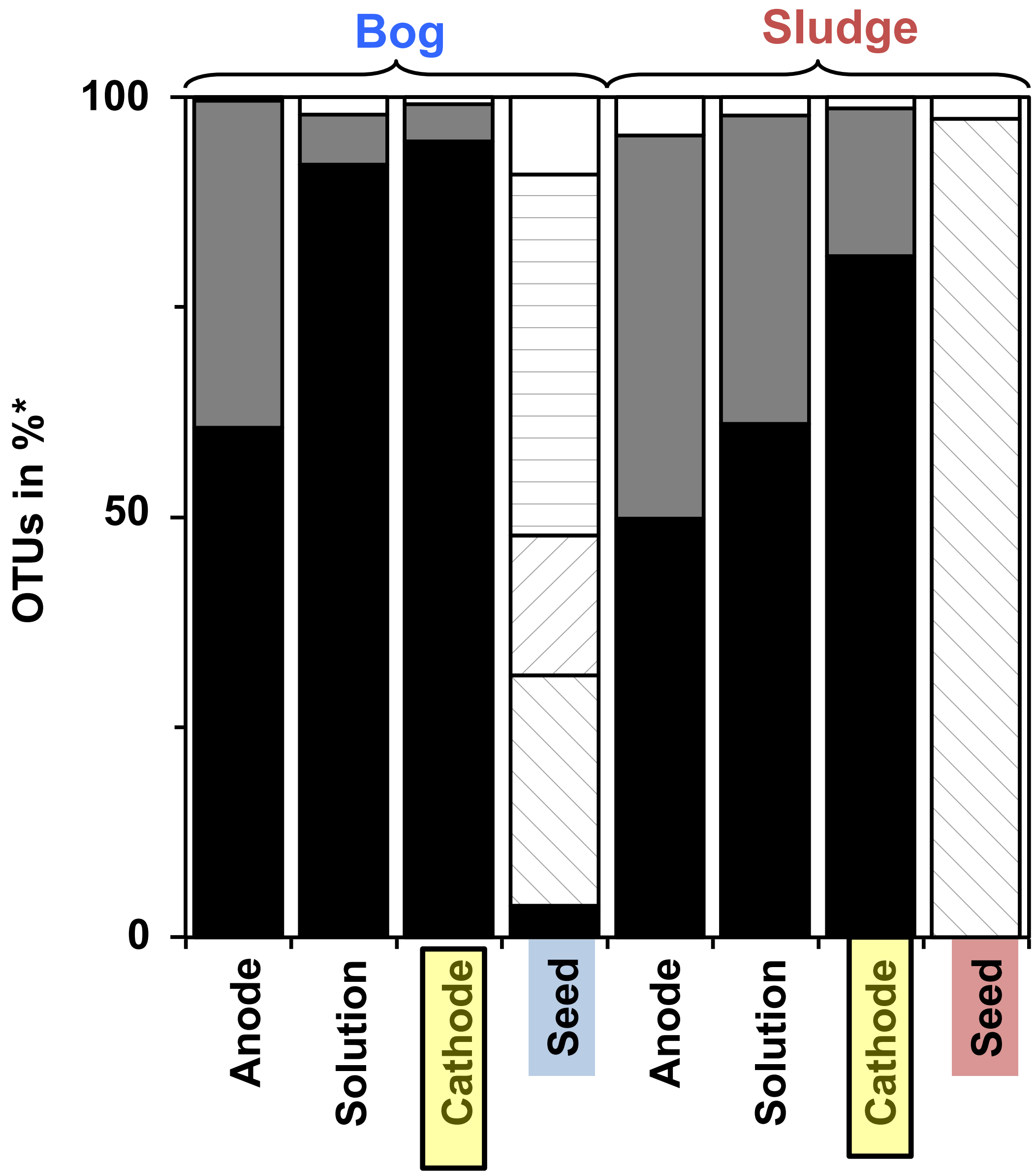

new 7/2009
Fred



Anode
Cathode
VMP3
BioLogic

Cathode Communities (*Archaea*) are mostly *Methanobacterim*

- **Others <10% each**
- **Miscellaneous Crenarchaeotic Gp**
- **Terrestrial Miscellaneous Gp**
- ***Methanosaeta***
- ***Methanobrevibacter***
- ***Methanobacterium***



- <u>Seed very different</u> from final communities
- Final Bog and Sludge communities **similar** to each other
- Mostly *Methanobacterium*

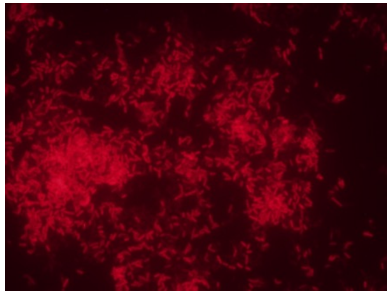
***OTU = operational taxonomic unit**

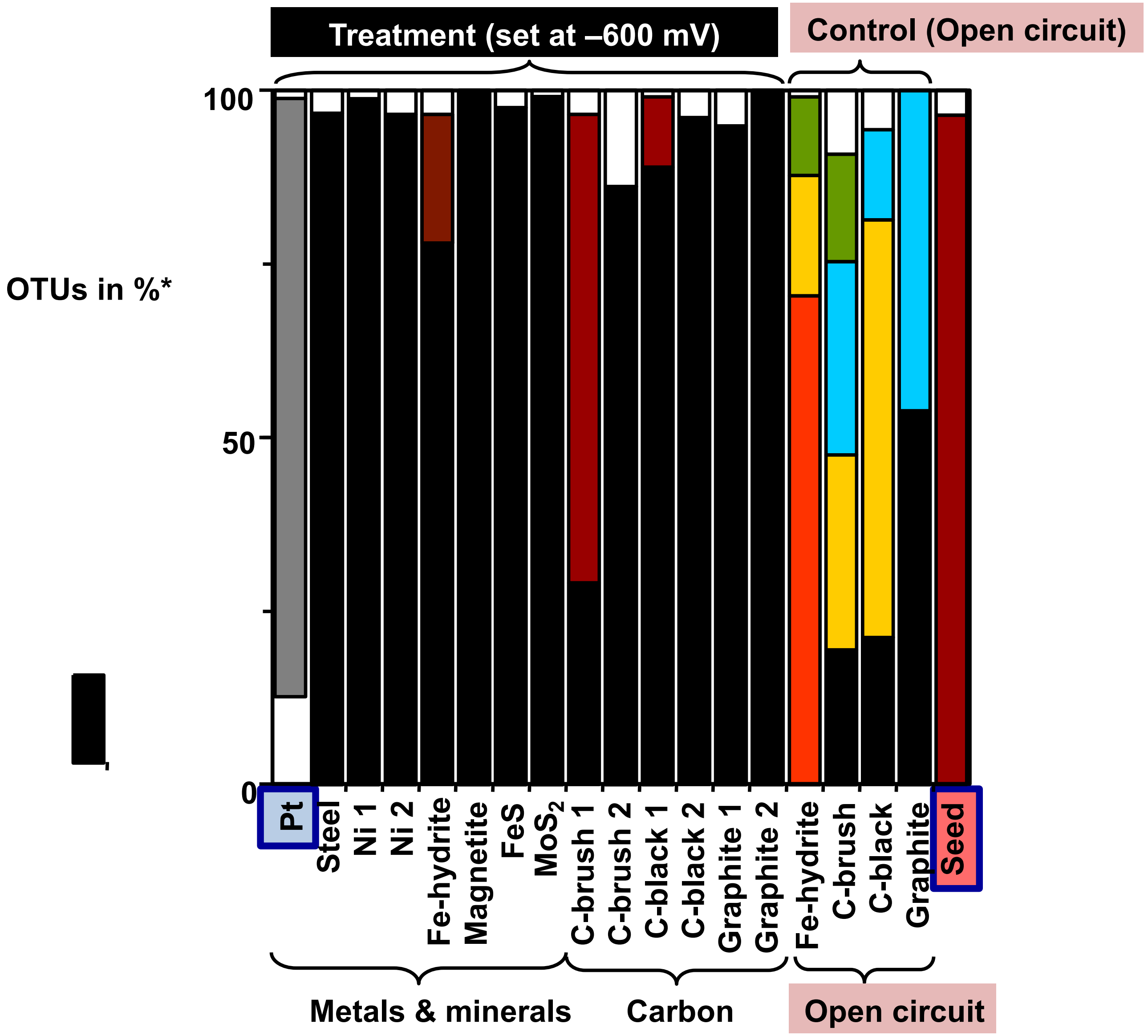
PennState

Siegert, Li, Yates, Logan (2015) *Frontiers Microbiol.*

Methanobacterium predominant (except with Pt)

Methanobacterium :
FISH probe



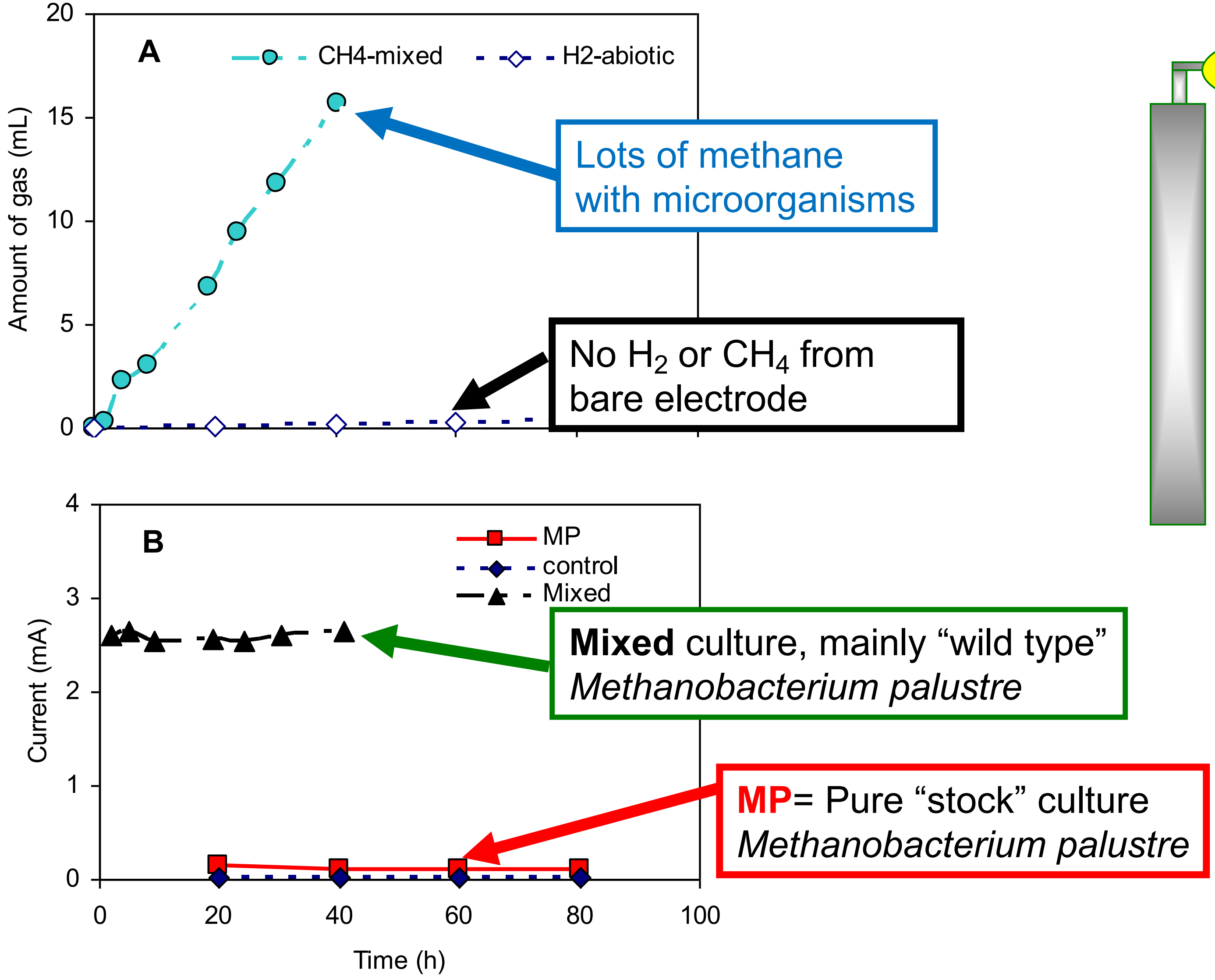


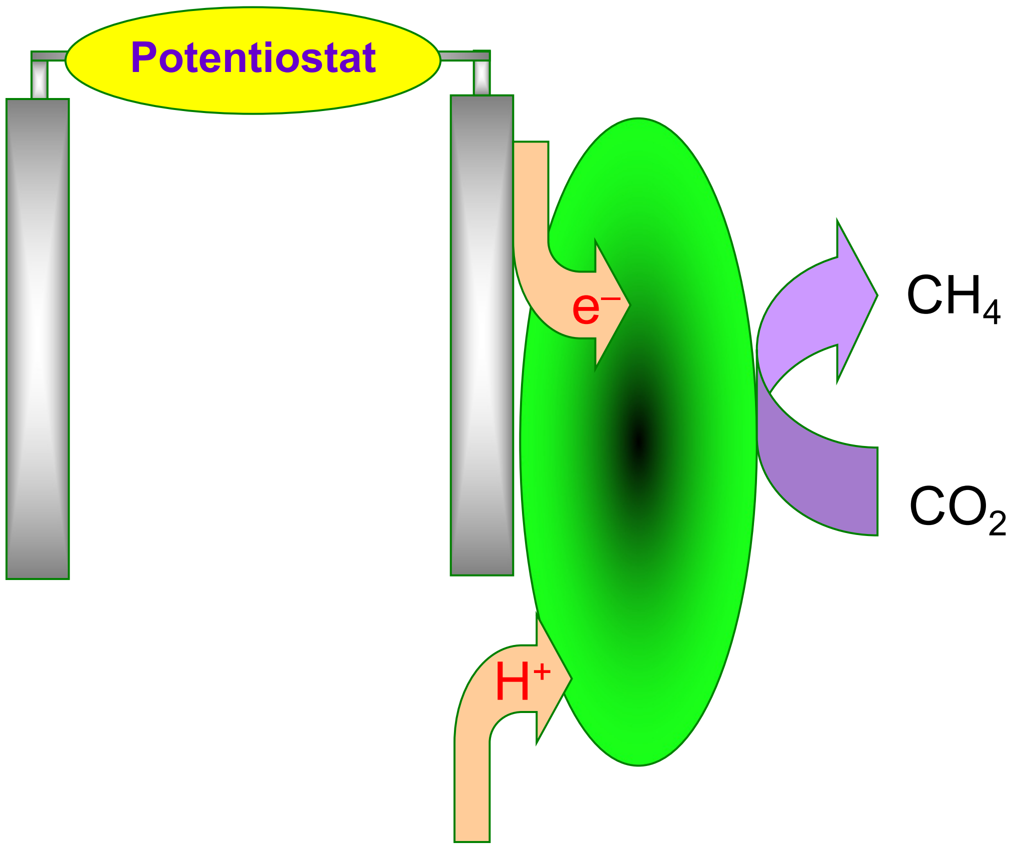
*OTU = operational taxonomic unit

Siegert, Yates, Spormann, Logan (2015) *ACS Sus. Chem. Engin.*

PennState

Electrotrophic Methanogens: facilitate current

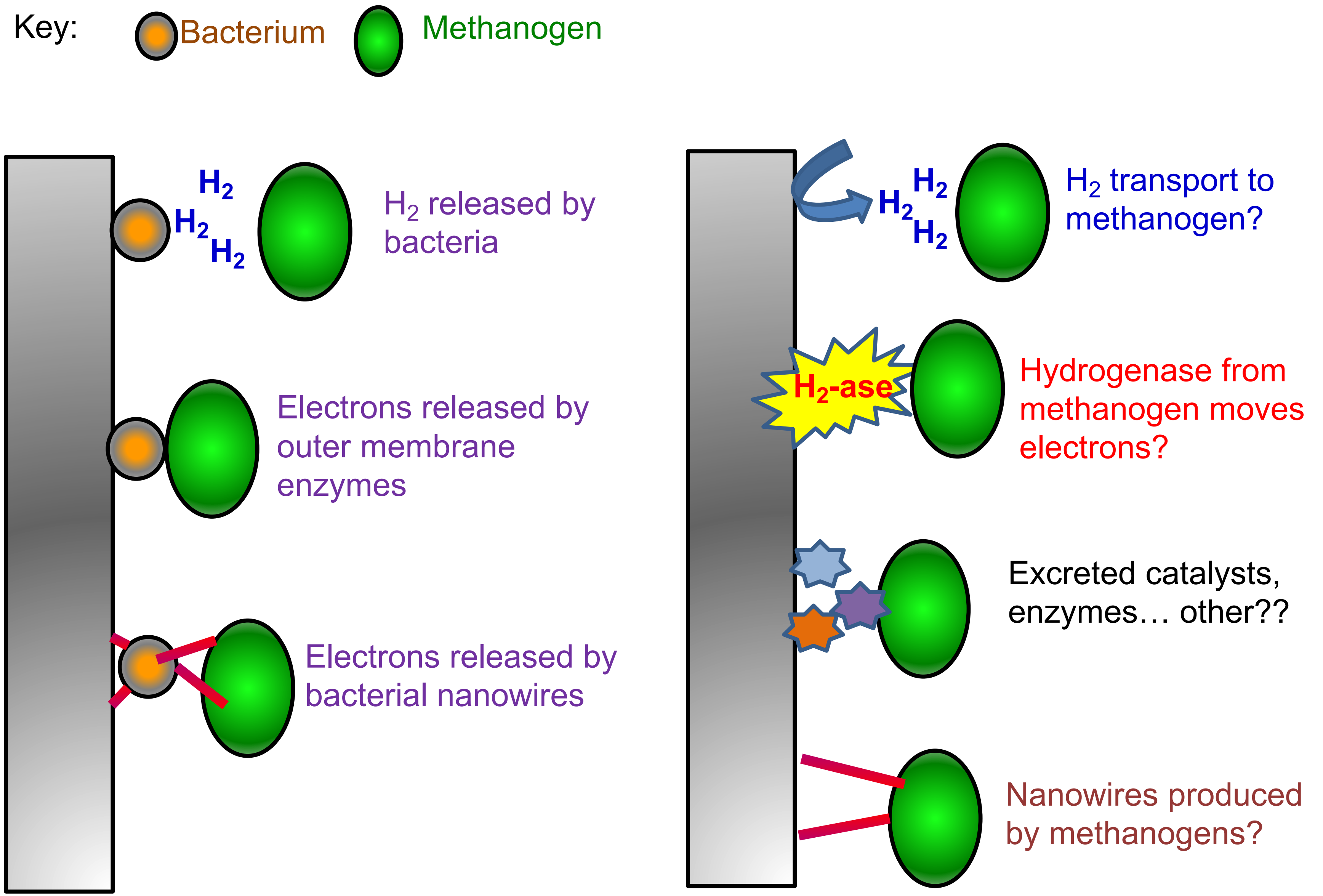




PennState

Cheng, Call & Logan (2009) Environ. Sci. Technol.

1b. How do electrons get to methanogens?



PennState

1c. Best cathode materials for methane production in MMCs?

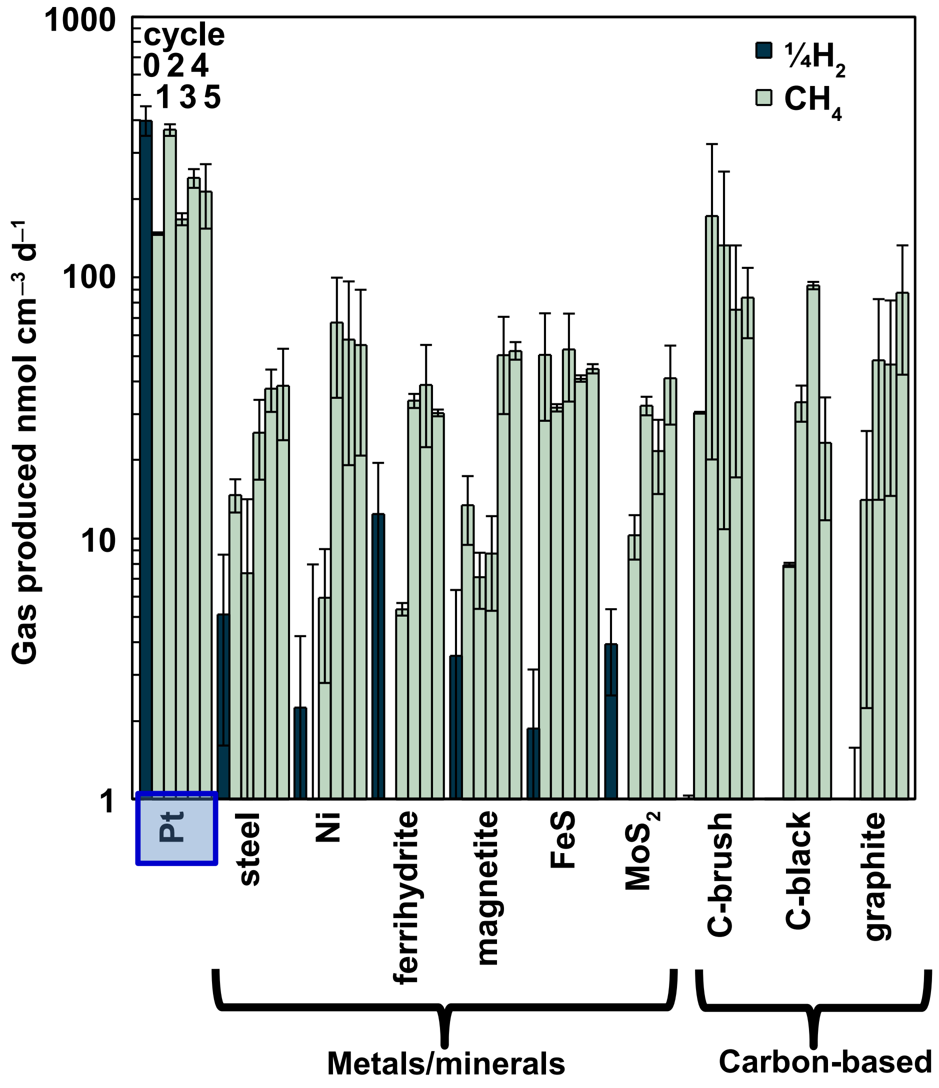
- Materials can affect MES through changing:
  - H_2 evolution rates: Adding catalysts impacts how fast H_2 can be released from the surface
  - How methanogens take in electrons or their enzymes interact with the surface
- Materials Tested:
  - **Platinum**: the best catalyst for H_2 evolution
  - Metals & Minerals that are good catalysts and inexpensive: **Stainless Steel, Ni, MoS_2; ferrihydrite, magnetite, FeS**
  - Carbon: not good catalyst, very cheap: **carbon fiber brushes** have very high surface area!

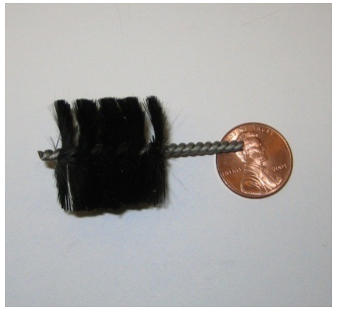
PennState

Siegert, Yates, Call, Zhu, Spormann, Logan (2014) *ACS Sus. Chem. Engin.*

Effect of cathode materials on CH_4 production

- If current forms H_2, that is the blue bar
  - 4 moles hydrogen needed to form 1 mole of methane
- Platinum (Pt) is the best
  - Noble metal, expensive
  - Agreement of blue and green bars indicates H_2 gas produced that was then used to make methane
- Carbon brushes
  - Next best material
  - High surface area of carbon brushes likely facilitates direct electron transfer

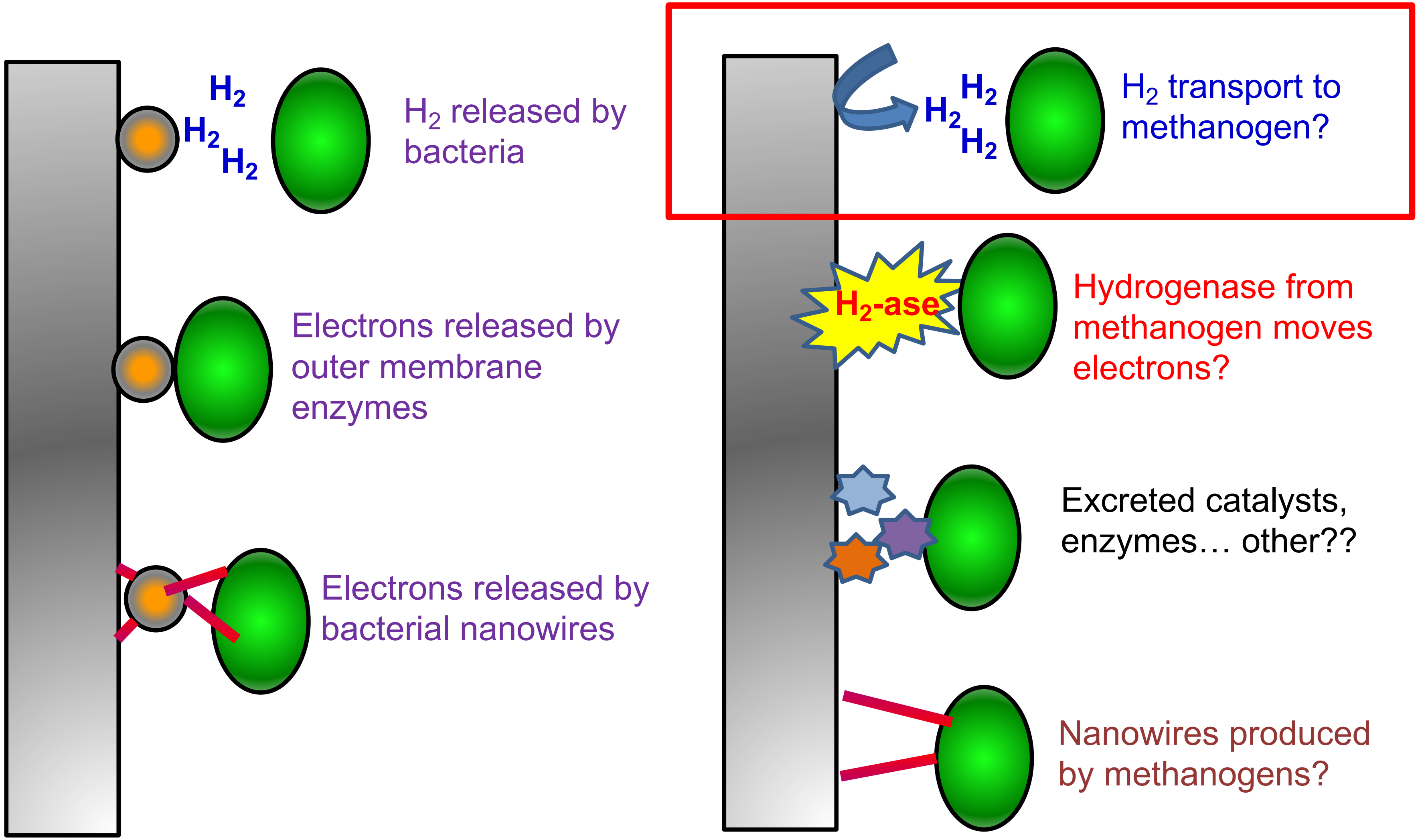




Siegert, Yates, Call, Zhu, Spormann, Logan (2014) *ACS Sus. Chem. Engin.*

PennState

Using H_2 likely most important for high rates



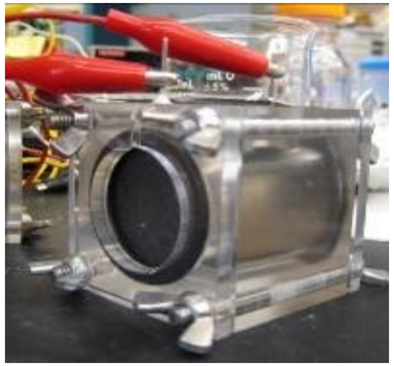
PennState

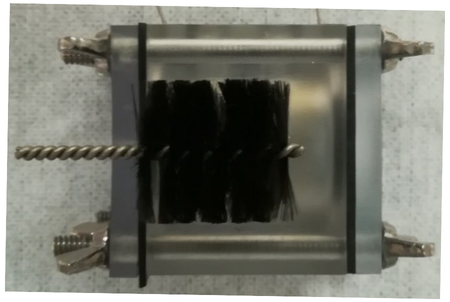
2a. Scaling up METs:

PennState

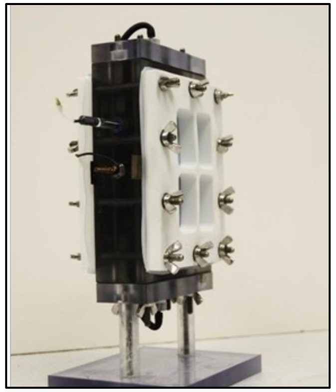
2a. Scaling up METs: Pilot-scale MFCs for electricity

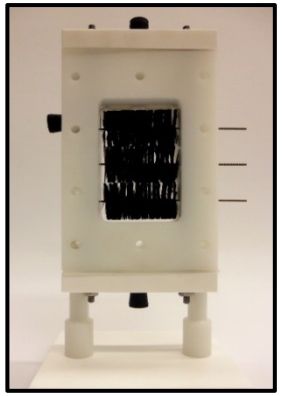
Gen 0: 0.025 L, 25 m²/m³



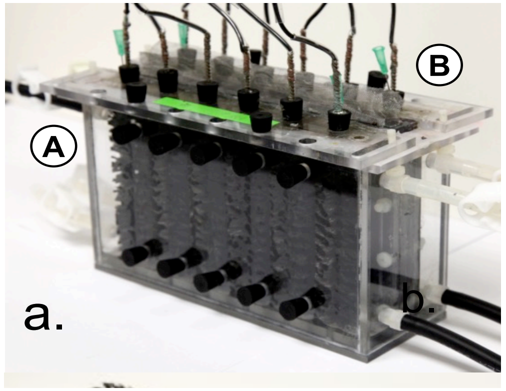


Gen 1: 0.13 L, 25 m²/m³

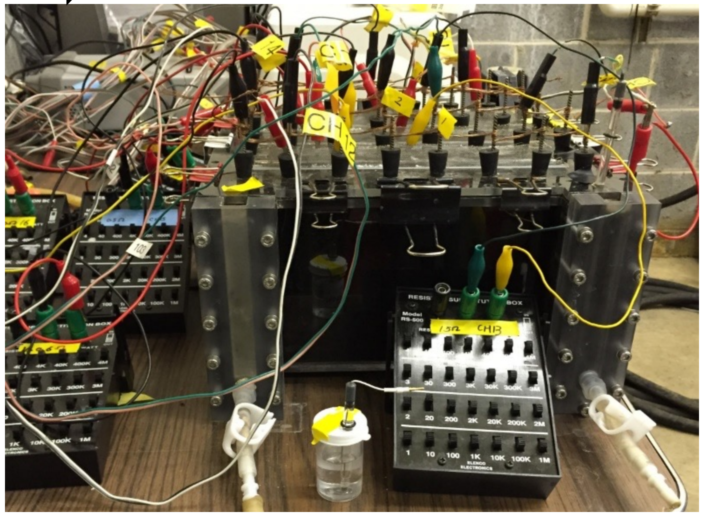




Gen 2: 2 L, 20 m²/m³

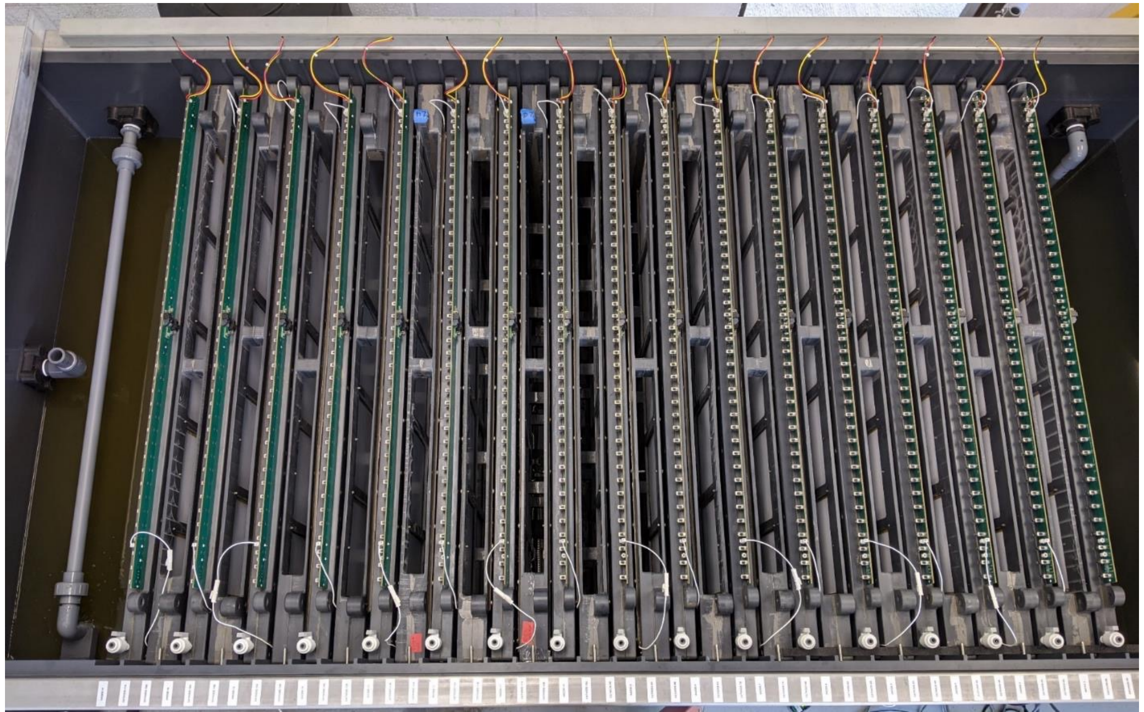


Gen 3: 6.1 L, 20 m²/m³



Pilot-Scale MFC:

850 L active volume, 25 m²/m³



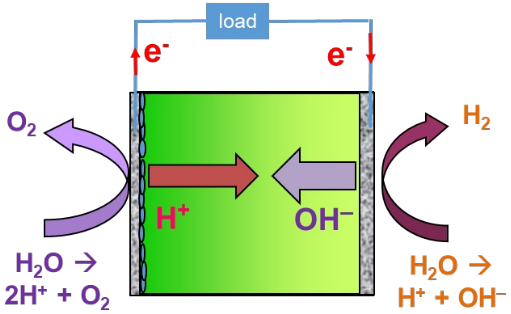
ESTCP

CERL

CDM Smith

PennState

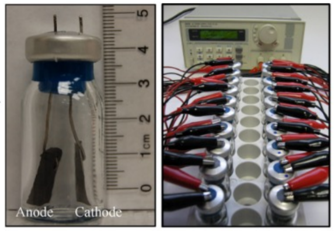
Scaling up MECs for H_2 gas: from 5 mL to 1000 L



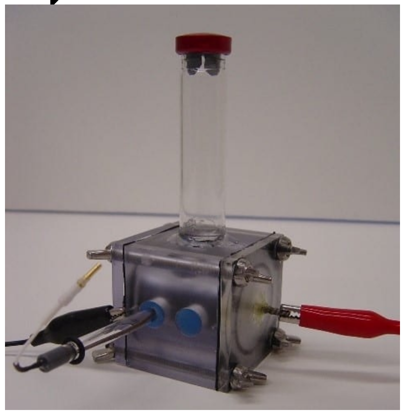
Single-Chamber MECs: $H_2 \rightarrow CH_4$

Thus, methane not H_2 is the product gas

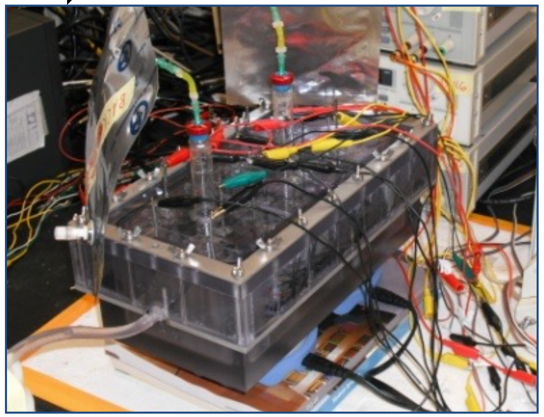
5 mL mini-MEC



28 mL MEC

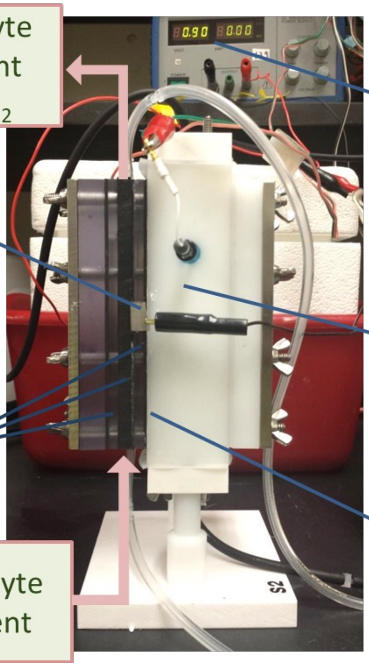


2.5 L MEC



1000 L MEC

<u>Two-Chamber</u> MECs are needed for H_2 recovery

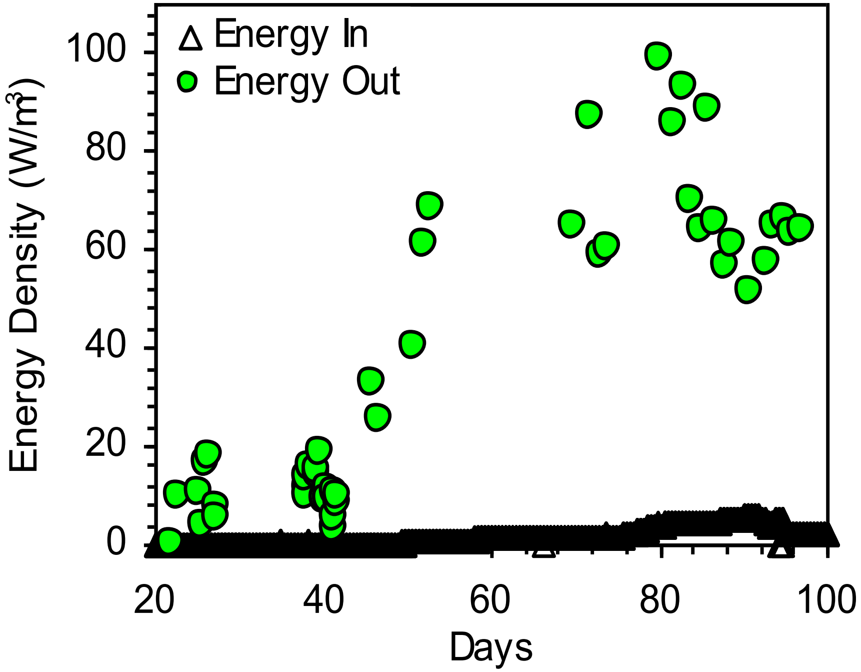


MECs can produce methane from organic matter in dilute wastewaters

CH_4 was produced from wastewater with small energy input

- Elec. Energy in = 6 W/m^3
- Energy Out (CH_4) = 99 W/m^3

16× more energy recovered than electrical energy put into the process



Cusick et al. (2011) *Appl. Microbiol. Biotechnol.*

PennState

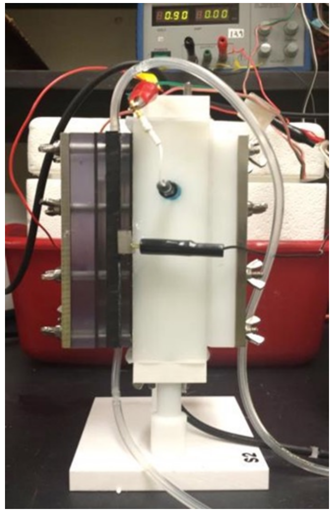
2c. Scaling up MES: Methane Generation from Water Splitting

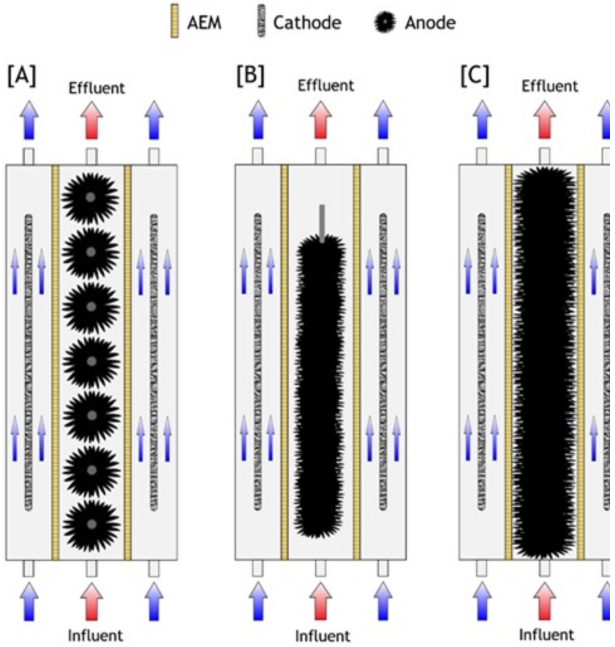
1 Chamber: Generate O_2 at the anode

2 Chamber Bottle reactors: not suitable for scaling up

2 Chamber Brush electrodes: Need too much space (need compact reactors)

2 C: keeps O_2 in separate chamber





Challenge 1 C system: O_2 kills methanogens

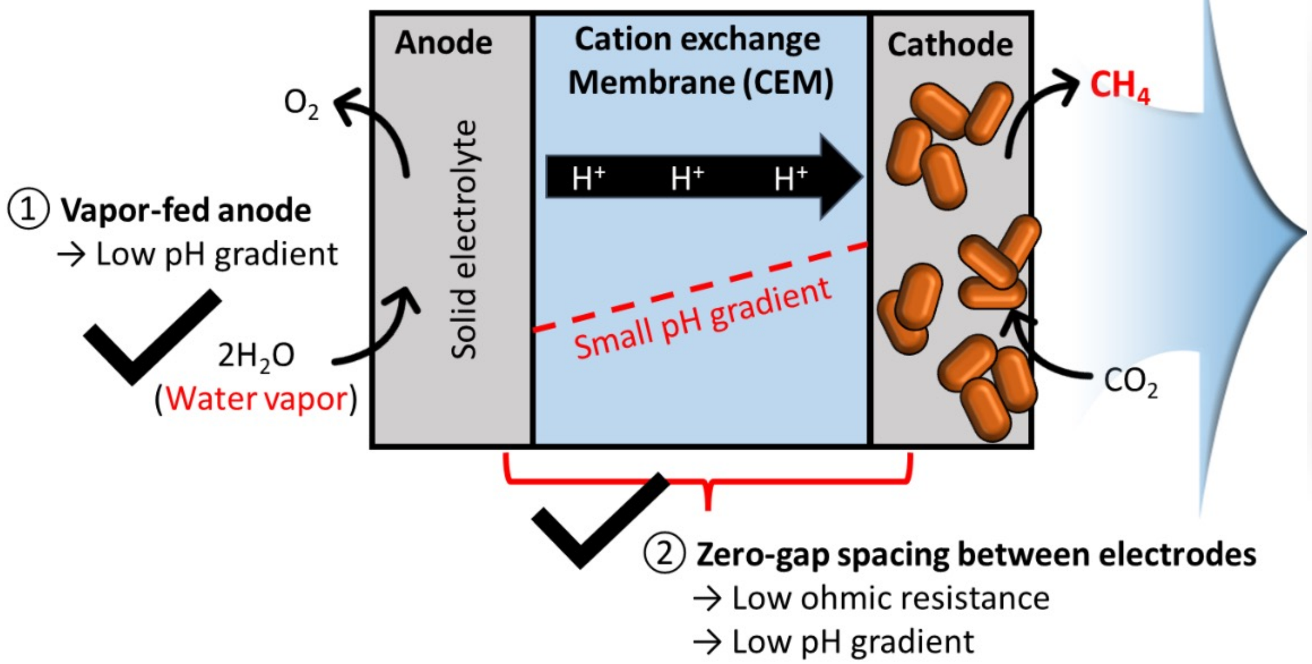
The Challenges of these 2 C systems

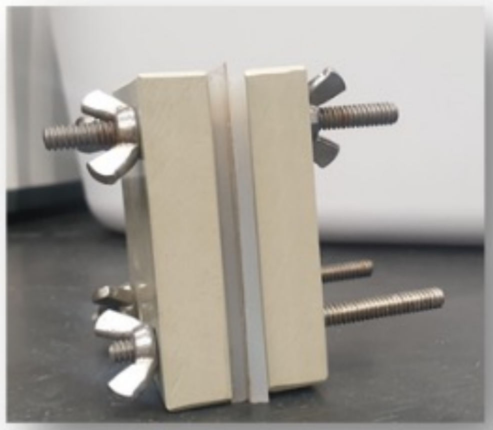
- Wide (or separate) chambers = large energy losses
- The electrode with methanogens gets a high pH

Compact MMC for water splitting & biocathodes

The process

- **Anode:** H^+ produced with O_2 generated by water splitting anode (electrochemical)
- **Membrane:** CEM (cation exchange membrane) transports only H^+ to cathode
- **Cathode:** H+ combines with OH- released from anode
- **Methane** is biologically produced by methanogens on the cathode

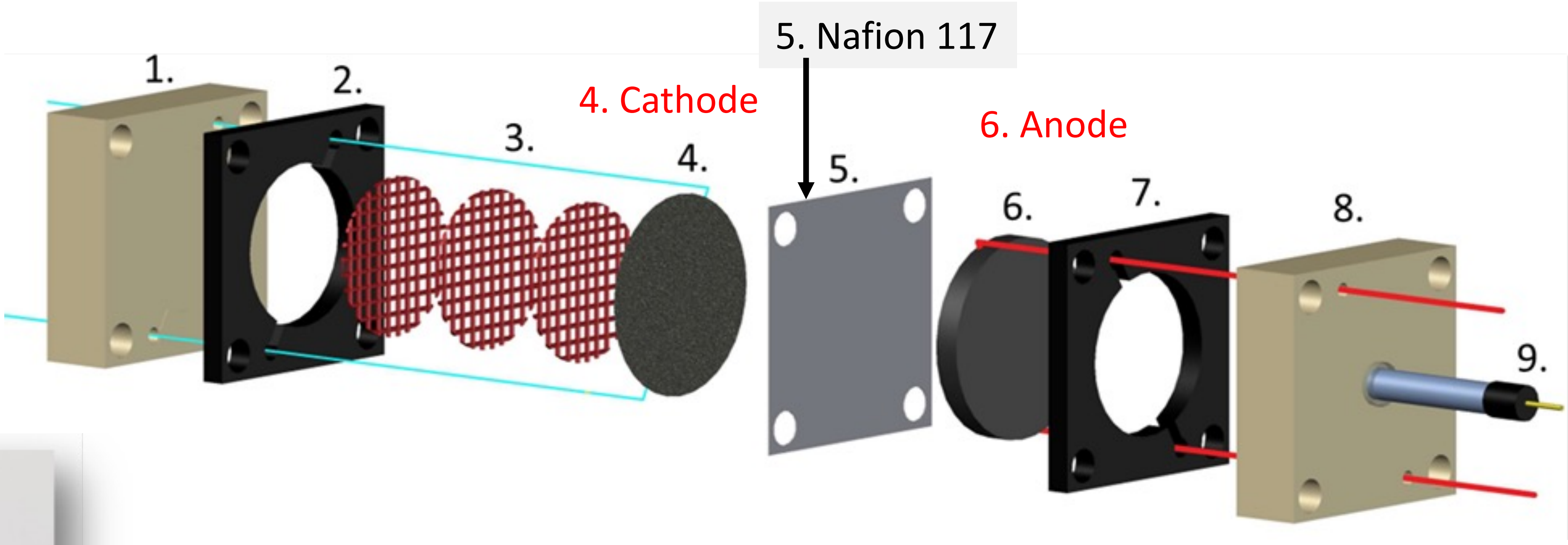


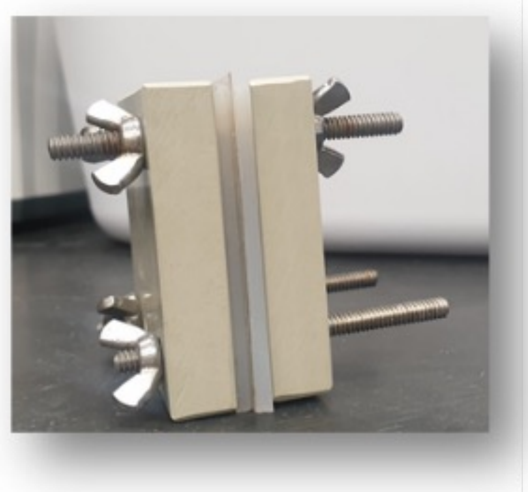


Reactor is very compact!

Baek, Rossi, Saikaly, Logan (2022) *Water Res.*

Water-splitting MMCs have not been scaled up …

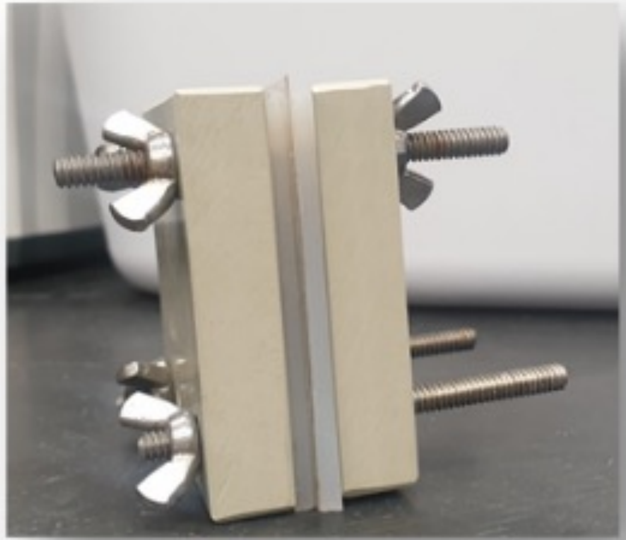




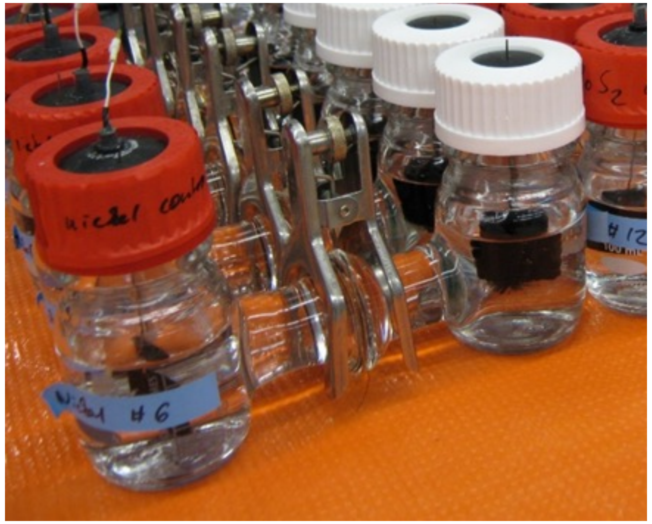
There can be many of these cell pairs in a stack.
Just one cell pair shown here

2d. What have we achieved in MMCs?

- New compact (slab) systems
  - Most energy efficient MMC ever designed: ohmic resistance was 2.4 ± 0.5 mΩ m^2
  - Improved gas production: 2.9 L/L-d (17 A/m^2)



- Previous (bottle) systems
  - Very energy intensive due to high ohmic resistance: 20-25 mΩ m^2 (10× higher)
  - 1000 × lower gas production (0.0062 L/L-d)



Costs to produce CH_4: Only electricity

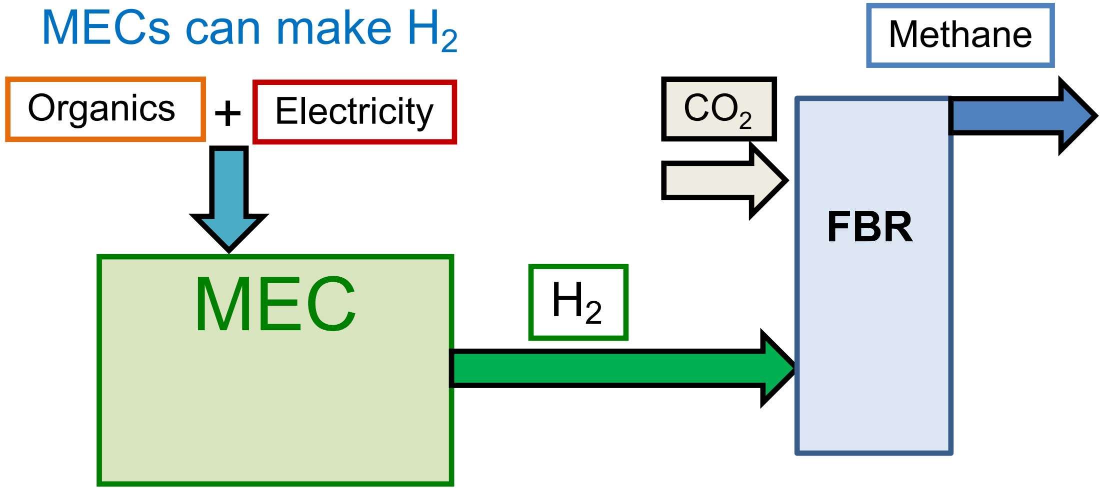
Conditions	Euro	Danish krone
Electricity cost	0.35 €/kWh	2.6 kr/kWh
Natural gas cost (home)- volume - energy	2.3 €/m^3 0.19 €/kWh	17 kr/m^3 1.4 kr/kWh
Renewable biomethane – volume - energy	2.5 €/m^3 0.23 €/kWh	19 kr/m^3 1.7 kr/kWh

- Energy in 1 m^3 of natural gas = 12.2 kWh
  - Same energy in 1.3 L of petrol
  - More energy needed than energy in the gas (thermodynamics)
- Efficiency of changing electricity → CH_4?
  - Currently 17% → This can be improved!
- For comparison: reverse process of CH_4→ electricity
  - Currently 33-65% efficiency based on energy

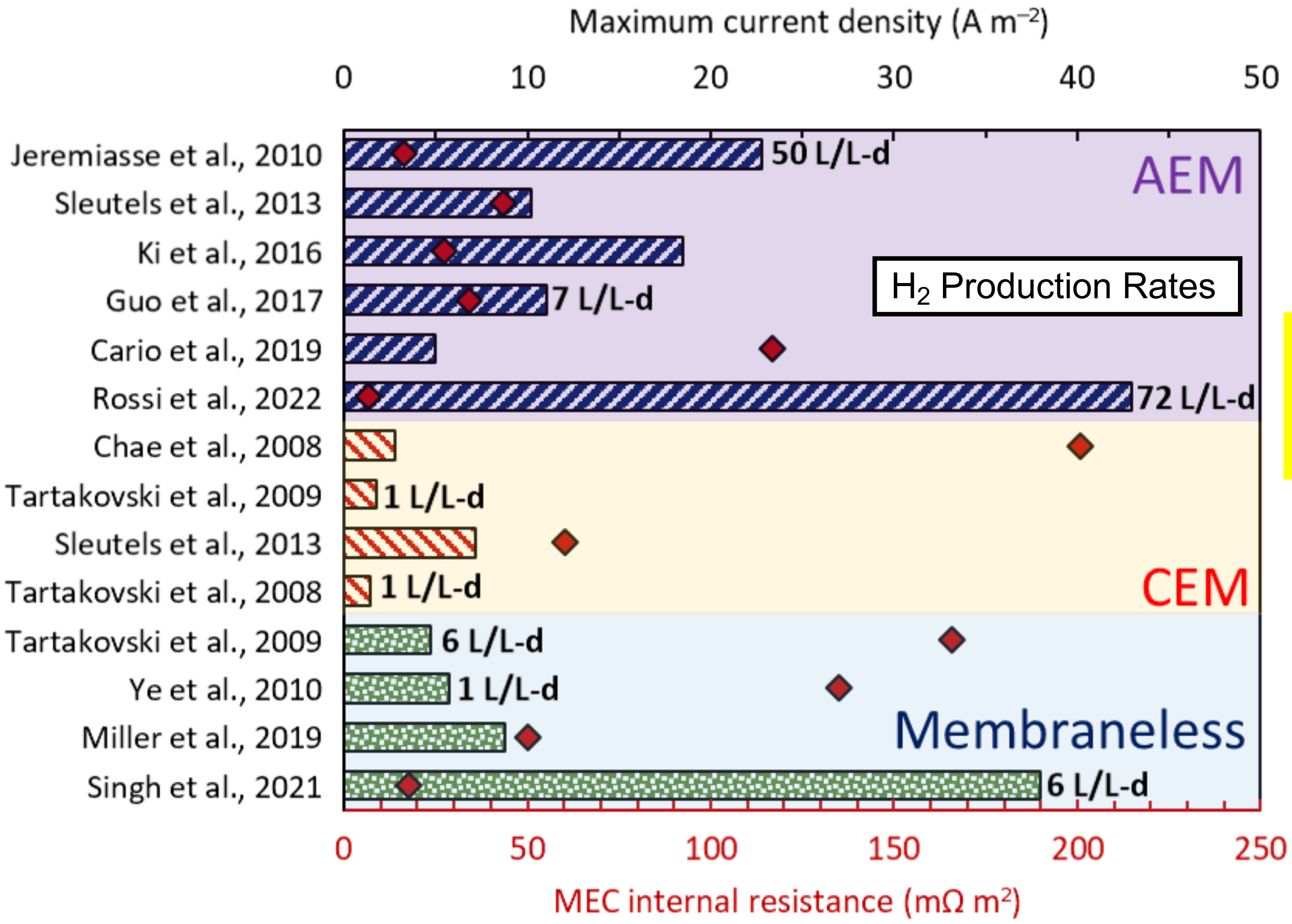
PennState

2e. Future Directions in Electrosynthesis of Methane

- Generate Hydrogen first?
  - Use and MEC? But that requires a source of organic matter for the anode.
  - Rates of MEC > MMC
- Cheap, efficient cathode catalysts
  - Brush and carbon electrodes lack a cathode catalyst.
  - Could we use non-precious metal Ni-based catalysts developed for MECs in MMCs?



H_2 production rates by MECs are higher than CH_4 in MMC



72 L/L-d H_2 =

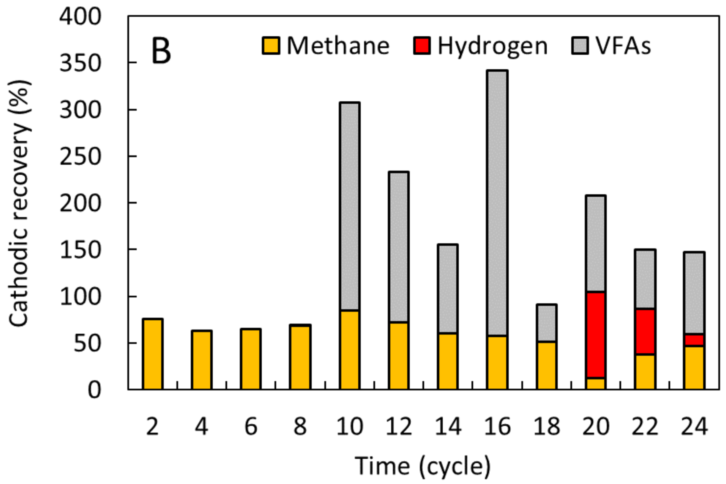
18 L/L-d CH_4

PennState

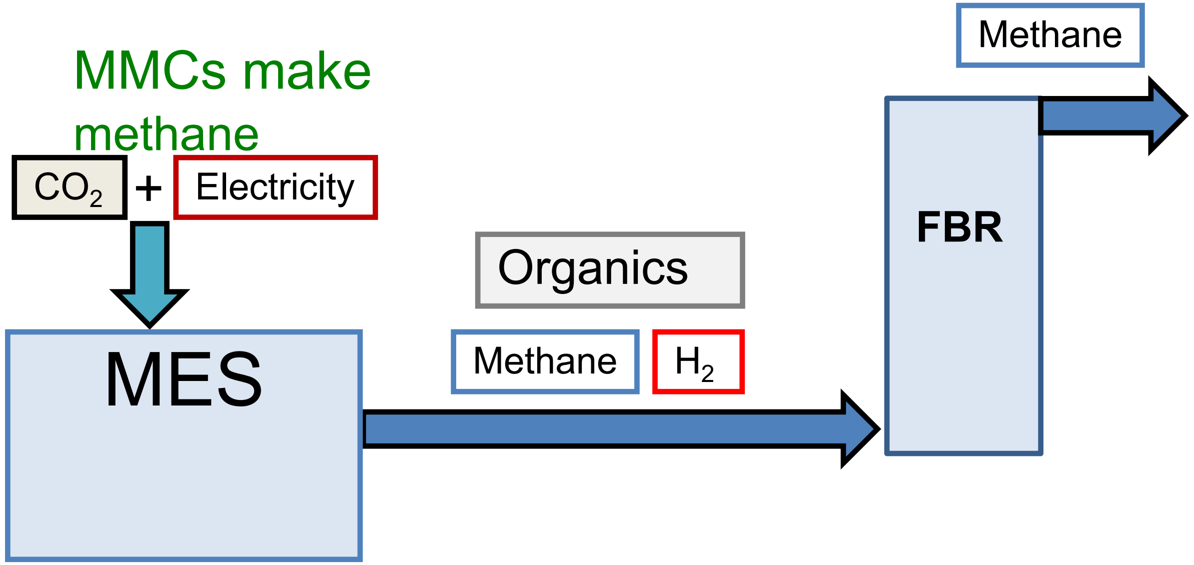
Rossi & Logan (2022) In preparation

Other chemicals can be produced in MES

- MMC indicates methane is primary product, but MES = other products
- Using mixed cultures (many microbes) and applying a high voltage can also release
  - H2 abiotically from the cathode
  - Organics or “VFAs” (acetate, formate, etc.) appear in later cycles at higher applied voltages
- Adding a fluidized bed bioreactor (FBR) could further convert these to more methane
  - Advantage is higher current density, so more methane per MES reactor

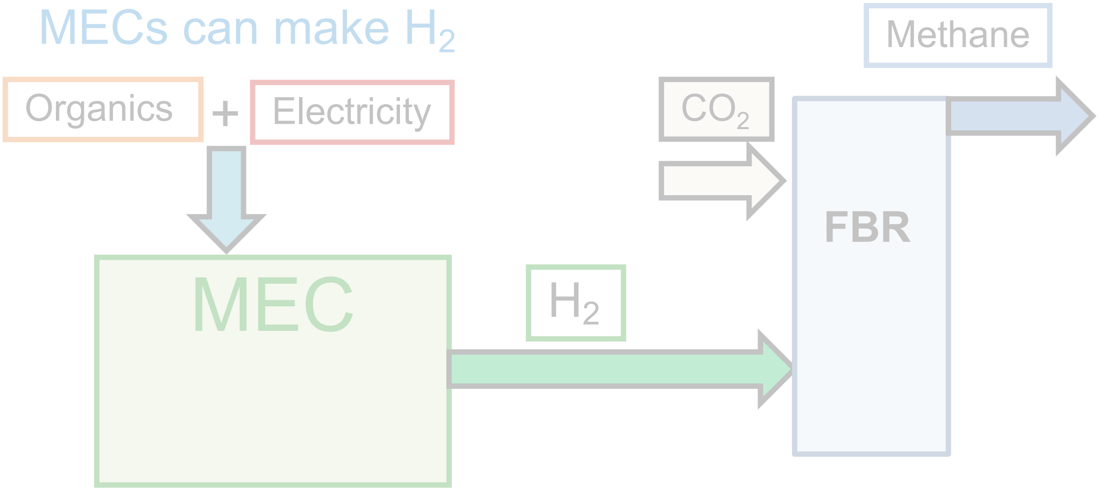


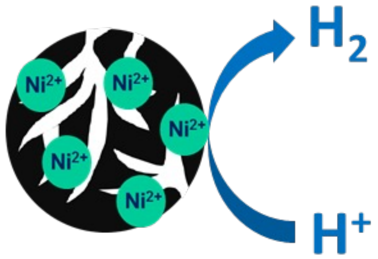
Can also produce H_2 and organics (VFAs)



2e. Future Directions in Electrosynthesis of Methane

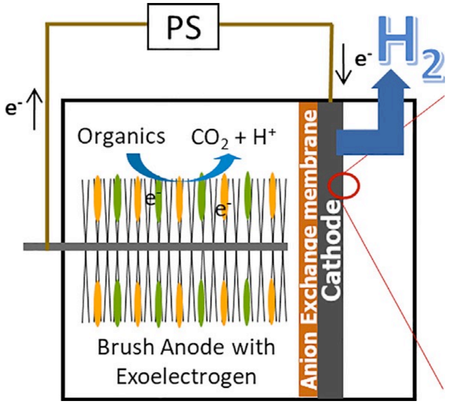
- Generate Hydrogen first?
  - Use and MEC? But that requires a source of organic matter for the anode.
  - Rates of MEC > MMC
- Cheap, efficient cathode catalysts
  - Brush and carbon electrodes lack a cathode catalyst.
  - Could we use non-precious metal Ni-based catalysts developed for MECs in MMCs?





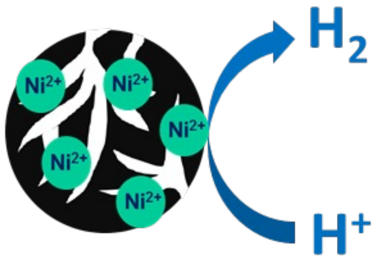
What are suitable materials and catalysts for MMCs?

- Need inexpensive catalysts
  - Carbon electrodes is not good catalysts.
- Materials previously tested
  - Non-precious metals like **stainless steel (SS)** or Ni-based catalysts such as **Ni** particles and **Ni_2P** used
- Better materials being developed

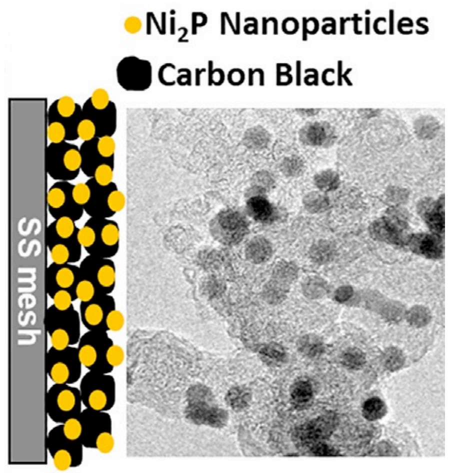


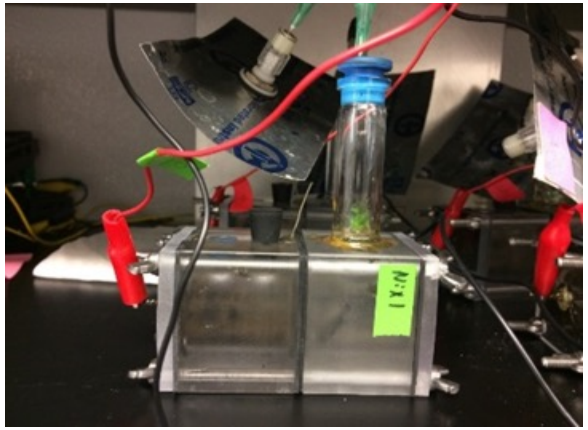
Stainless Steel wool cathodes

Nickel particles, pNi on activated carbon



Nickel Phosphide Ni_2P

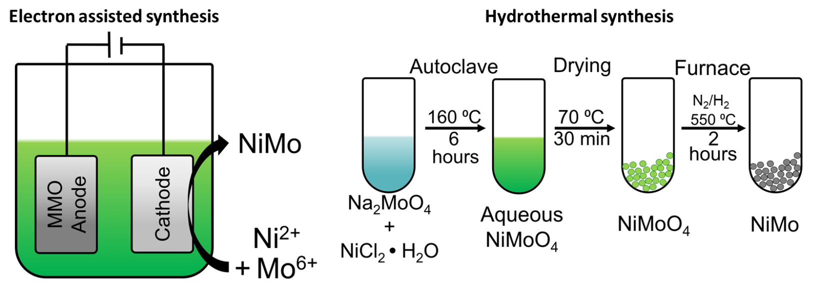




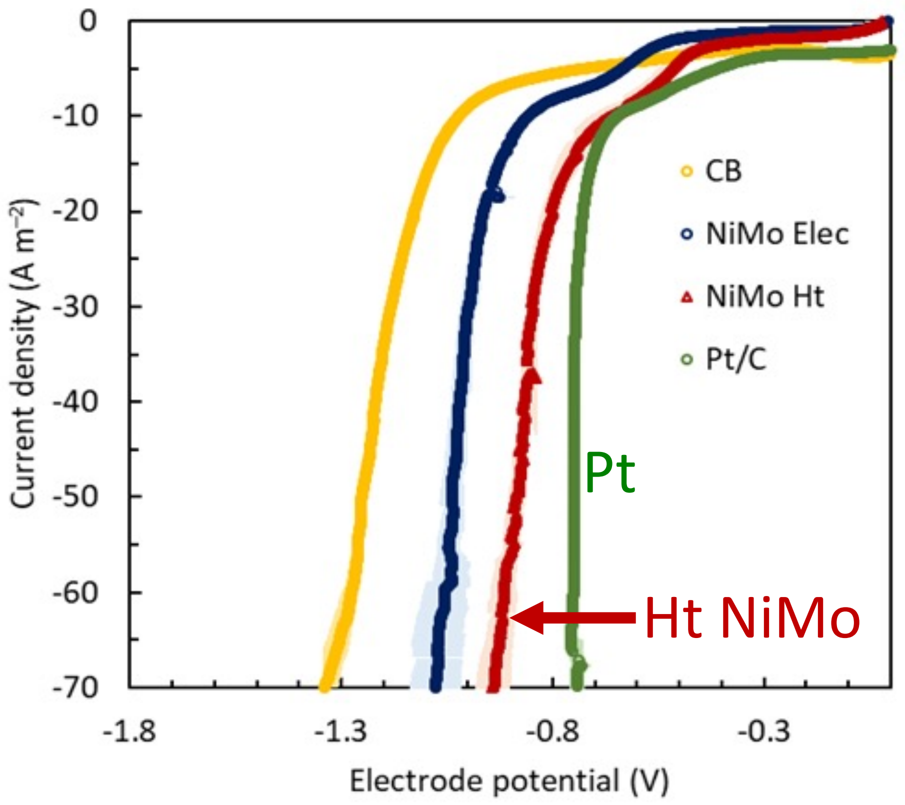
PennState

New, more effective Pt Catalyst: NiMo

- **Method 1**: Hydrothermal method (Ht) (shown on right)
  - Many steps
  - High energy use



- **Method 2**: Electrochemical method (Elec)
  - Simple procedure: Electrochemical deposition of catalyst is very desirable
  - Well controlled conditions
  - But… lower performance than Ht method (so far)

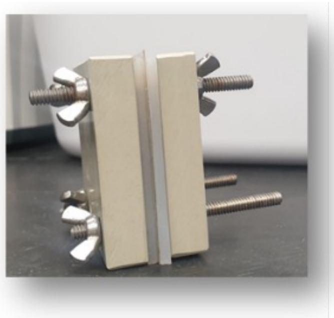


Rossi, Nicholas, Logan (2022) *Submitted*

3. Scaling Up Compact Reactors

- **MFCs** and **MECs** have reached 1000 Liter scale
- Engineering 1000 L **MMC** will be a fun engineering challenge!
- Stay tuned…!

What will the MMC look like?



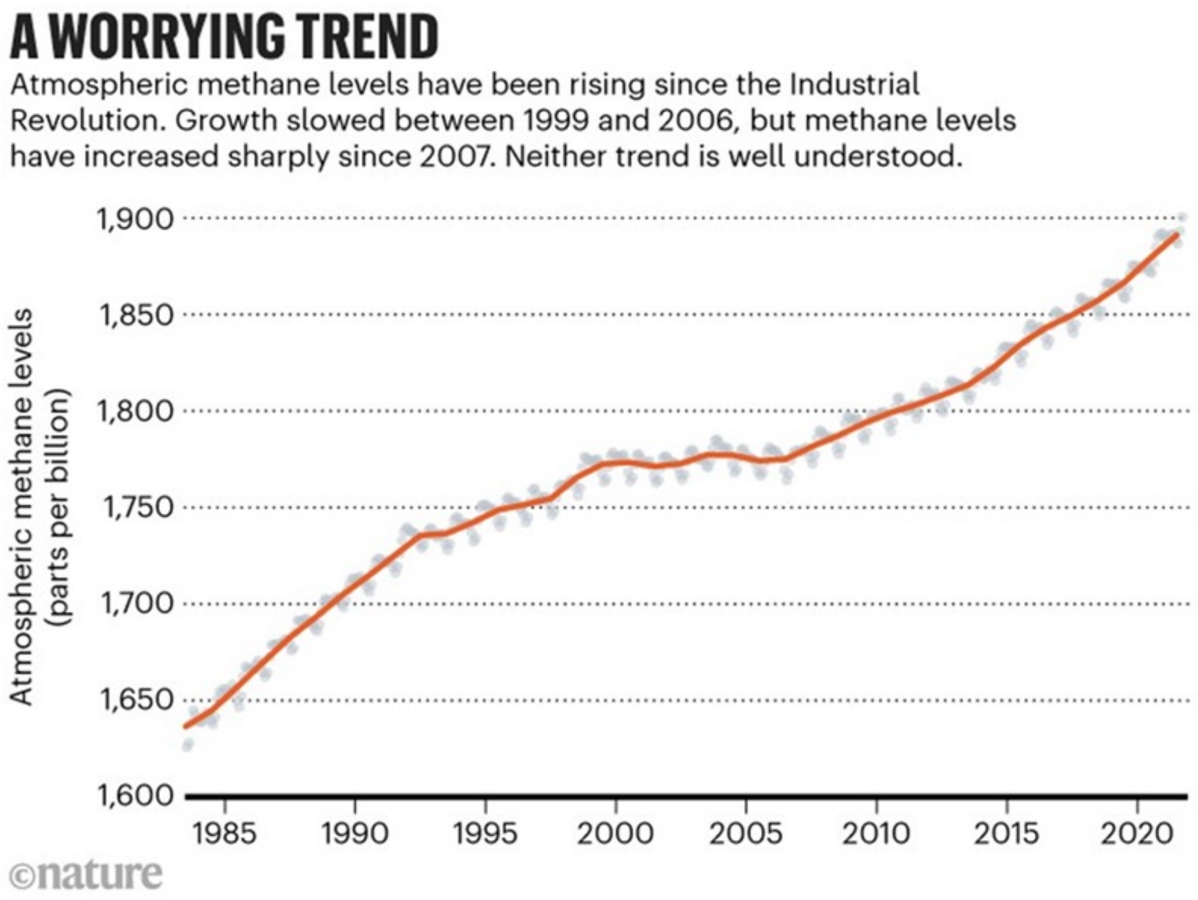
Active area = 7 cm^2
(1 electrode)

Active area = 0.42 m^2
(4200 cm^2) x 6 electrodes

PennState

Final Note: Avoid Methane Emissions!

- Methane is a potent greenhouse gas, with a global warming potential (GWP) of:
  - 25× CO_2 over 100 yr
  - 85× CO_2 over 20 yr (more appropriate)
- Almost no difference in atmospheric impact from fossil or renewable CH_4
- Redefining the GWP of methane (from 25 to 85) increases GHG emissions by 25% in the USA



Scientists raise alarm over ‘dangerously fast’ growth in atmospheric methane (nature.com)

CONCLUSIONS: Green Methane Makes Sense!

- Advances in MET designs have made it possible to develop thin and energy-efficient reactors for CH_4 and H_2 production.
- Achieved 3 L/L-d of CH_4 in preliminary (non-optimized) tests.
- Should be able to substantially increase CH_4 production rates due to 89 L/L-d of H_2, equivalent to 18 L/L-d of CH_4.

Acknowledgements for Funding:

NSF

NREL NATIONAL RENEWABLE ENERGY LABORATORY

U.S. DEPARTMENT OF ENERGY

SERDP DOD · EPA · DOE

PennState

ESTCP

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology
Water Desalination and Reuse Center

Special acknowledgements to:

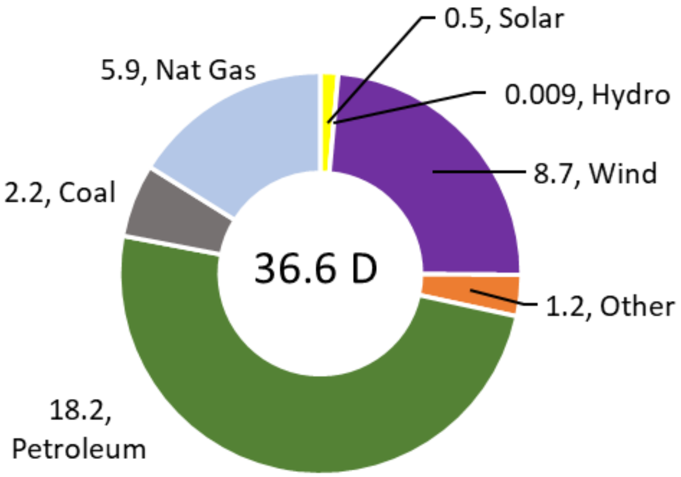
Dr. Ruggero Rossi
Asst. Research Prof.
(Penn State→ Johns Hopkins Univ.)
Pioneering work on zero-gap MFCs and MECs.

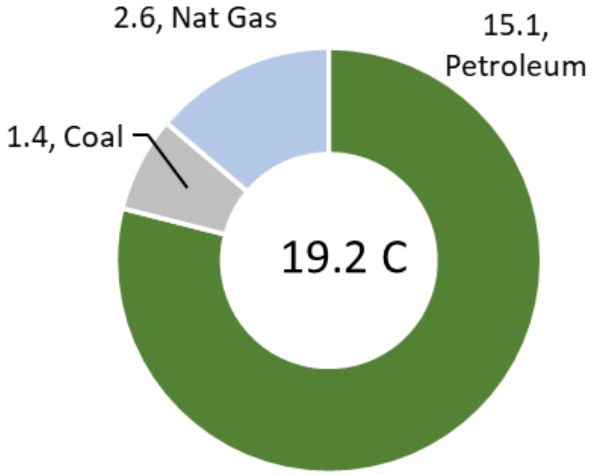
Dr. Gahyun Baek
(Research Institute of Industrial Science and Technology (RIST), Korea)
MES experiments on making methane in zero-gap reactors.

Challenges for Energy in Denmark

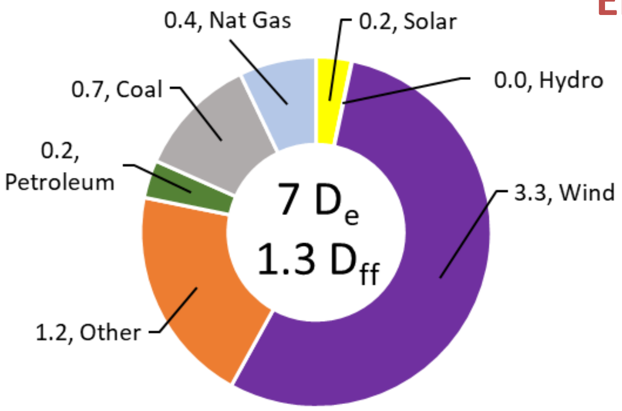
- High amount of <u>Petroleum Use</u>
  - 28% of all energy is renewable
  - If you electrify 8.8 D_e replaces 26.3 D_{ff} (assuming 33% fuel to electricity), **total = 19.1 D**
- Energy embedded in the <u>food system</u>
  - Much of the energy consumption is externally consumed (food grown elsewhere)

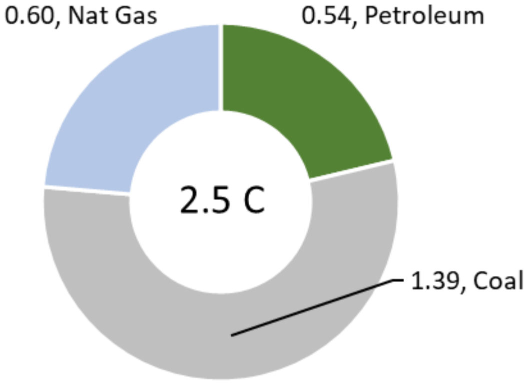
All Energy





Electricity





Examples of Volumetric Current Densities

Technology	A_{cat} (m^2/m^3)	I_A (A/m^2)	I_v (A/m^3)	Rate ($kg/d\text{-}m^3$)
MEC- Reports	62	6.5	400	0.36 (H_2)
- Max	50	50	2500	2.25 (H_2)
MMC- Reports	5	0.11	0.55	1.6 (CH_4)
- Max	50	50	2500	4.5 (CH_4)
MES- Reports	0.5	200	100?	0.54 (acetate)
- Max	100	50	5000	34 (acetate)

1100 A/m^3 = 1 kg $H_2/d\text{-}m^3$

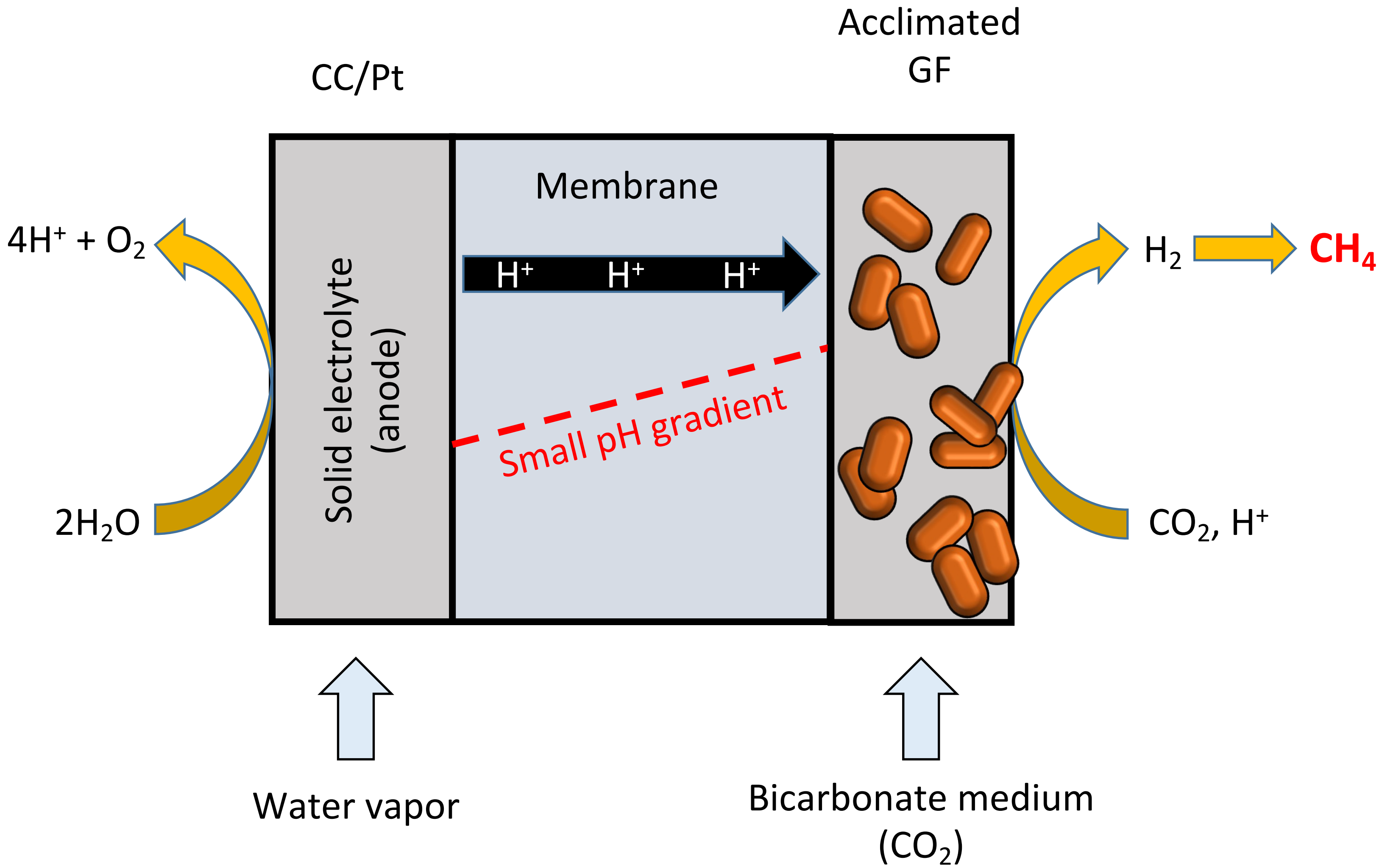
1 kg H_2 = 2 kg CH_4 = 7.5 kg CH_3COOH

PennState

Examples of Scaling up METs

Technology	Challenges / Opportunities
MFC	- Can recover electrical power for particle-free solutions - Wastewater: Maximize current (throw away power)
MEC	Electrical power input but H_2 gas is a valuable product
MES/MMC	The "power to gas" technology has great potential and opportunities to inject C-neutral CH_4 fit into gas pipelines

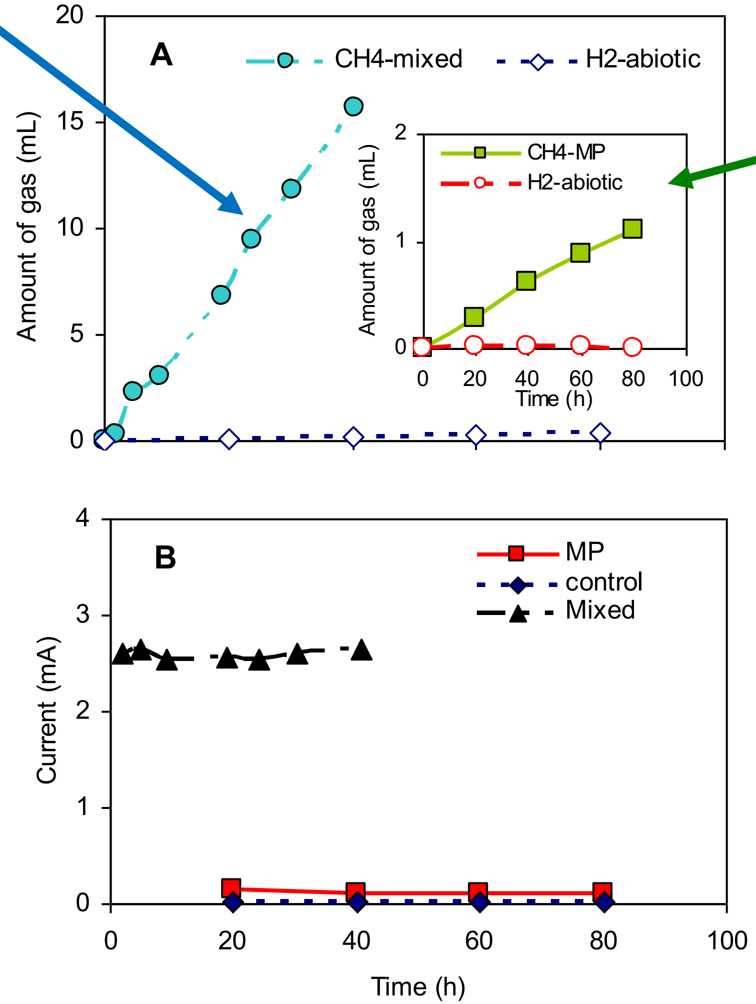
New MMC Design: Thin, compact reactors



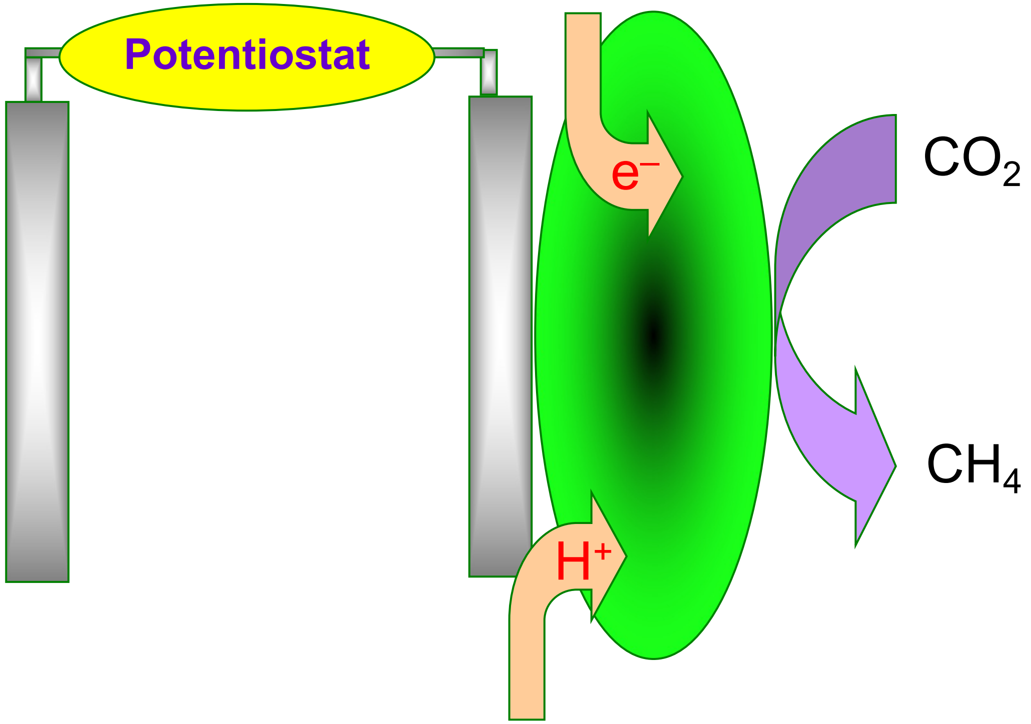
PennState

Electrotrophic Methanogens

Mixed culture (*Methanobacterium palustre*)



Pure culture of ATCC
Methanobacterium palustre

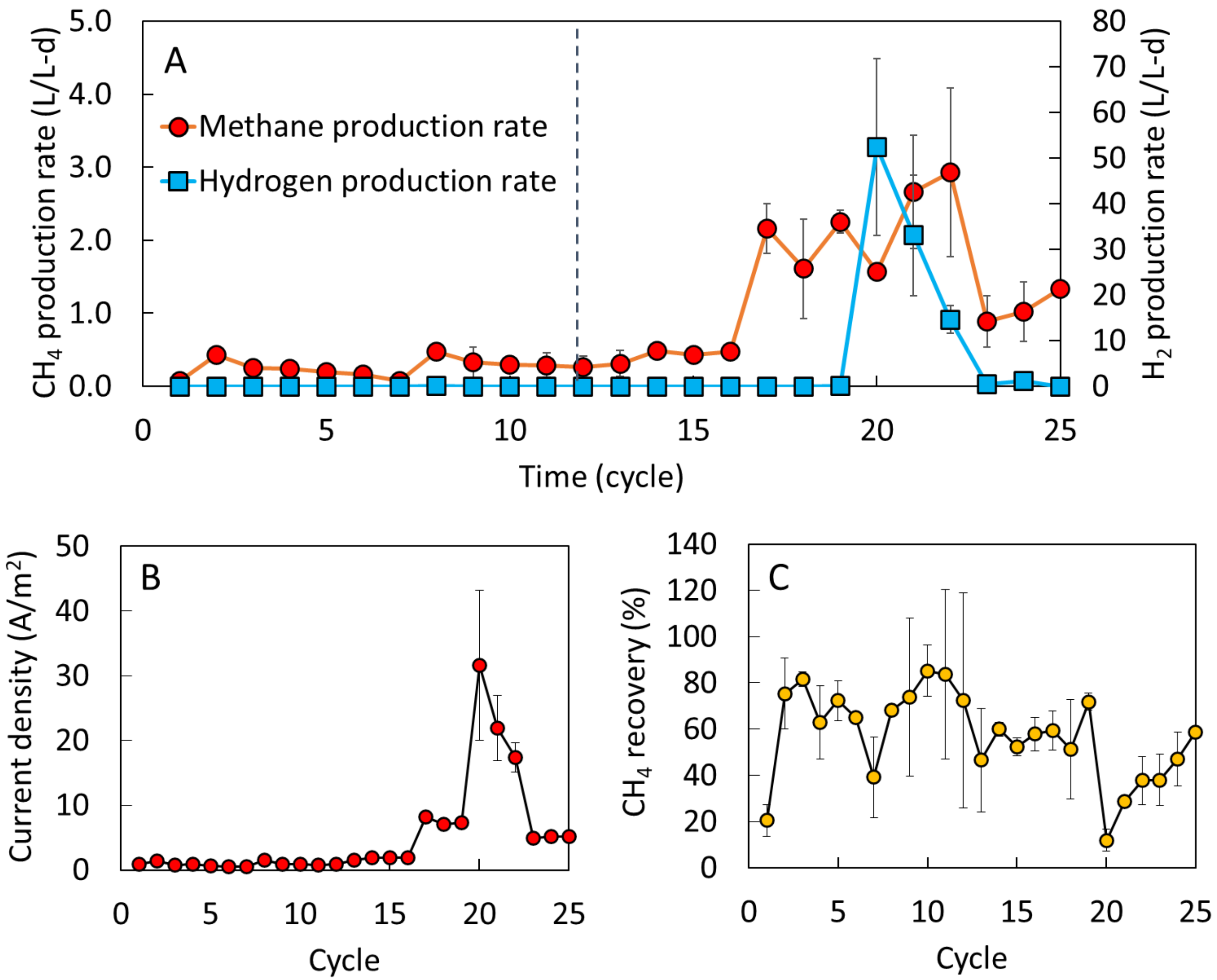


Cheng, Call & Logan (2009) *Environ. Sci. Technol.*

PennState

- Water splitting at the anode. Using Pt. Two phases:
  - 1-2: Carbon cloth (degraded)
  - 3-6: Titanium
- Increased applied voltages
  - 2.0 – 3.1 V
  - H2 measured at 3.1 V
  - Returning to 2.5 V showed lower H_2; likely biocathode damage
- Methane recovery: highest with 2.8 V
  - ~ 10 A m^2
  - ~ 2 L/L-d CH_4

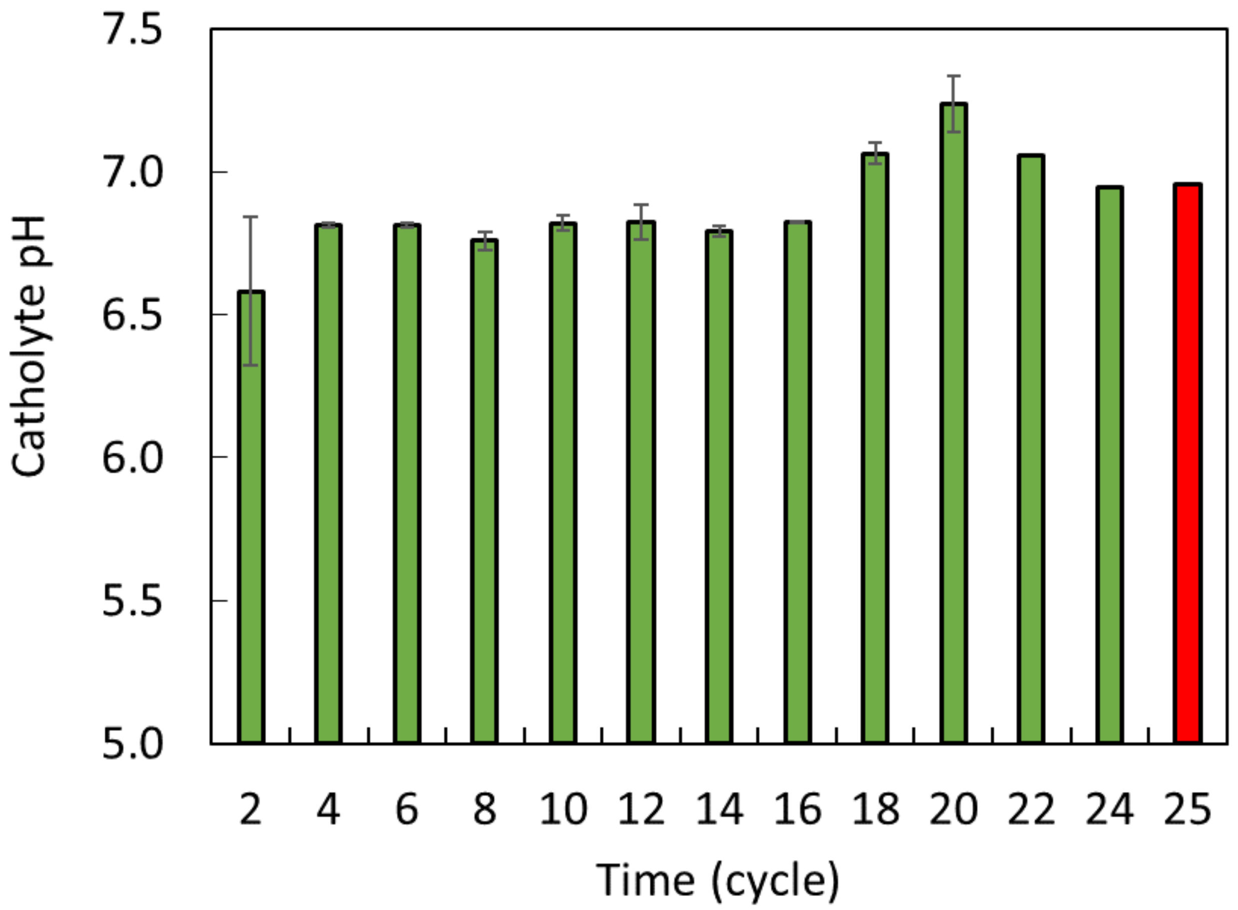
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Duration (cycles)	1–7	8–11	12–16	17–19	20–22	23-25
Anode material	CC/Pt	CC/Pt (new)	Ti/Pt	Ti/Pt	Ti/Pt	Ti/Pt
E_{ap} (V)	2.0	2.0	2.5	2.8	3.1	2.8



The zero-gap configuration maintains pH

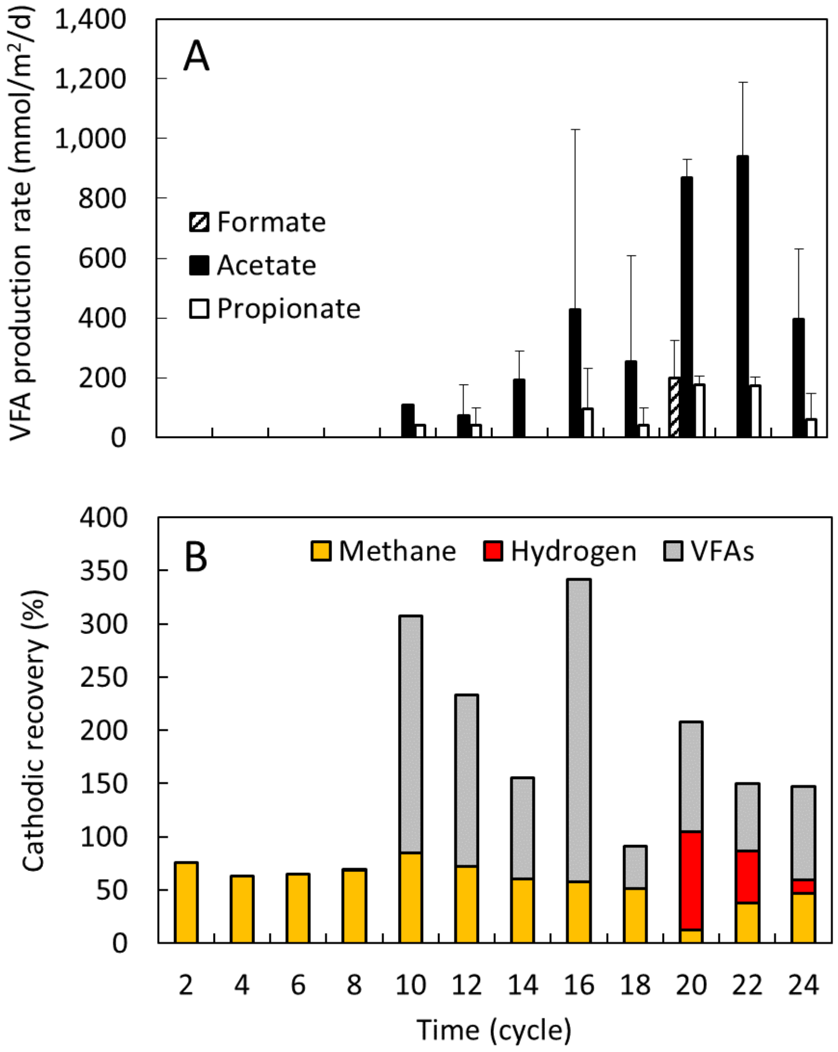
- Need to avoid alkaline catholyte pH
- 1-24 cycles: catholyte switched each cycle (~1-2 d)
  - 6.6 <pH < 7.2
- 25th cycle: extended for 6 days
  - No change in pH

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Duration (cycles)	1–7	8–11	12–16	17–19	20–22	23-25
Anode material	CC/Pt	CC/Pt (new)	Ti/Pt	Ti/Pt	Ti/Pt	Ti/Pt
E_{ap} (V)	2.0	2.0	2.5	2.8	3.1	2.8



VFAs produced in addition to methane

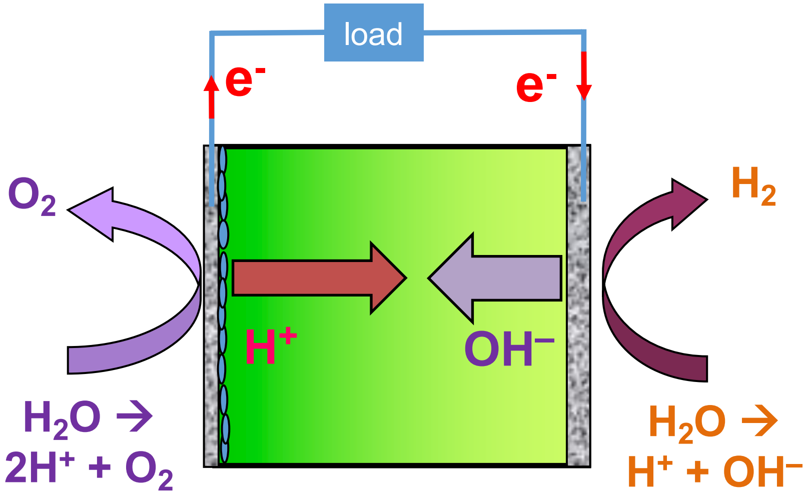
Primarily: Acetate, propionate, formate



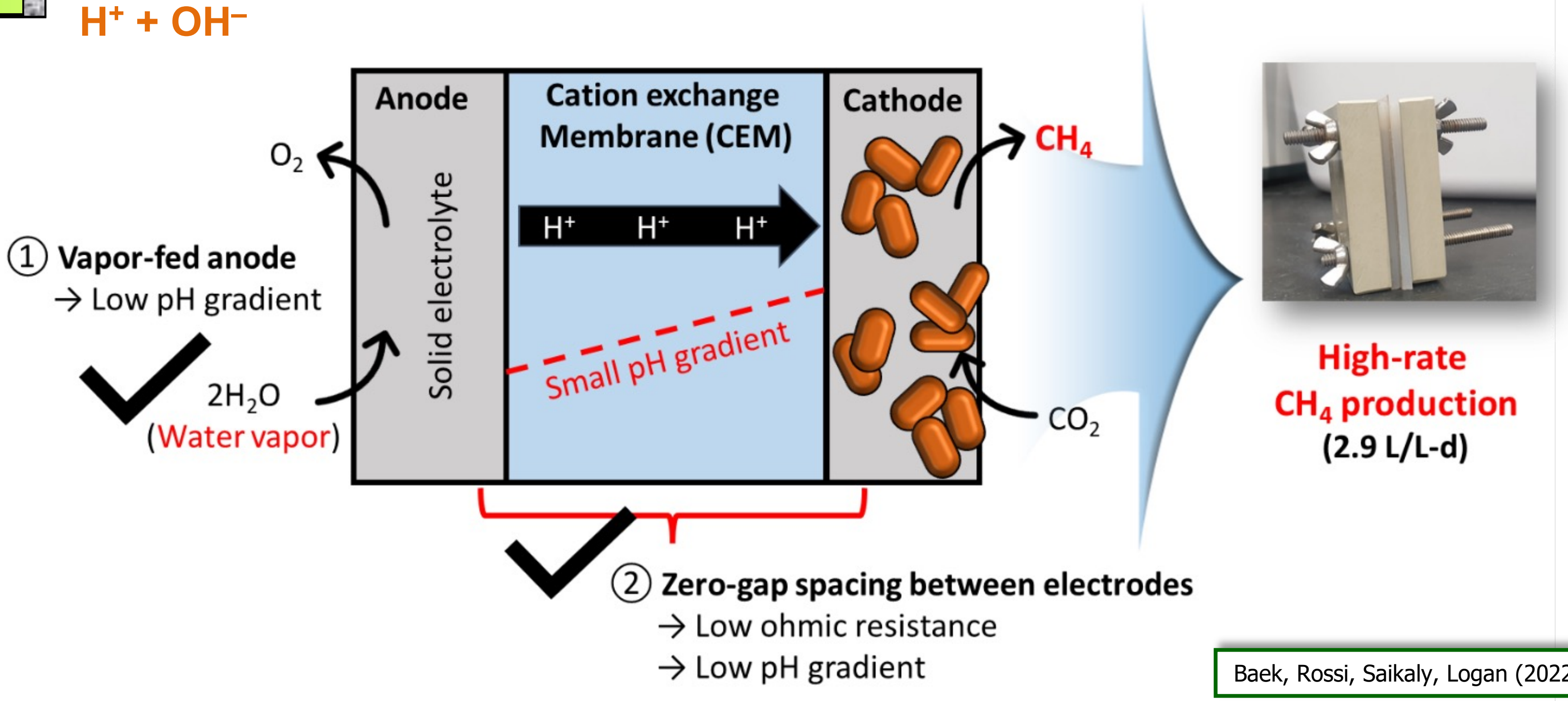
Methanobacteriaceae and Firmicutes

OTU	Phylum	Family	Genus	MES1 (%)	MES2 (%)	AVG (%)
OTU 1	*Euryarchaeota*	*Methanobacteriaceae*	*Methanobrevibacter*	32.5	38.8	**35.7**
OTU 2	*Firmicutes*	*Clostridiaceae 1*	*Clostridium sensu stricto 1*	12.4	9.4	**10.9**
OTU 3	*Firmicutes*	*Eubacteriaceae*	*Eubacterium*	12.7	3.6	**8.2**
OTU 4	*Bacteroidetes*	*Rikenellaceae*	-	7.0	9.3	**8.1**
OTU 5	*Proteobacteria*	*Rhodocyclaceae*	*Azospira*	4.0	12.1	**8.0**
OTU 6	*Proteobacteria*	*Pseudomonadaceae*	*Pseudomonas*	6.5	3.5	**5.0**
OTU 7	*Proteobacteria*	*Burkholderiaceae*	*Alcaligenes*	4.1	3.6	**3.8**
OTU 8	*Actinobacteria*	*Nocardiaceae*	*Gordonia*	1.6	2.6	**2.1**
OTU 9	*Firmicutes*	*Lachnospiraceae*	*Tyzzerella*	1.8	1.7	**1.7**
OTU 10	*Euryarchaeota*	*Methanobacteriaceae*	*Methanobrevibacter*	2.0	1.0	**1.5**

MES: Methane Generation by Water Splitting & Biocathodes



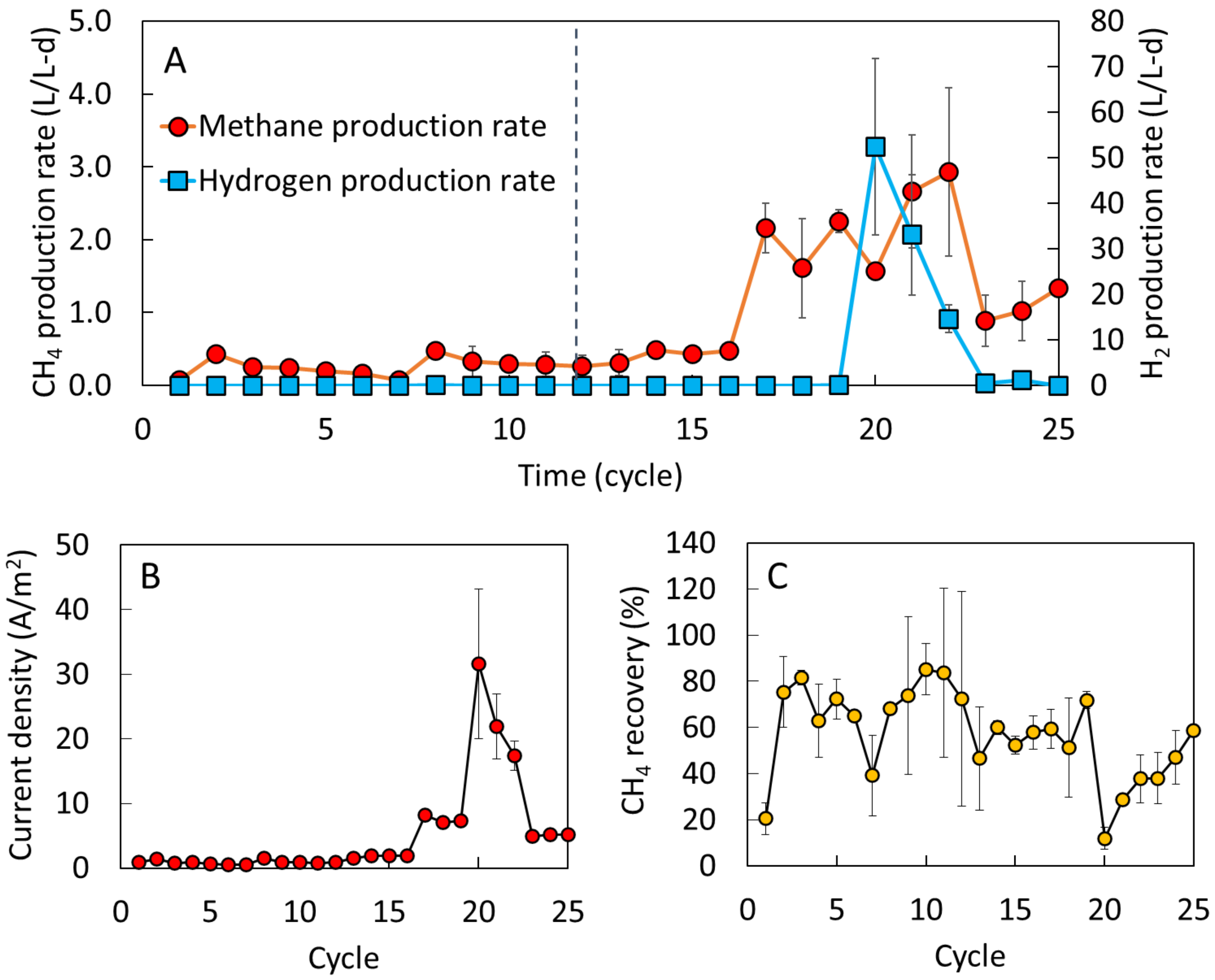
- **H^+ produced with O_2 by water splitting anode**
- A **CEM** is used for MES (Not an AEM that is used in MFC or MEC) to facilitate H^+ transport



Baek, Rossi, Saikaly, Logan (2022) *Water Res.*

- Water splitting at the anode. Using Pt. Two phases:
  - 1-2: Carbon cloth (degraded)
  - 3-6: Titanium
- Increased applied voltages
  - 2.0 – 3.1 V
  - 3.1 V too high (H_2 measured)
- Methane recovery:
  - Highest at 2.8 V
  - 2 L/L-d CH_4 (10 A m^2)

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Duration (cycles)	1–7	8–11	12–16	17–19	20–22	23-25
Anode material	CC/Pt	CC/Pt (new)	Ti/Pt	Ti/Pt	Ti/Pt	Ti/Pt
E_{ap} (V)	2.0	2.0	2.5	2.8	3.1	2.8



Does adding electrodes into AD work?

Environmental Science & Technology

Critical Review

Cite This: Environ. Sci. Technol. 2018, 52, 10241−10253

pubs.acs.org/est

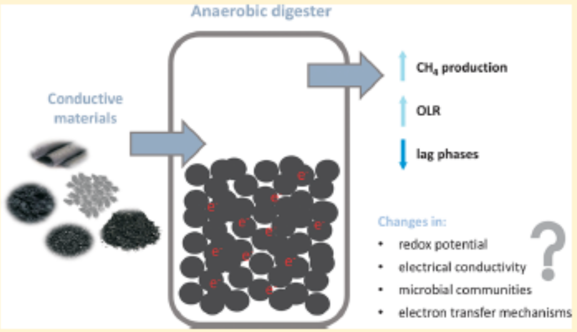
Methane Production and Conductive Materials: A Critical Review

Gilberto Martins,* Andreia F. Salvador, Luciana Pereira, and M. Madalena Alves

Centre of Biological Engineering, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal

Supporting Information

ABSTRACT: Conductive materials (CM) have been extensively reported to enhance methane production in anaerobic digestion processes. The occurrence of direct interspecies electron transfer (DIET) in microbial communities, as an alternative or complementary to indirect electron transfer (via hydrogen or formate), is the main explanation given to justify the improvement of methane production. Not disregarding that DIET can be promoted in the presence of certain CM, it surely does not explain all the reported observations. In fact, in methanogenic environments DIET was only unequivocally demonstrated in cocultures of *Geobacter metallireducens* with *Methanosaeta harundinacea* or *Methanosarcina barkeri* and frequently *Geobacter* sp. are not detected in improved methane production driven systems. Furthermore, conductive carbon nanotubes were shown to accelerate the activity of methanogens growing in pure cultures, where DIET is not expected to occur, and hydrogenotrophic activity is ubiquitous in full-scale anaerobic digesters treating for example brewery wastewaters, indicating that interspecies hydrogen transfer is an important electron transfer mechanism in those systems. This paper presents an overview of the effect of several iron-based and carbon-based CM in bioengineered systems, focusing on the improvement in methane production and in microbial communities' changes. Control assays, as fundamental elements to support major conclusions in reported experiments, are critically revised and discussed.



Water Research 146 (2018) 244–255

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

ELSEVIER

Interfacing anaerobic digestion with (bio)electrochemical systems: Potentials and challenges

Jo De Vrieze [a, 1], Jan B.A. Arends [a, 1], Kristof Verbeeck [a, 1], Sylvia Gildemyn [a, b], Korneel Rabaey [a, *]

[a] Center for Microbial Ecology & Technology (CMET), Ghent University, Coupure Links 653, B-9000, Gent, Belgium
[b] OWS nv, Dok Noord 5, 9000, Gent, Belgium

ARTICLE INFO

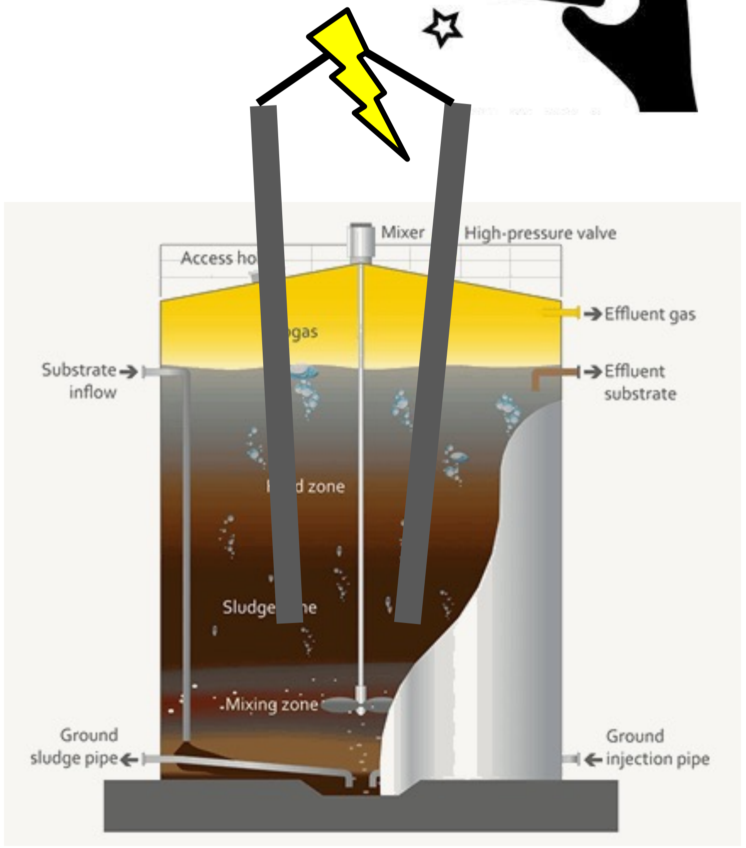
Article history:
Received 6 June 2018
Received in revised form 14 August 2018
Accepted 17 August 2018
Available online 12 September 2018

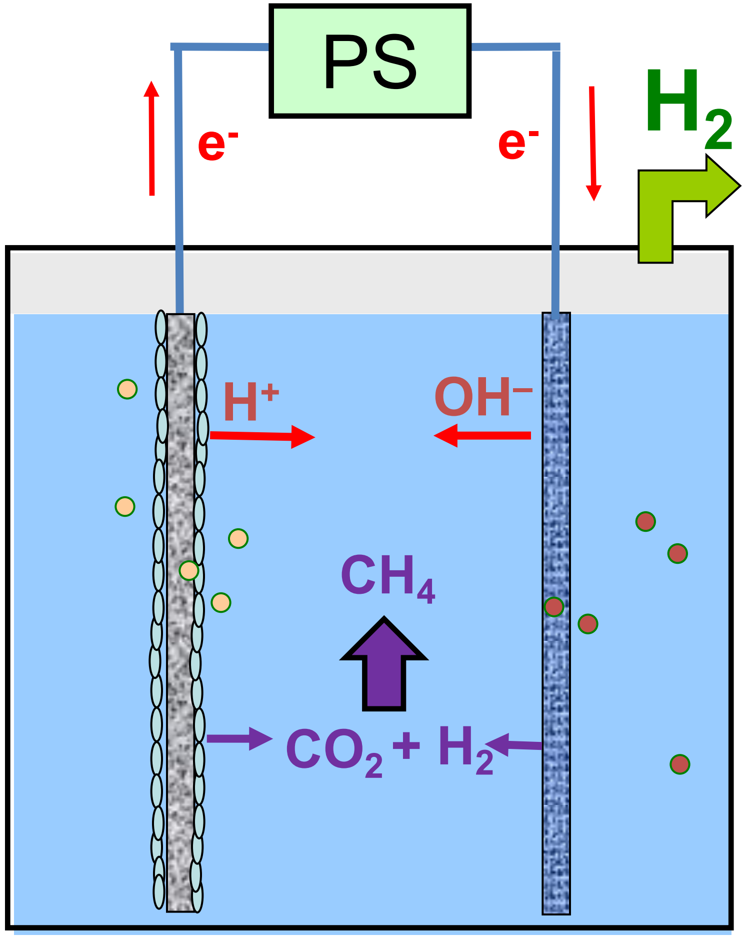
Keywords:
Anaerobic digestion
Bioelectrochemical system
Biogas
Methane
Resource recovery

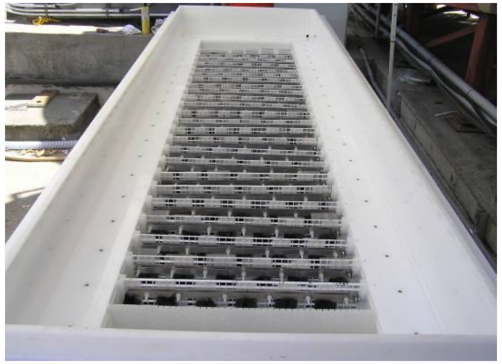
ABSTRACT

For over a century, anaerobic digestion has been a key technology in stabilizing organic waste streams, while at the same time enabling the recovery of energy. The anticipated transition to a bio-based economy will only increase the quantity and diversity of organic waste streams to be treated, and, at the same time, increase the demand for additional and effective resource recovery schemes for nutrients and organic matter. The performance of anaerobic digestion can be supported and enhanced by (bio) electrochemical systems in a wide variety of hybrid technologies. Here, the possible benefits of combining anaerobic digestion with (bio)electrochemical systems were reviewed in terms of (1) process monitoring, control, and stabilization, (2) nutrient recovery, (3) effluent polishing, and (4) biogas upgrading. The interaction between microorganisms and electrodes with respect to niche creation is discussed, and the potential impact of this interaction on process performance is evaluated. The strength of combining anaerobic digestion with (bio)electrochemical technologies resides in the complementary character of both technologies, and this perspective was used to distinguish transient trends from schemes with potential for full-scale application. This is supported by an operational costs assessment, showing that the economic potential of combining anaerobic digestion with a (bio)electrochemical system is highly case-specific, and strongly depends on engineering challenges with respect to full-scale applications.

Using MECs for Enhanced Anaerobic Digestion?

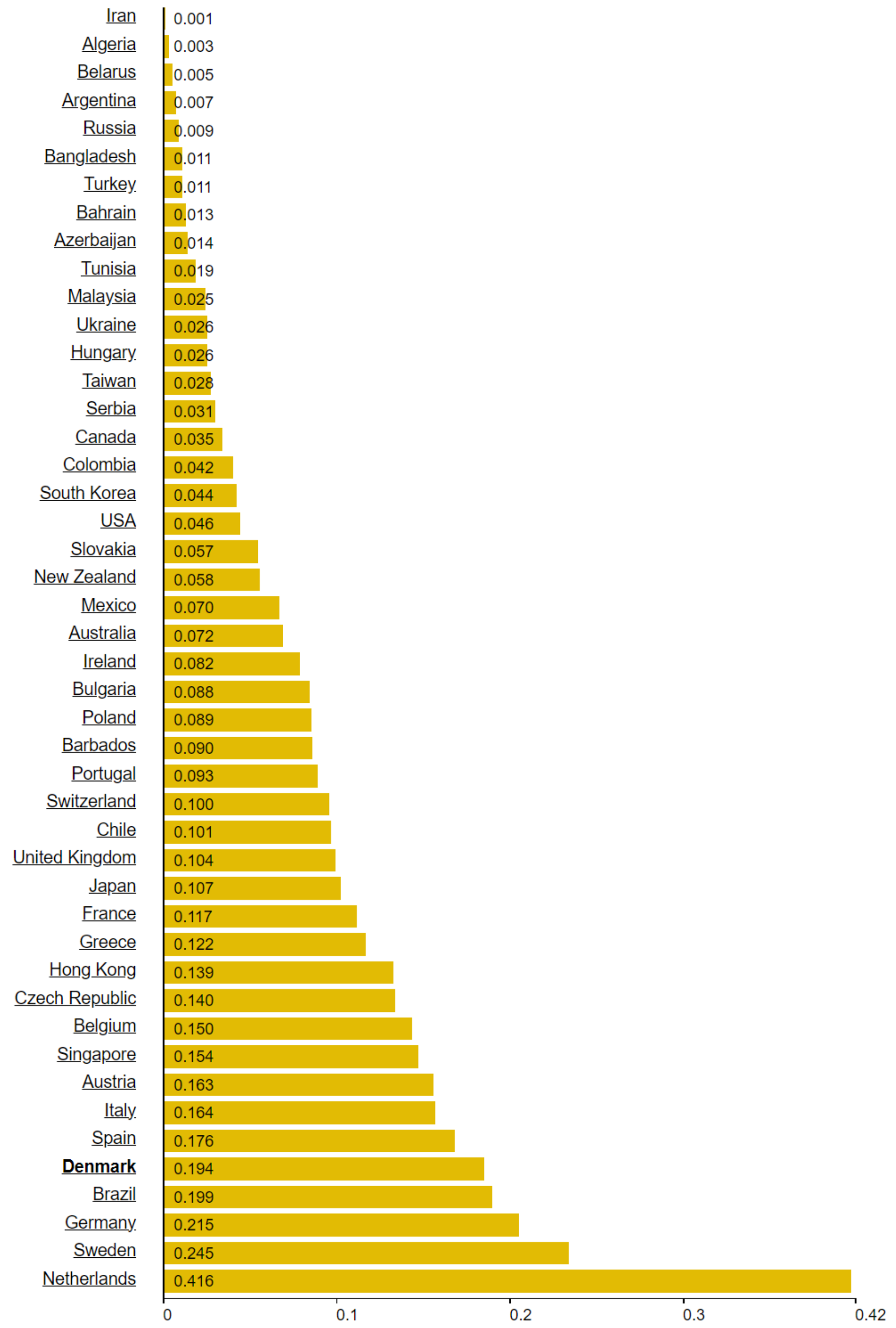






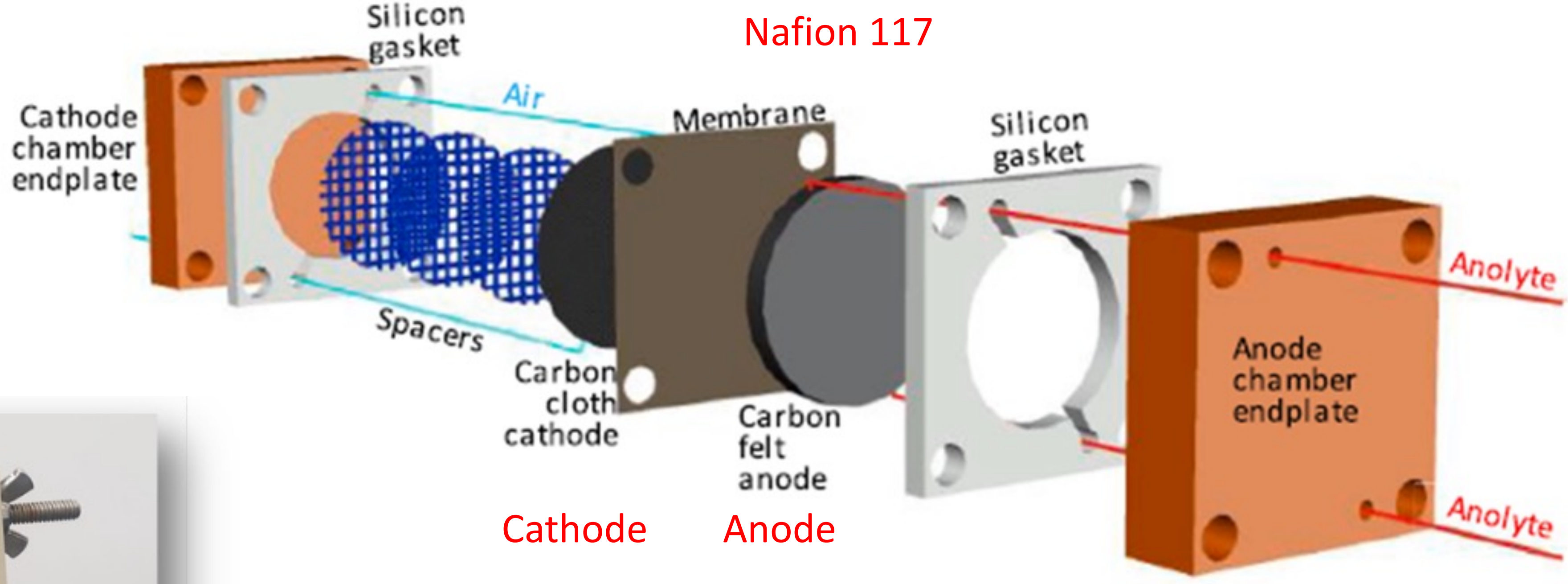
Liu, Grot & Logan (2008) *Environ. Sci. Technol.*

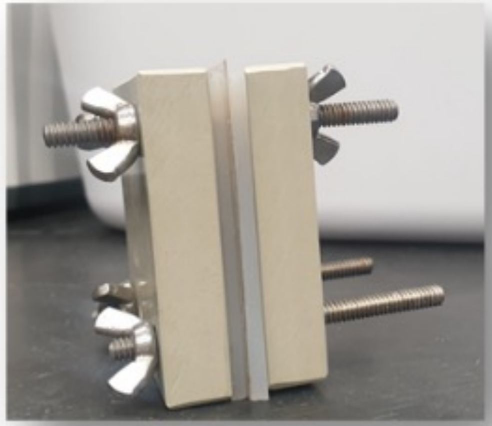
Natural gas prices for households, March 2022
(kWh, U.S. Dollar)



PennState

Water-splitting MMCs have not been scaled up …





There can be many of these cell pairs in a stack.
Just one cell pair shown here