Microbial Fuel Cell and Reverse Electrodialysis Technologies for Renewable Power Generation From Biomass and Salinity Gradients

Bruce E. Logan
Penn State University

Engineering Energy & Environmental Institute

Water

Global Water Demand

- 1 billion people lack adequate drinking water
- 2 billion people lack adequate sanitation

- By 2025, ¼ of all people could live in areas that face severe water shortages.

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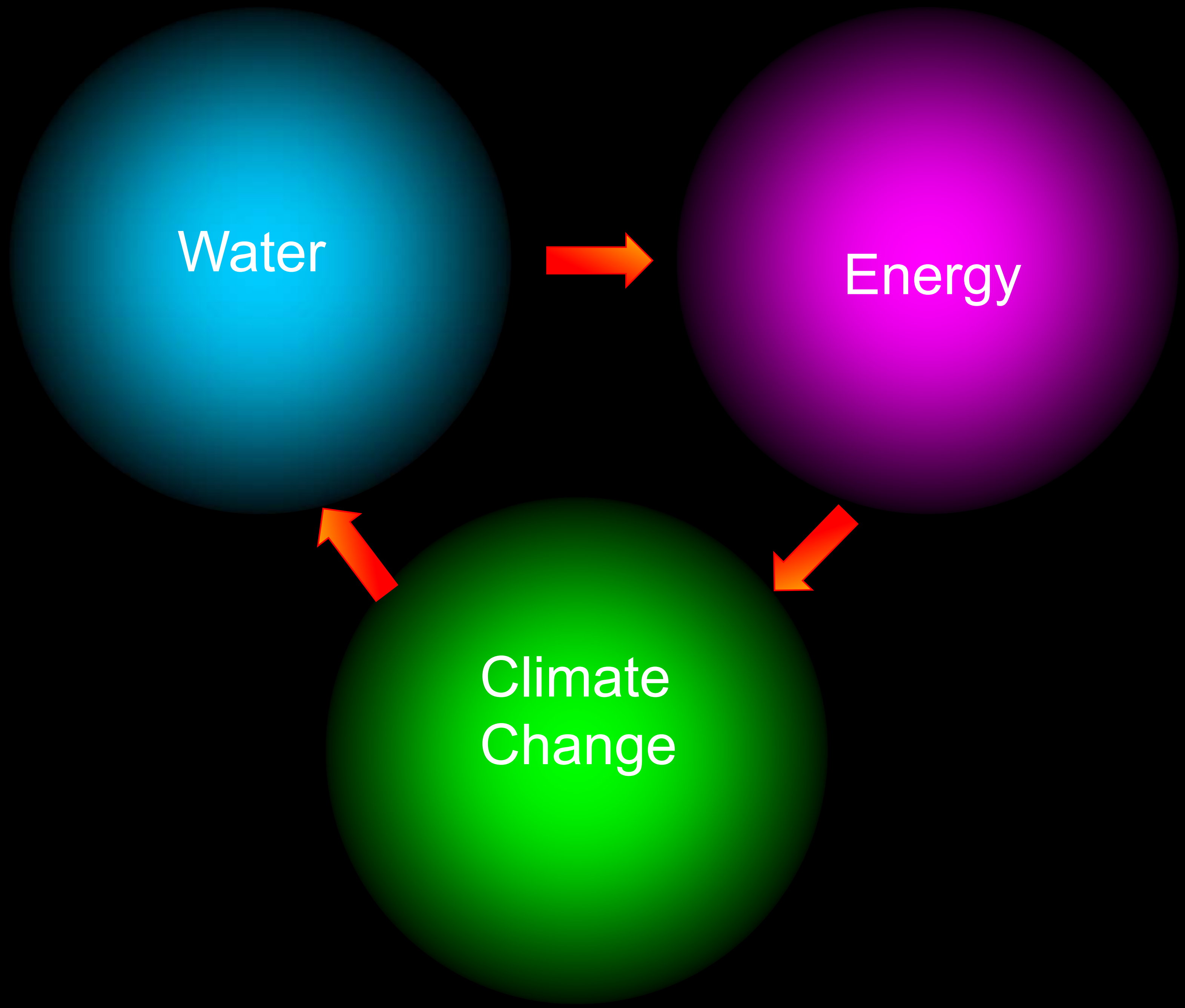
Water
Energy
Climate
Change

Energy

Energy Demands

- Global Energy Use (power = energy/time)
  - 13,500 GW (= 13.5 TW)

    (27,000 GW needed by 2050)
- Energy use in the USA
  - 3340 GW energy (continuous) currently used
  - **600 GW generated as electricity**

→ 1 large nuclear power plant produces ~ 1 GW

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Power Consumption by People

Energy

2000 Calories/day
(2,000 kcal/d, 8.4 MJ/d)

100 W

25 W "down the drain" (2 MJ/d)

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Energy

Energy & The Water Infrastructure

Water

- **Annual energy used for the water infrastructure**
  - 30 GW (USA), or 5-6% of all electricity generated
- Wastewater treatment:
  - 15 GW
  - 0.6 kWh/m^3 (0.12 to 1-2 kWh/m^3)
- Drinking water treatment?
  - Desalination requires 3.7 – 650 kWh/m^3

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Goal of my research:

- Make our water infrastructure *energy-sustainable* in the next 20 to 25 years

How do I achieve this goal?

- Develop sustainable/green/CO_2 neutral *renewable energy*

Where do I get the energy from?

- Water… (??)

Energy & The Water Infrastructure

Energy

Water

- **Energy USED for wastewater treatment**
  - 15 GW (USA)
  - **0.6 kWh/m^3** (range: 0.12 to 1-2 kWh/m^3)

- **New energy SOURCE? (waste)water**
  - Domestic & Industrial wastewaters contain **17 GW** (USA)
  - Domestic wastewater contains (in the organic matter) about **2-5 kWh/m^3**; or 4 - 10 times that needed using conventional treatment!

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New Energy Sources Available using Microbial Electrochemical Technologies (METs)

- **Wastewater** : Organic matter in water (USA)
  - **17 GW** in wastewater

    (Save 45 GW energy/yr used + produce 17 GW = 62 GW net change)
- **Cellulose Biomass Energy**: Get biomass→ water
  - **600 GW** available (based on 1.34 billion tons/yr of lignocellulose)

    (this is how much electrical power is produced in USA)

- **Salinity Gradient Energy-** Salt & Fresh-waters (global values)
  - **980 GW** (from the 1900 GW available from river/ocean water)

    (20 GW available where WW flows into the ocean)
- **Waste Heat Energy**→ Capture heat in "water" (USA)
  - **500 GW** from industrial "waste heat"
  - **1000 GW** from power plant waste heat

    (Does not include solar and geothermal energy sources)

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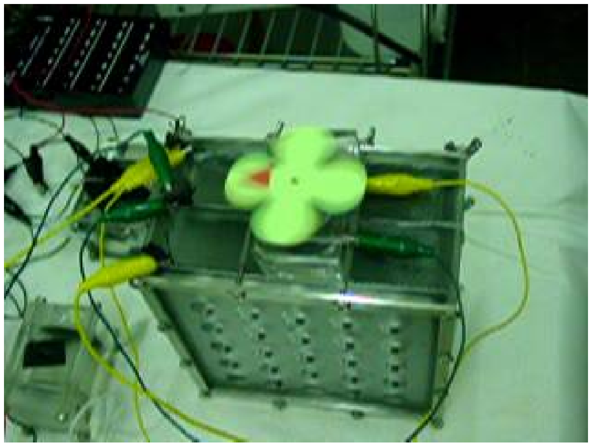
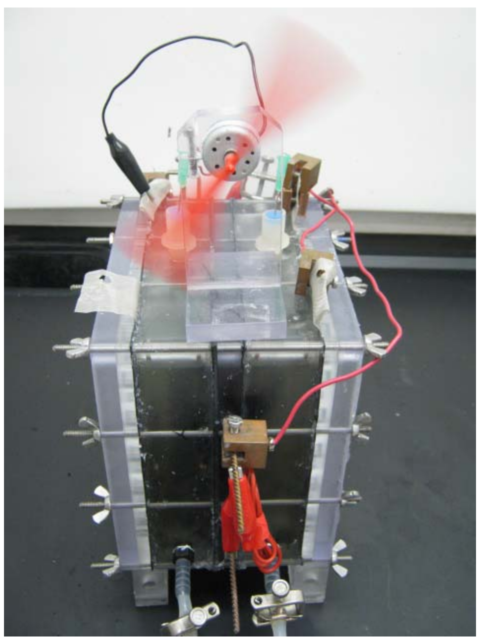
Logan and Rabaey (2012) *Science*
Logan and Elimelech (2012, *Nature*

Demonstration of a Microbial Fuel Cell (MFC)





MFC webcam
(live video of an MFC running a fan)

www.engr.psu.edu/mfccam

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New Water Technologies

- Every revolutionary idea moves through three stages
  - 1- It can’t be done
  - 2- It's possible, but it's not worth doing (too $$)
  - 3- I said it was a good idea all along.
- Examples in water technologies
  - RO membranes for desalination
  - MBRs for wastewater treatment
  - Microbial fuel cells?

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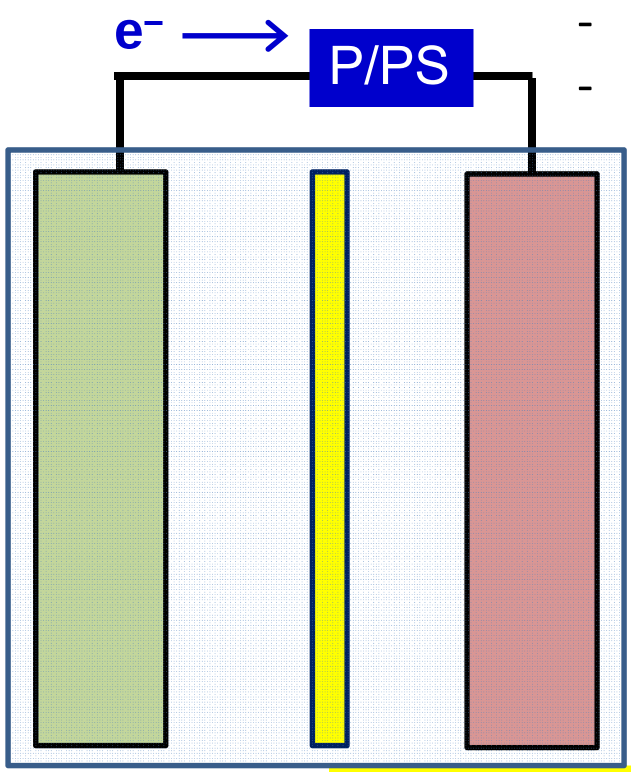
MxCs

Microbial Electrochemical Technologies (METs)

Power
- Generated (P)
- Added (PS)



Anode
- Microbes (Bioanode)
- Abiotic (no microbes)

Cathode
- Microbes (Biocathode)
- Abiotic (no microbes)

Membrane
- None
- 1 or more

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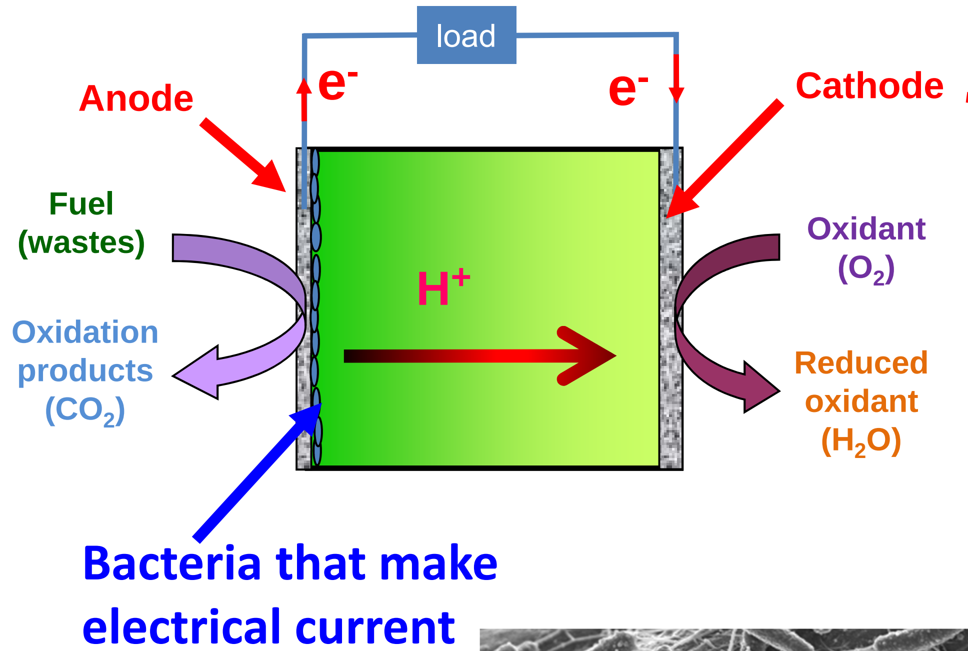
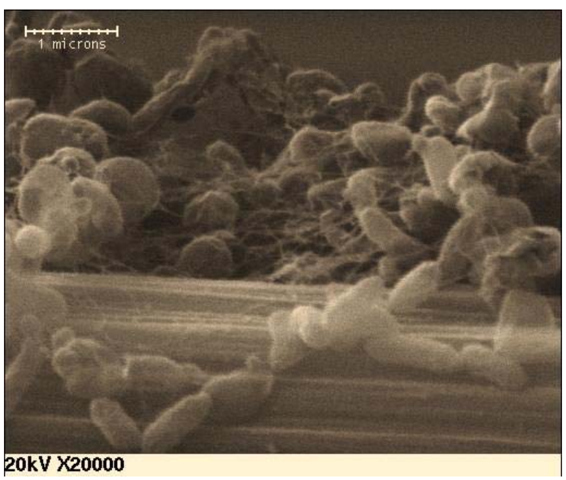
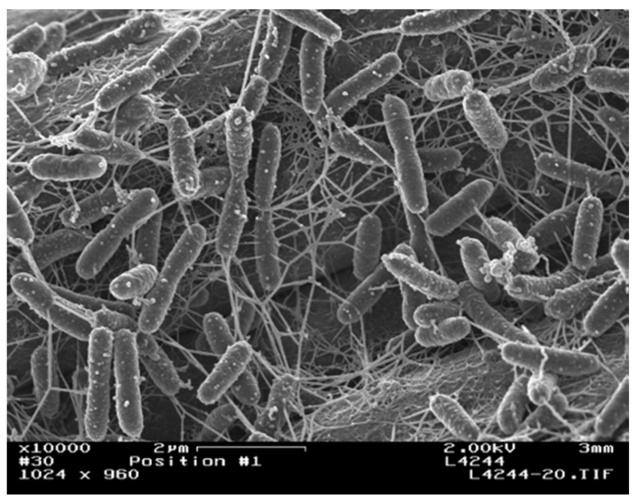
MFCs

Electrical power generation in a Microbial Fuel Cell (MFC) using exoelectrogenic microorganisms



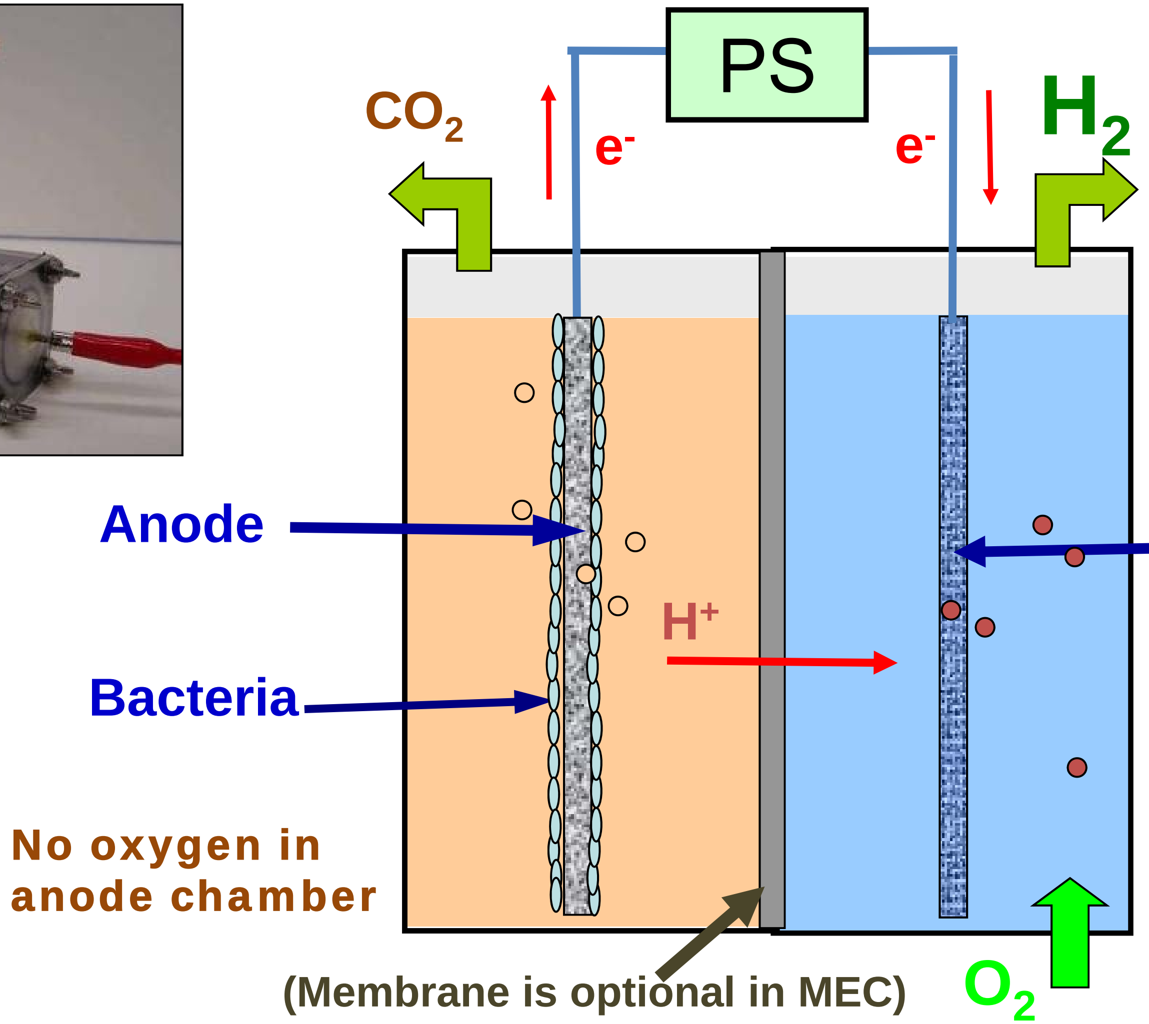




Liu et al. (2004) *Environ. Sci. Technol.*

MECs

H_2 Production at the cathode using microbes on the anode in Microbial **E**lectrolysis **C**ells

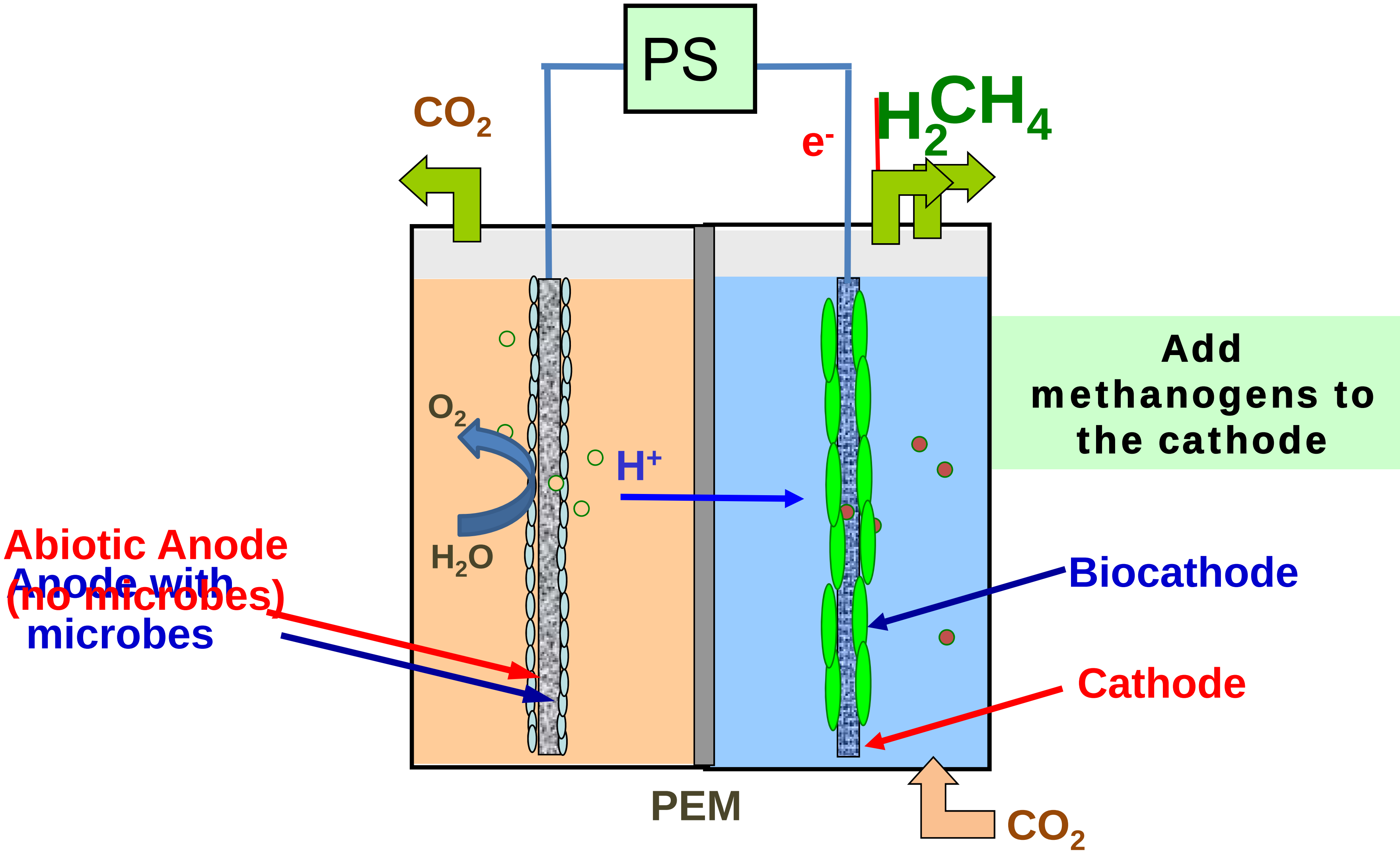


>0.25 V needed
(vs 1.8 V for water electrolysis)

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

MMCs

CH_4 Production at the cathode using microbes on the cathode in **M**icrobial **Methanogenesis C**ells



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

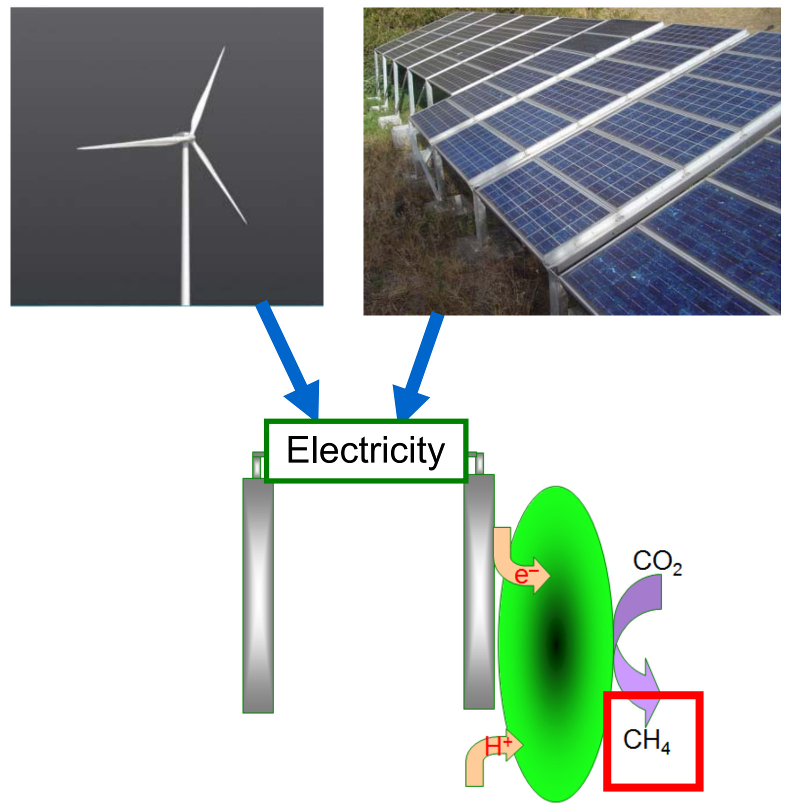
MECs used to harvest methane from renewable forms of electricity generation

Anaerobic digesters

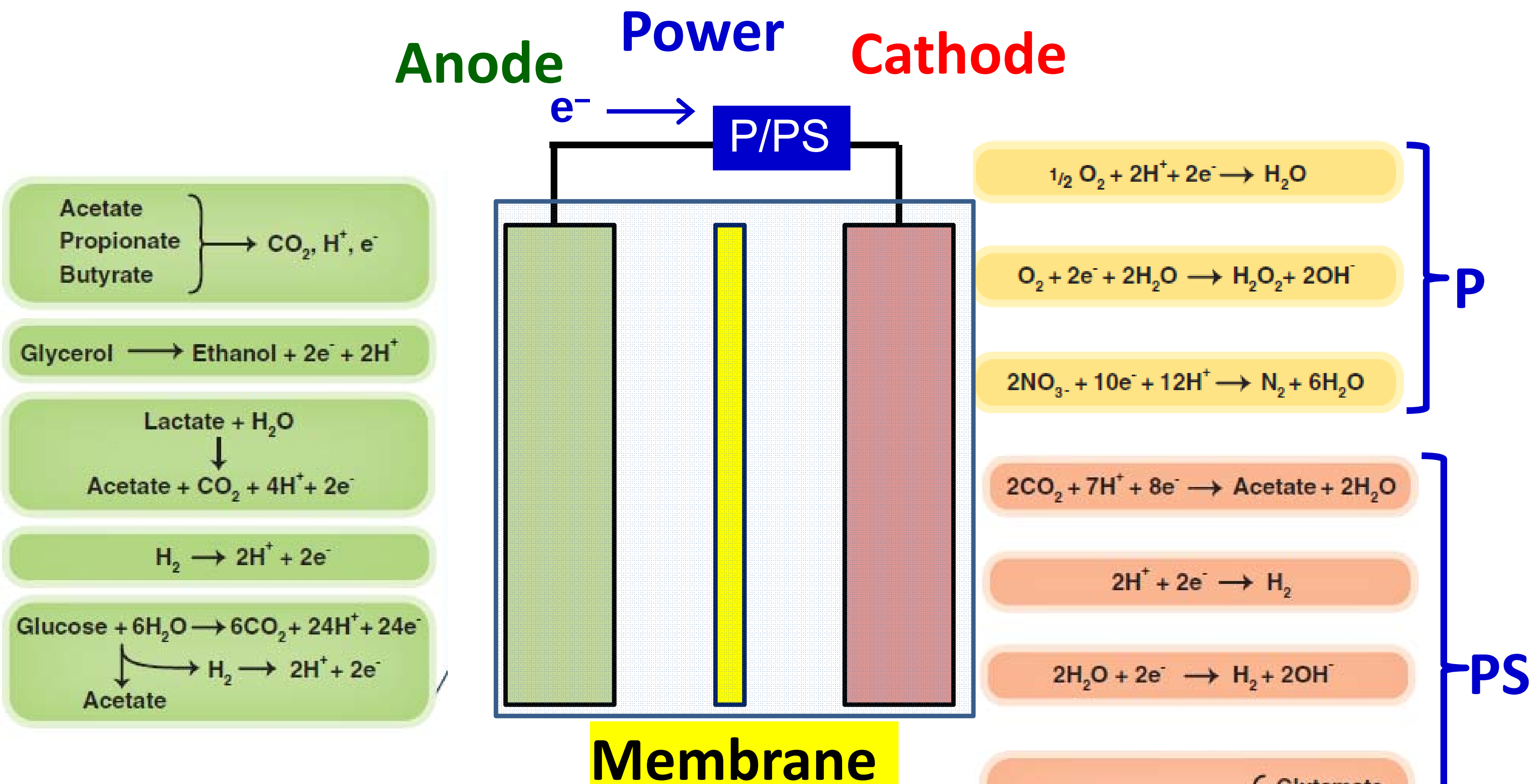
(methane from organic matter)

MMCs

Methane from renewable electricity



METs Microbial Electrochemical Technologies (METs)



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Adapted from: Logan and Rabaey (2012) *Science*

Focus points

- Electromicrobiology
  - Bioanodes: Electron transfer from bacteria to electrodes
  - Biocathodes: Biofuel production via electromethanogensis
- Engineering: Microbial electrochemical technologies for wastewater treatment
  - Materials
  - Performance
- Salinity gradient energy
  - Methods of energy production
  - Combining MFCs with salinity gradient energy
- Conclusions and Acknowledgments

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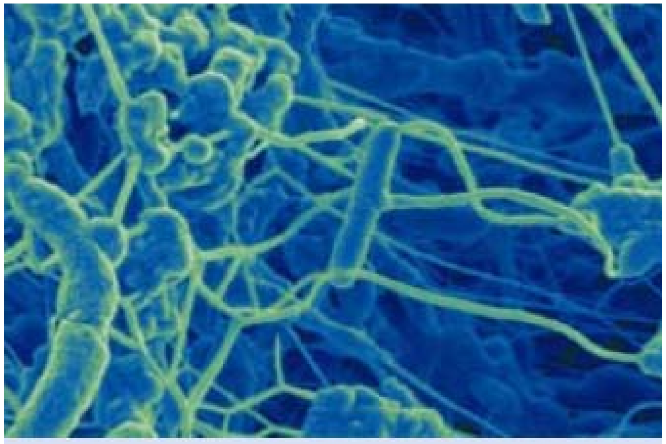
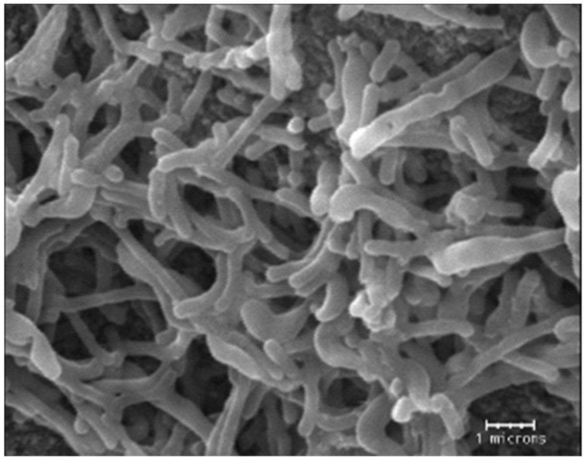
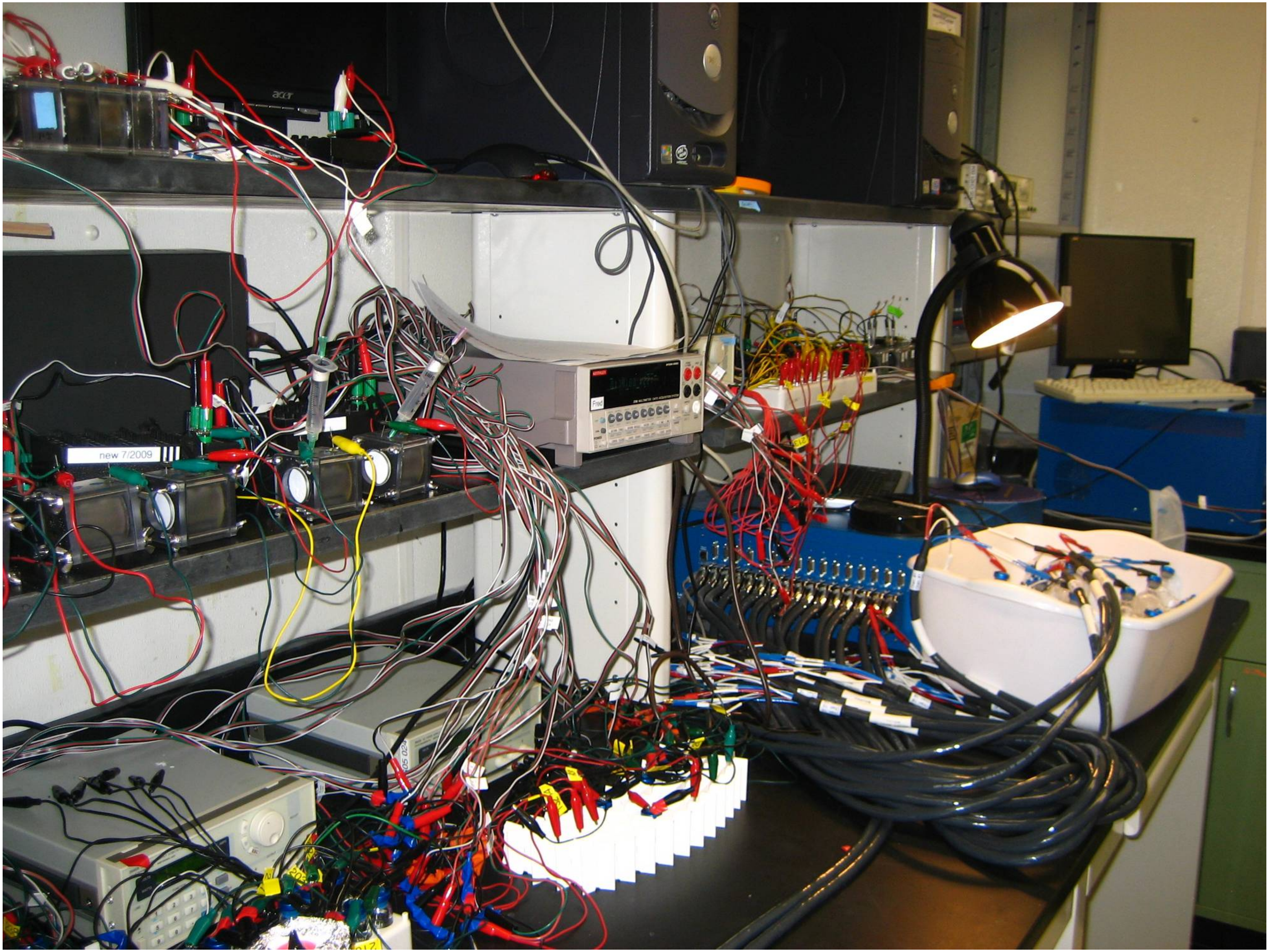
Electro-active Microorganisms

- Electromicrobiology
  - New sub-discipline of microbiology examining exocellular electron transfer



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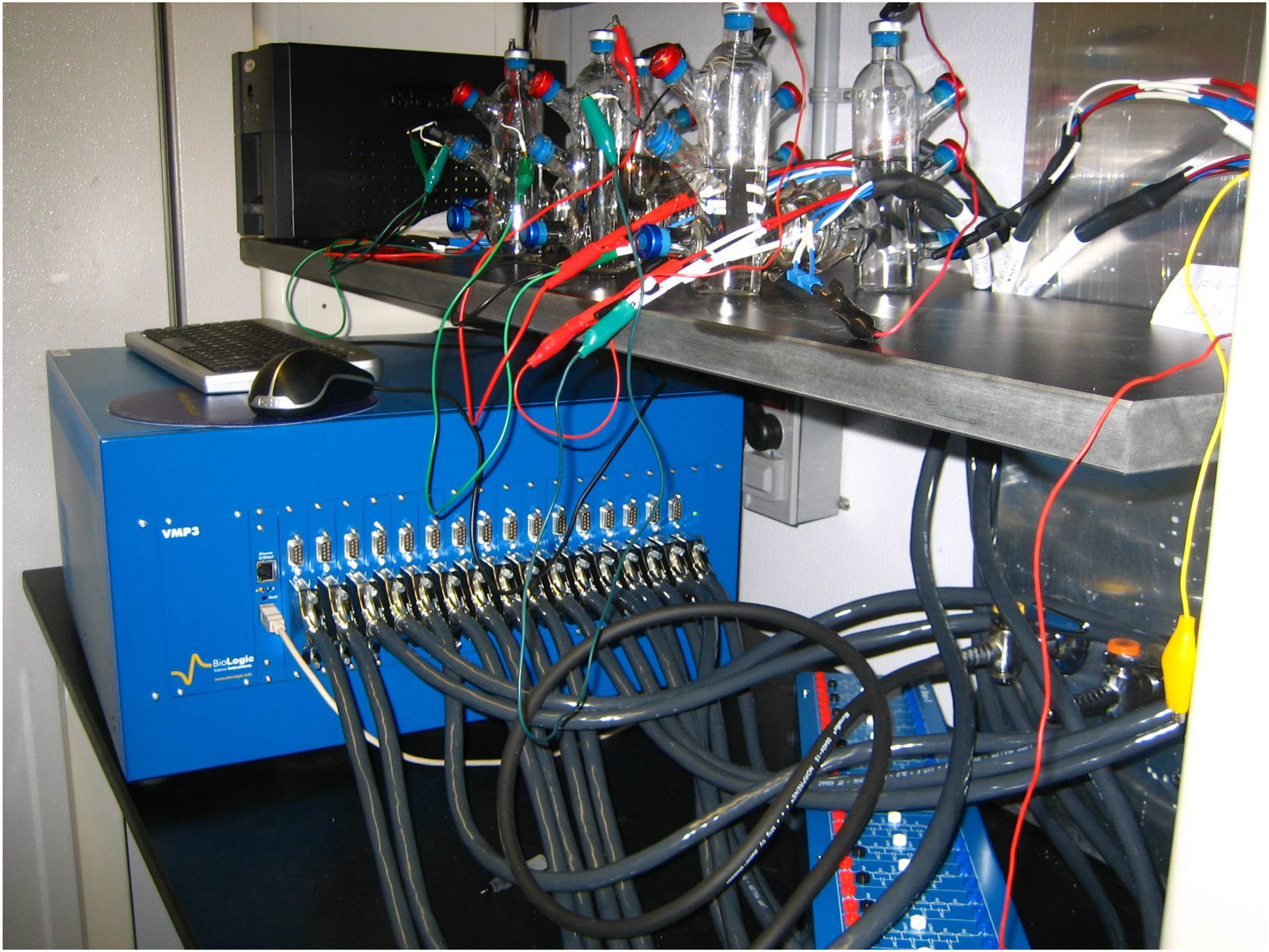
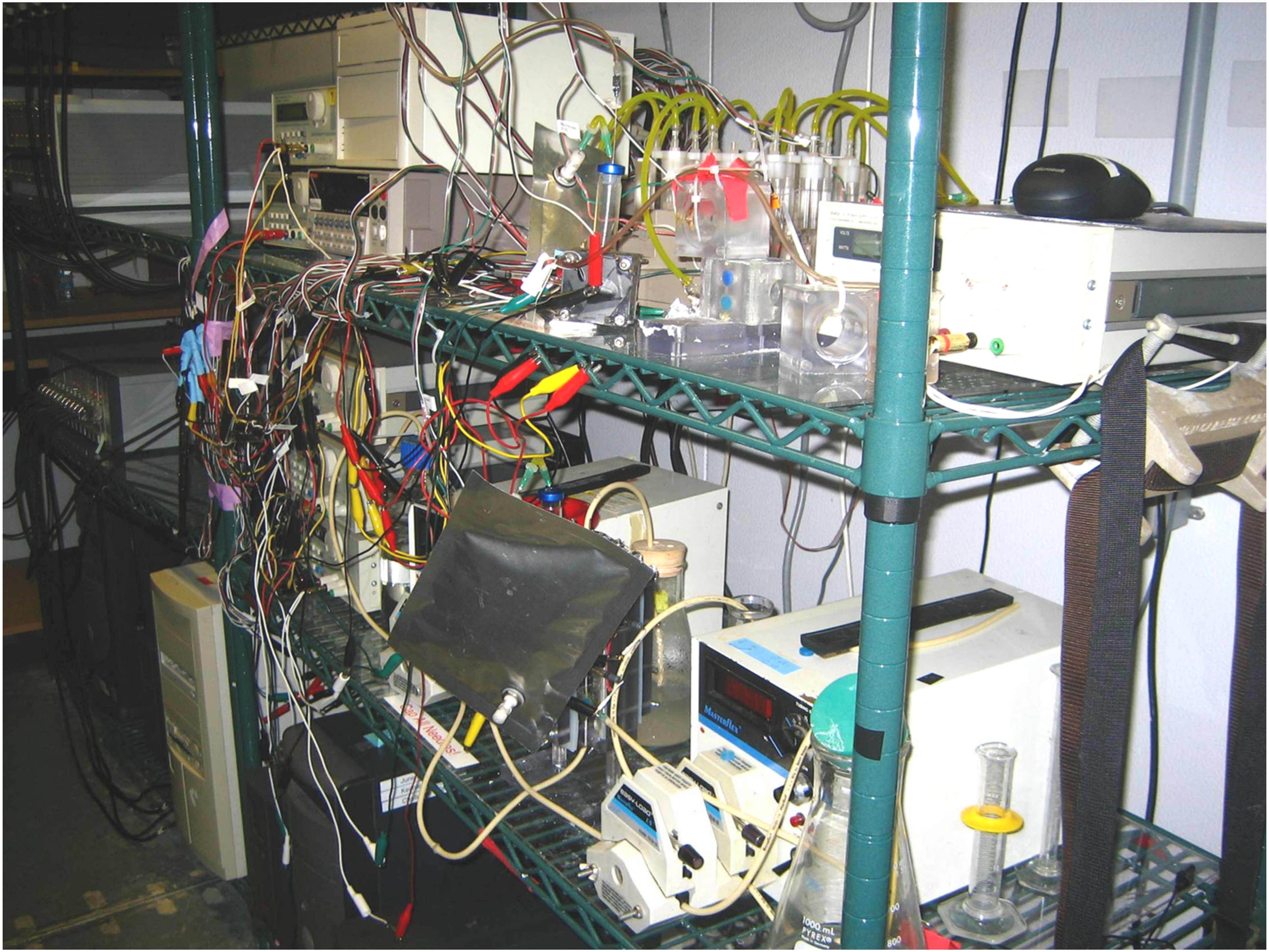

VMP3
BioLogic

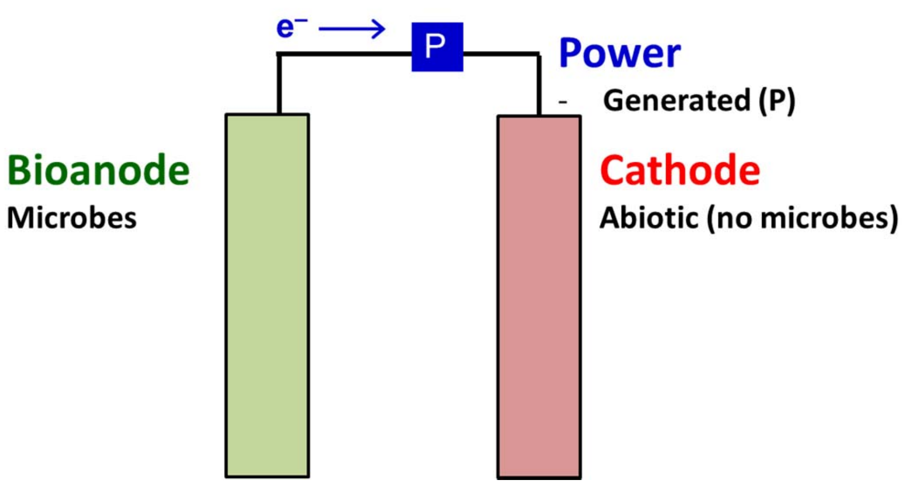


MASTERFLEX
1000 mL
PYREX

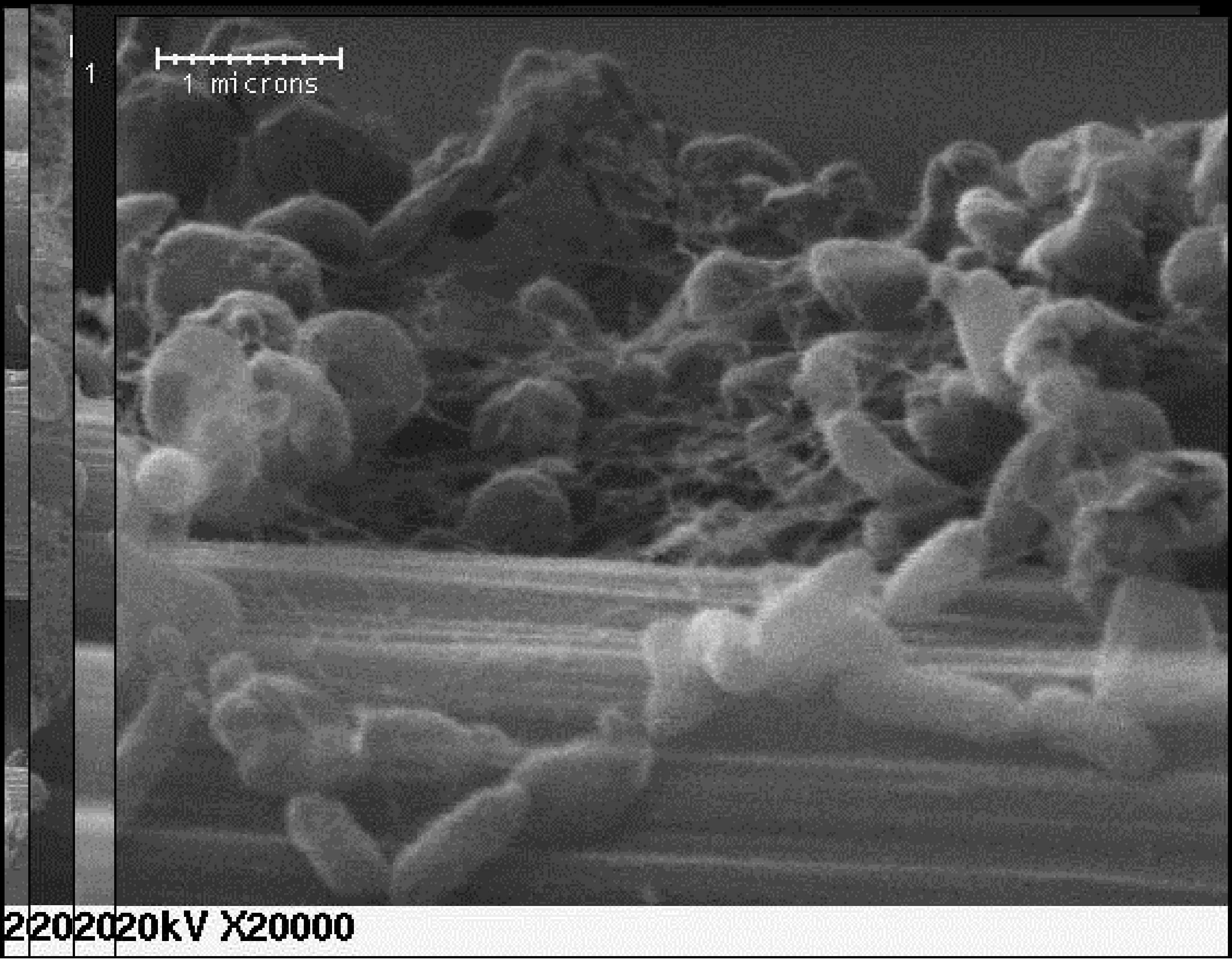
Electro-active Microorganisms

- Exoelectrogens

  Microbes able to transfer electrons to the outside the cell

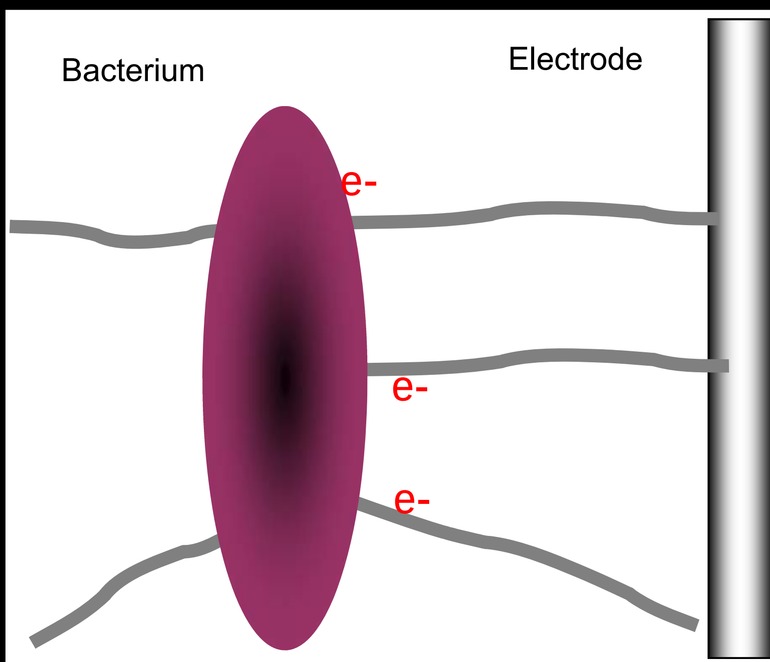


<u>Exoelectrogens</u>: Bacteria rapidly colonize the anode

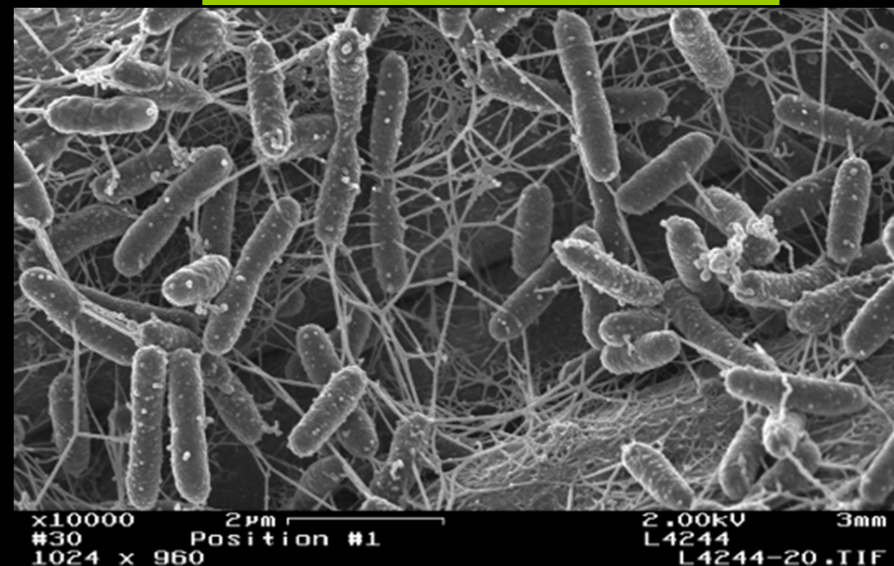


Mechanisms of electron transfer in the biofilm:

Nanowires produced by bacteria !



Gorby & 23 co-authors (2010) *PNAS*



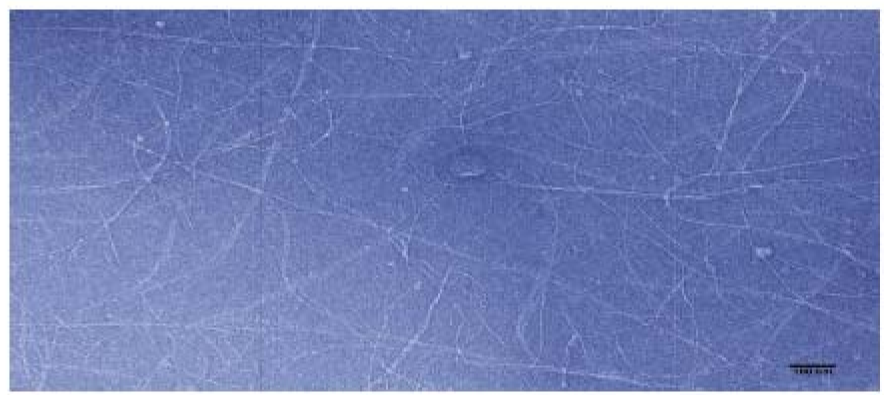
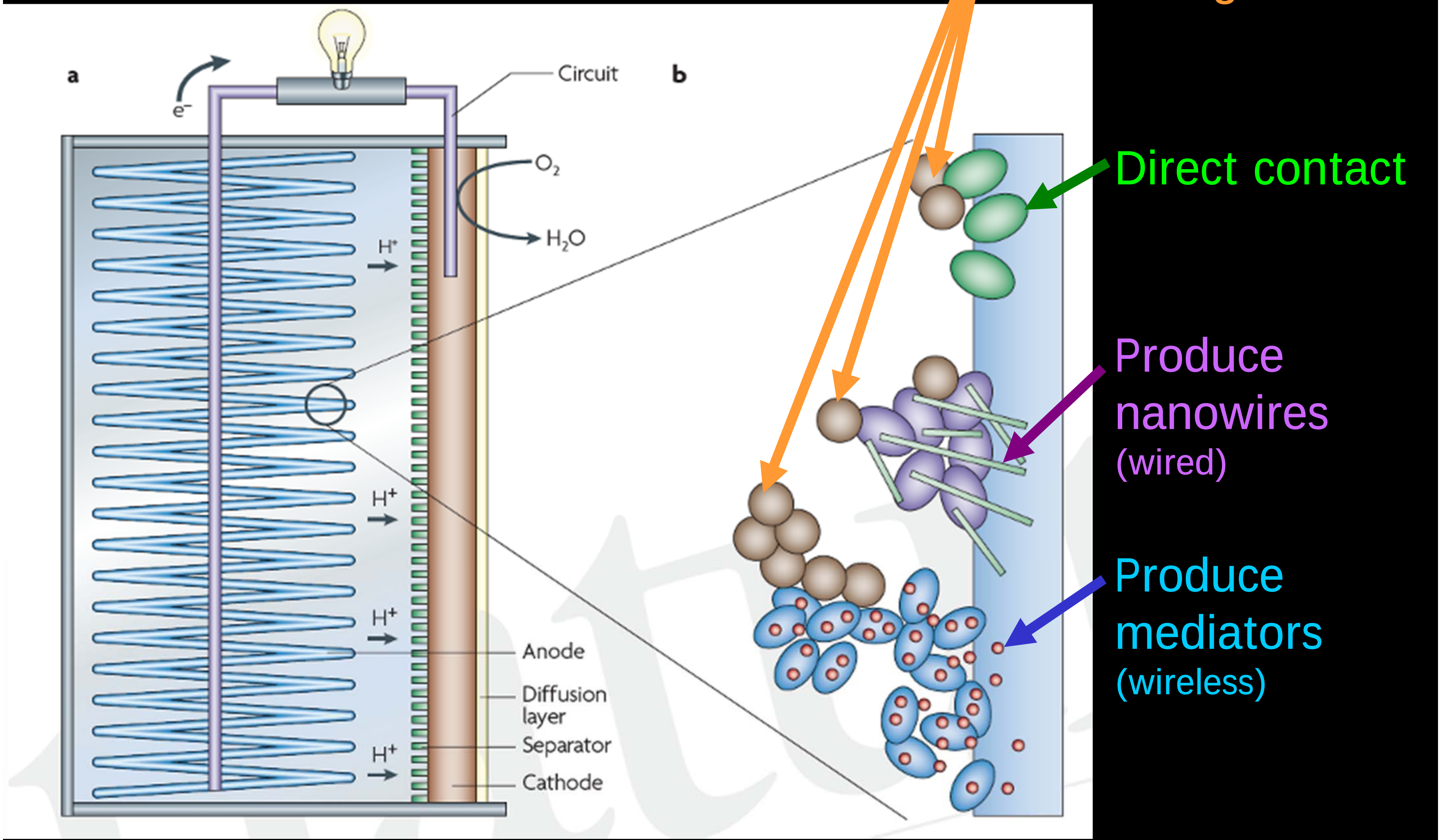


Figure 1. Colorized transmission electron micrograph of microbial nanowire networks secreted by *Geobacter sulfurreducens*. Scale bar, 100 nm.

Malvankar & Lovley (2012) *ChemSusChem*

Getting “wired”

Electrogenic biofilm ecology



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

How long are the wires?

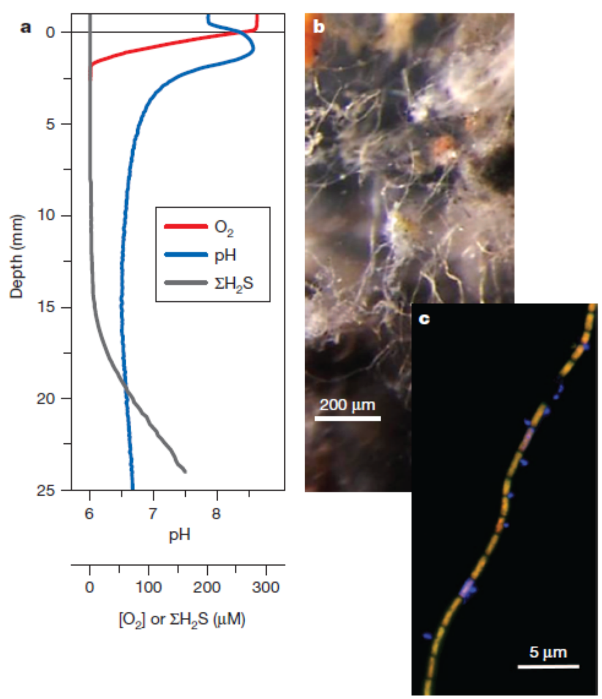
Nanowires in Nature- Ocean sediments “wired” over unprecedented length scales

doi:10.1038/nature11586

Filamentous bacteria transport electrons over centimetre distances

Christian Pfeffer[1], Steffen Larsen[2], Jie Song[3], Mingdong Dong[3], Flemming Besenbacher[3], Rikke Louise Meyer[2,3], Kasper Urup Kjeldsen[1], Lars Schreiber[1], Yuri A. Gorby[4], Mohamed Y. El-Naggar[5], Kar Man Leung[4,5], Andreas Schramm[1,2], Nils Risgaard-Petersen[1] & Lars Peter Nielsen[1,2]

RESEARCH ARTICLE

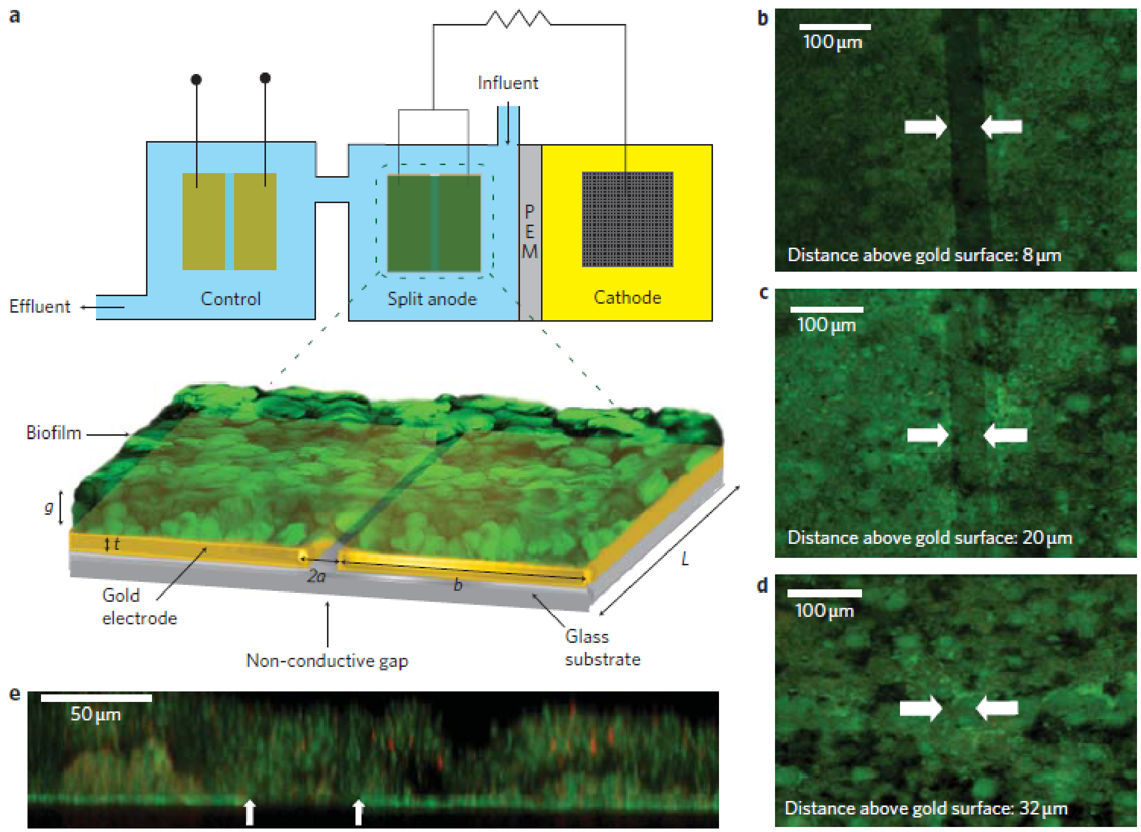


- Individual nanowires that connect cells are individually 10-100 nanometers (nm=10^{-9} m)
- Biofilms on electrodes 10-50 micrometers (μm=10^{-6} m)
- Filamentous bacteria can help wire up cells over distances of 40 millimeters (mm=10^{-3} m)

Pfeffer et al. (2012) *Nature*

Electrical conductivity of "nanowires" can span across the biofilm length (cm? meters?)

LETTERS NATURE NANOTECHNOLOGY DOI: 10.1038/NNANO.2011.119



Malvankar et al. (2011) *Nature Nanotechnol.*

What microbes are on the anodes?

- Tested reactors over 2 months from 3 sources
  - Penn State wastewater treatment plant (P)
  - UAJA wastewater treatment plant (U)
  - Freshwater bog sediments (B)
- Performance analysis: Power production
- Community analysis
  - Clone libraries
  - Pyrosequencing
  - DGGE
  - FISH

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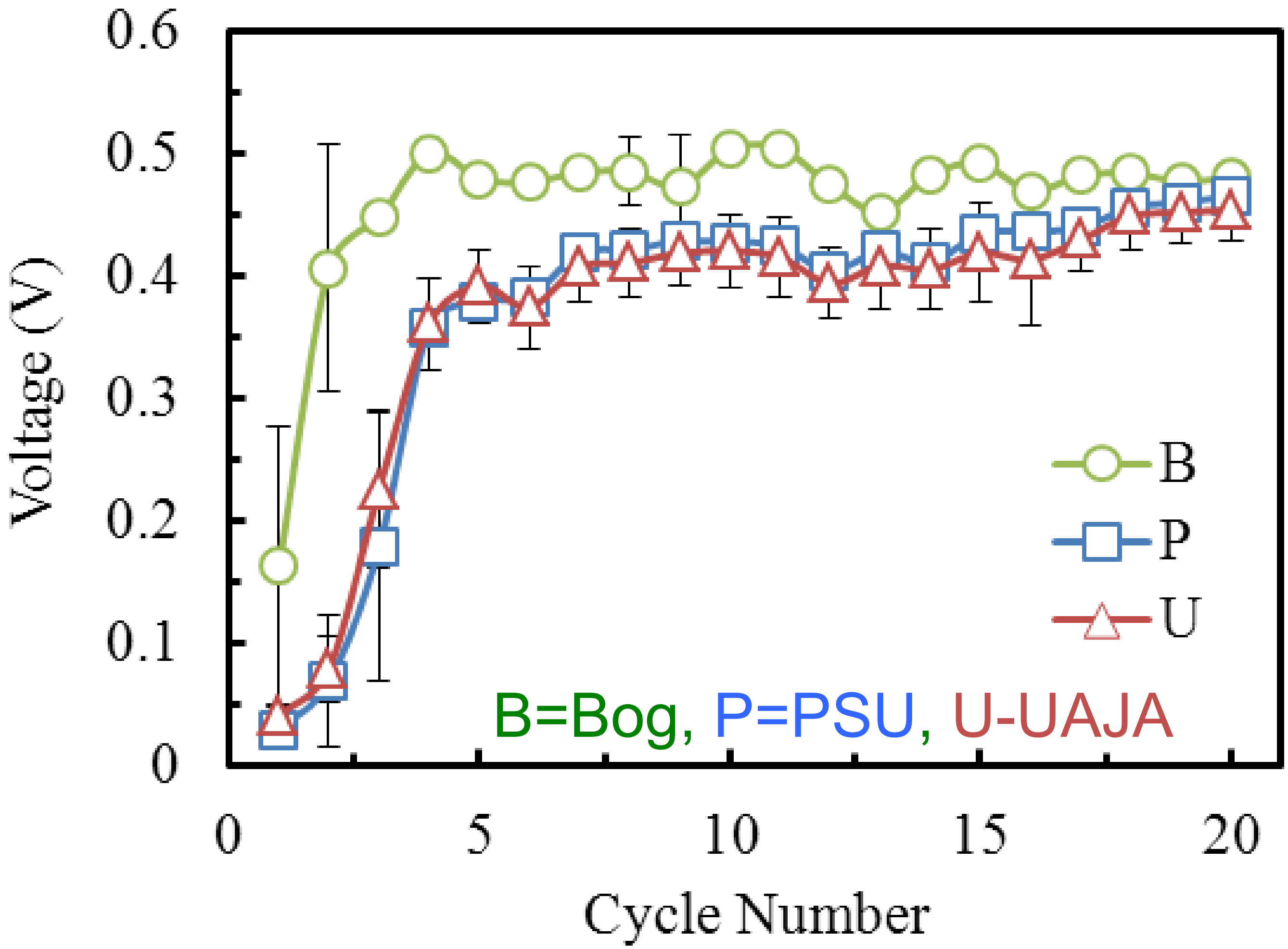
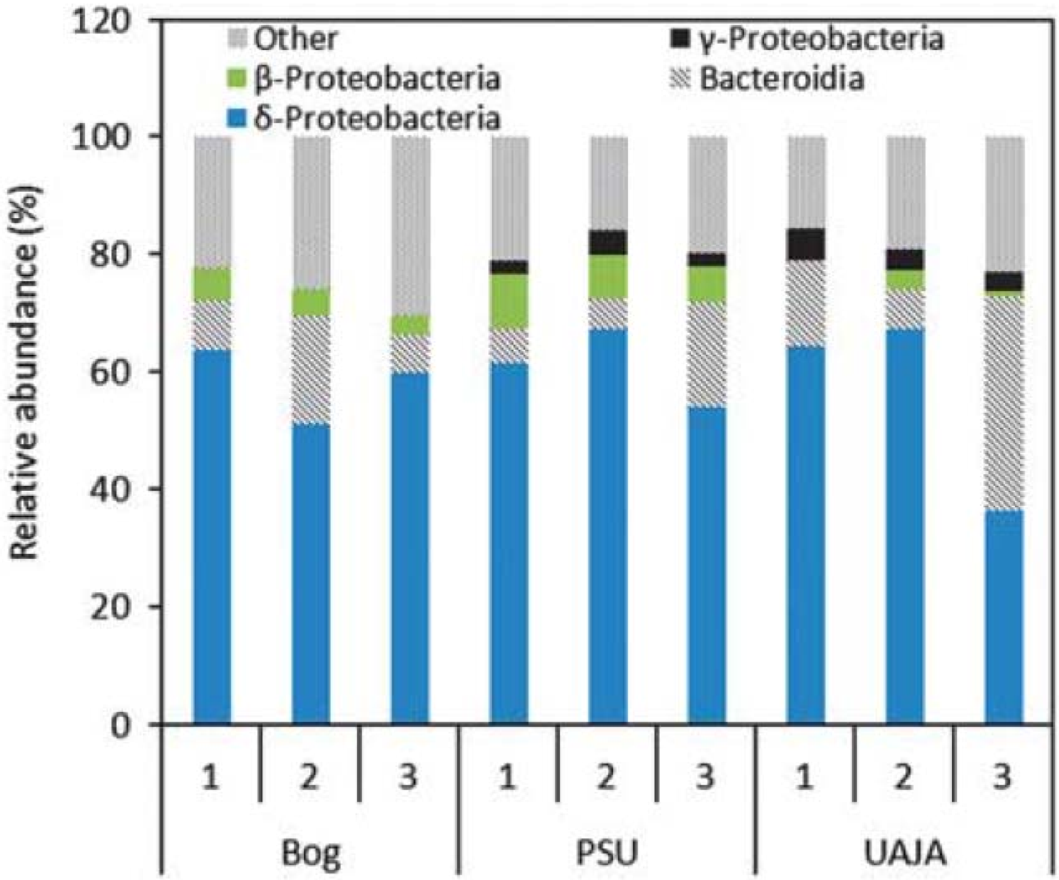
Yates et al. (2012) *ISME J.*

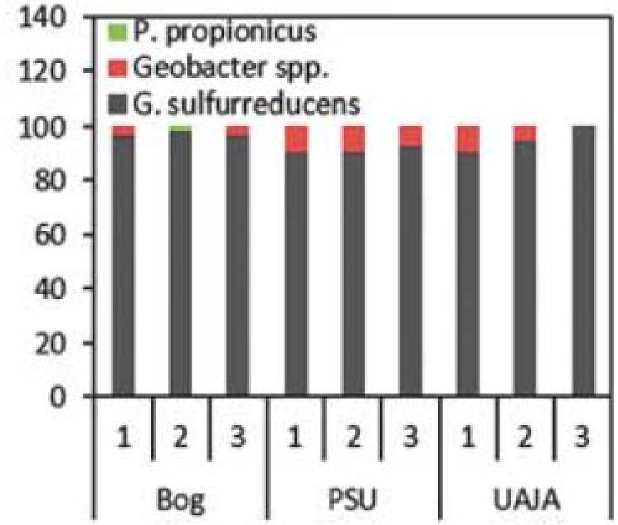
Bog produced power most rapidly but all inocula converged in power



Yates et al. (2012) *ISME J.*

Pyrosequencing: mostly Delta Proteobacteria… and of those, almost all sequences most similar to *Geobacter sulfurreducens*





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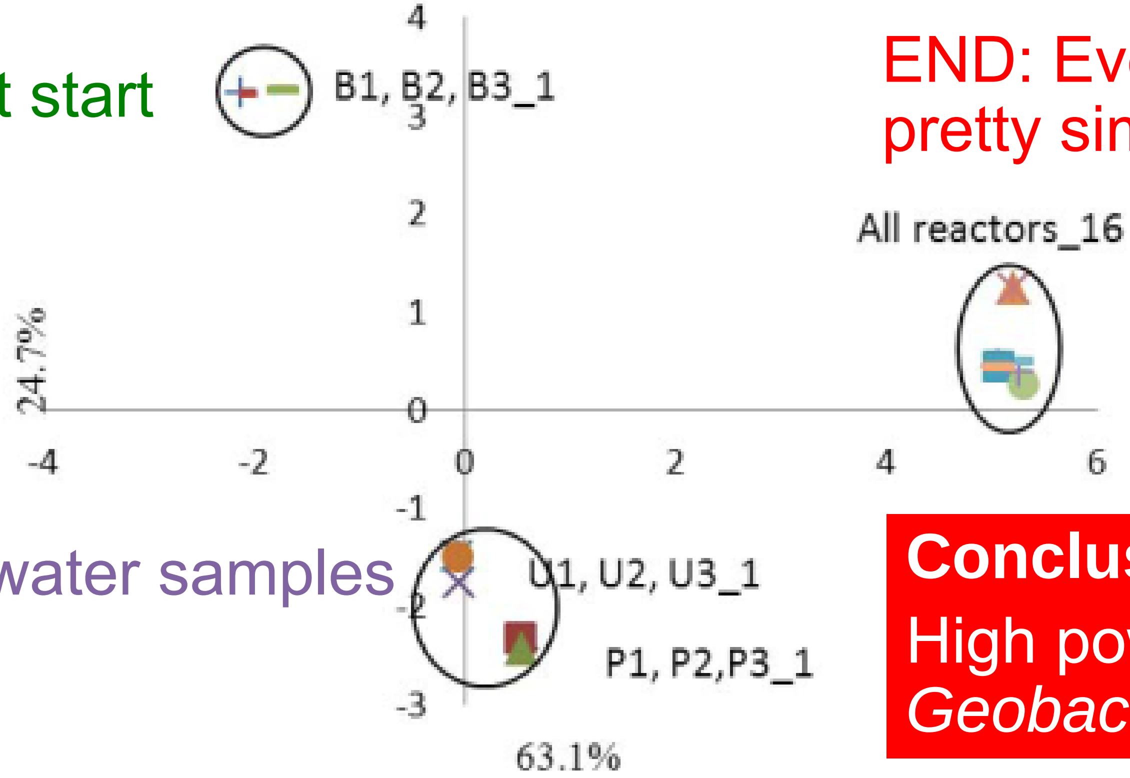
Yates et al. (2012) *ISME J.*

DGGE used to show changes in community diversity over time

Bog at start

END: Everything pretty similar



Wastewater samples at start

Conclusion:

High power requires *Geobacter* spp.

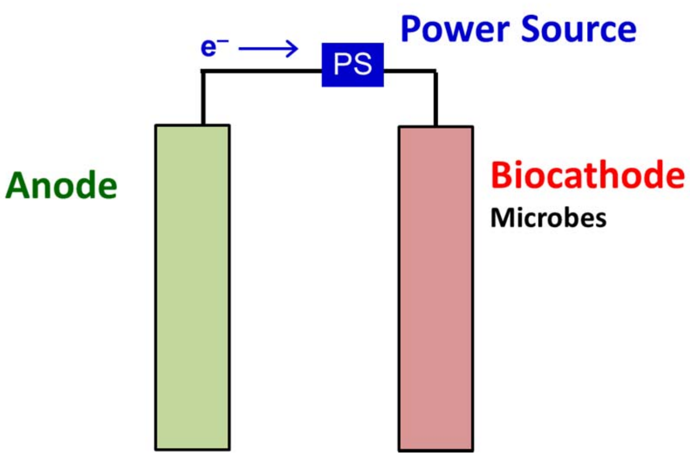
B=Bog, P=PSU, U=UAJA

Yates et al. (2012) *ISME J.*

Electro-active Microorganisms

- Electrotrophs

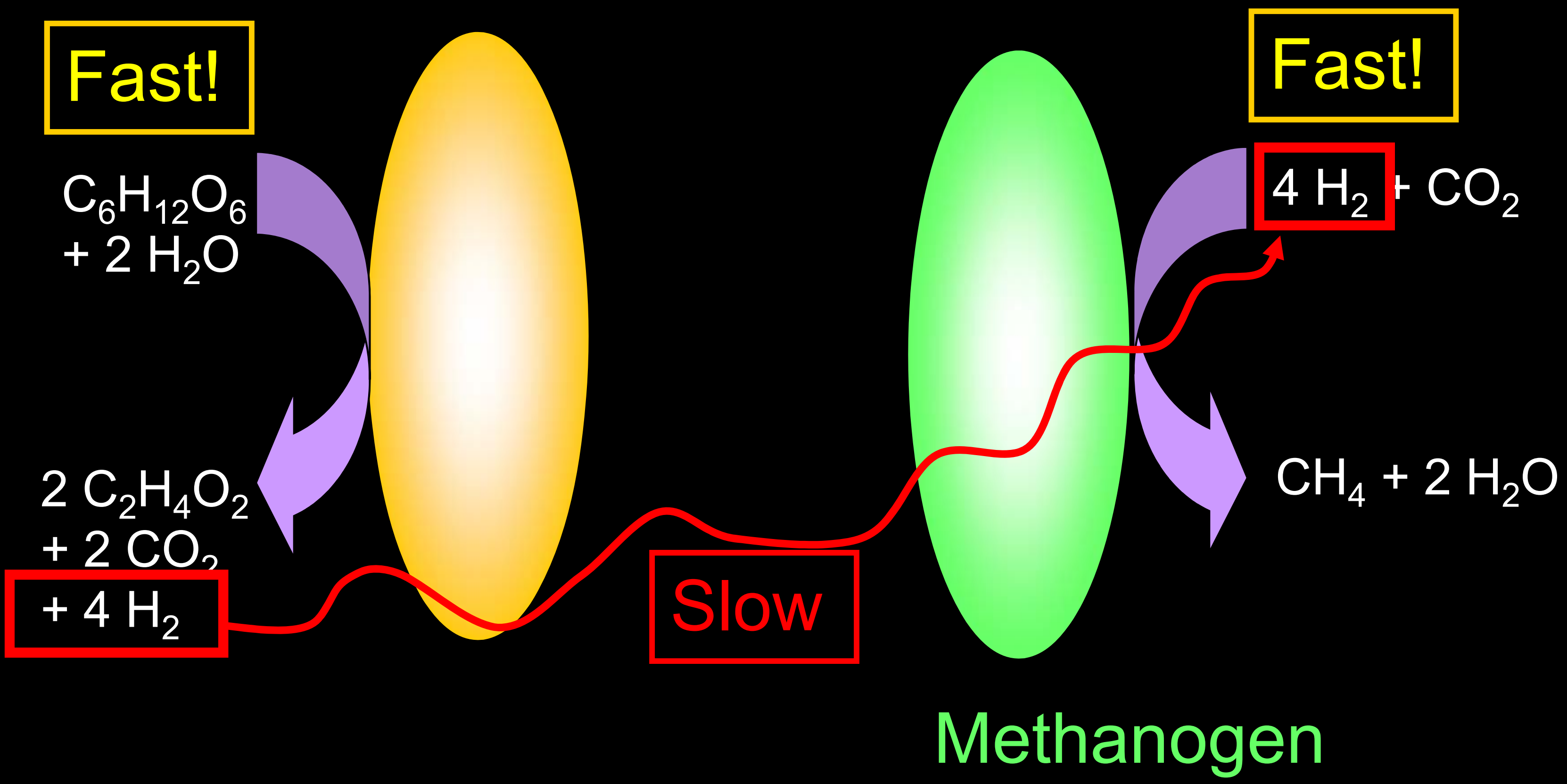
  Microbes that can accept electrons into the cell



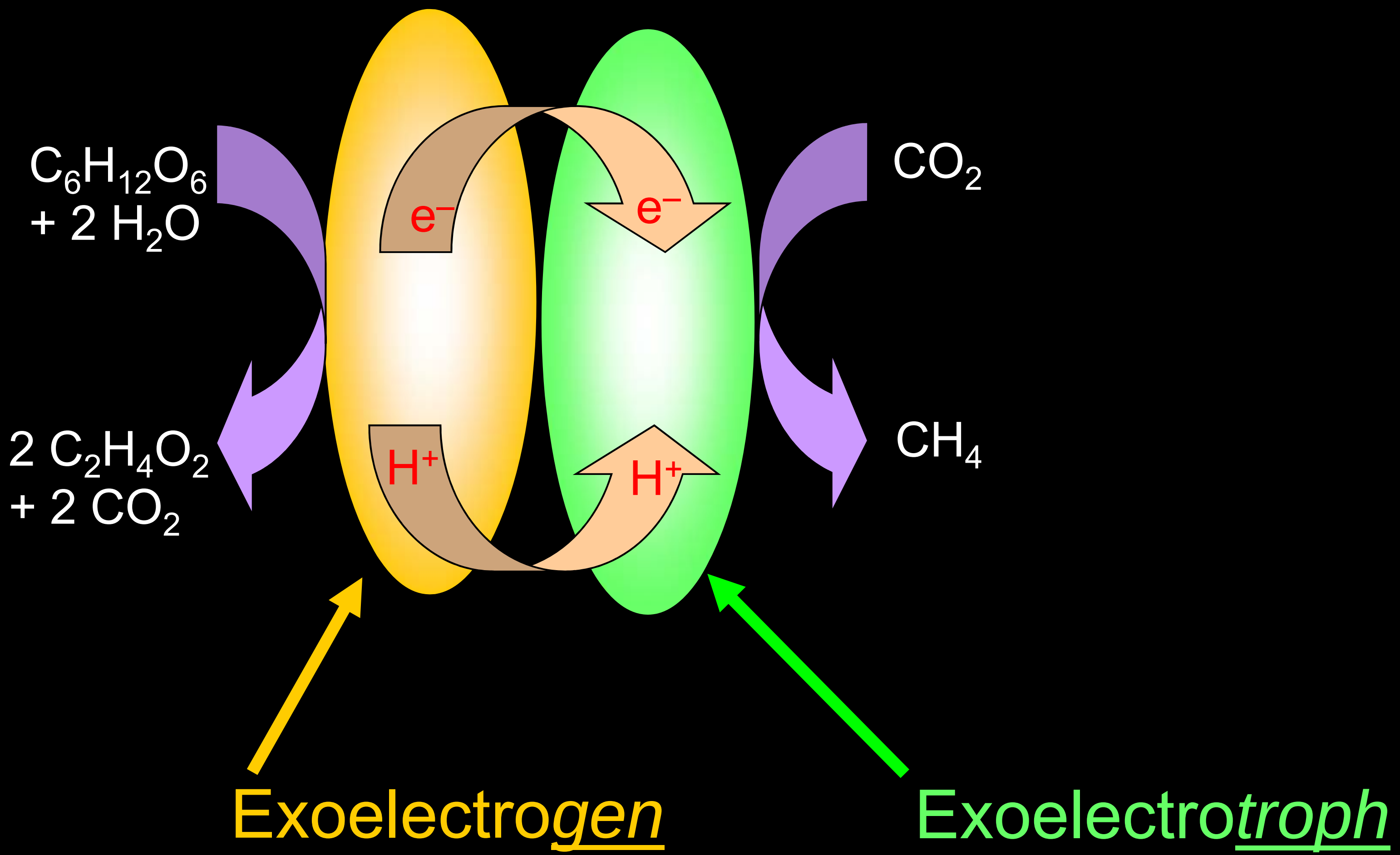
Chemicals used (examples)

- Dissolved oxygen
- Nitrate
- CO_2 - Reduction by methanogens, called "Electromethanogenesis"

Methanogens: Conventional model based on interspecies *hydrogen* transfer



New model includes exoelectroactive microorganisms: electron transfer



What is the evidence for electromethanogensis?

- Nanowire connections
- Experiments:
  - Mixed cultures
  - Pure cultures
- New studies on methane production

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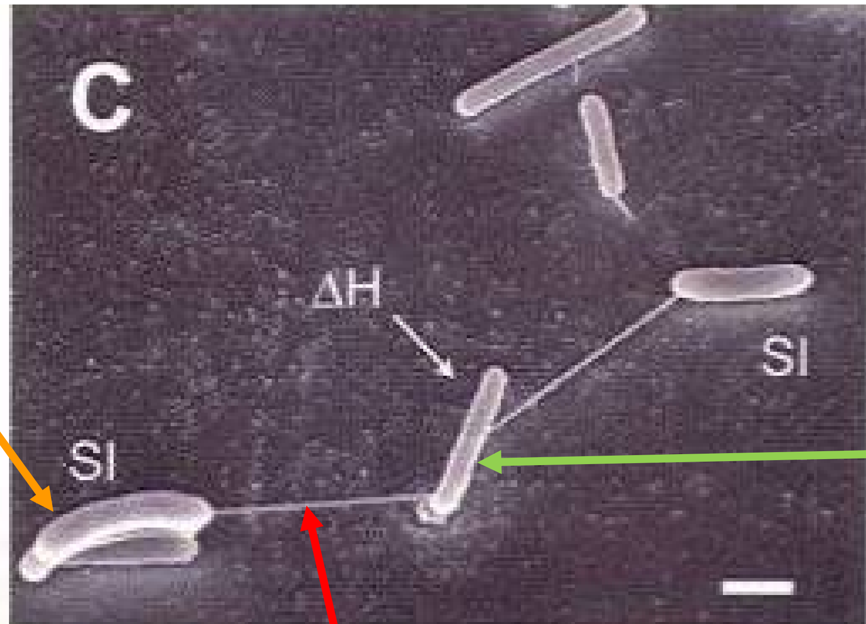
First evidence of direct <u>interspecies</u> <u>*electron*</u> transfer (2006)

SI- ferments propionate, releases electrons



ΔH: Methanogen accepts electrons, makes methane

Nanowires connect fermentative and methanogenic microorganisms

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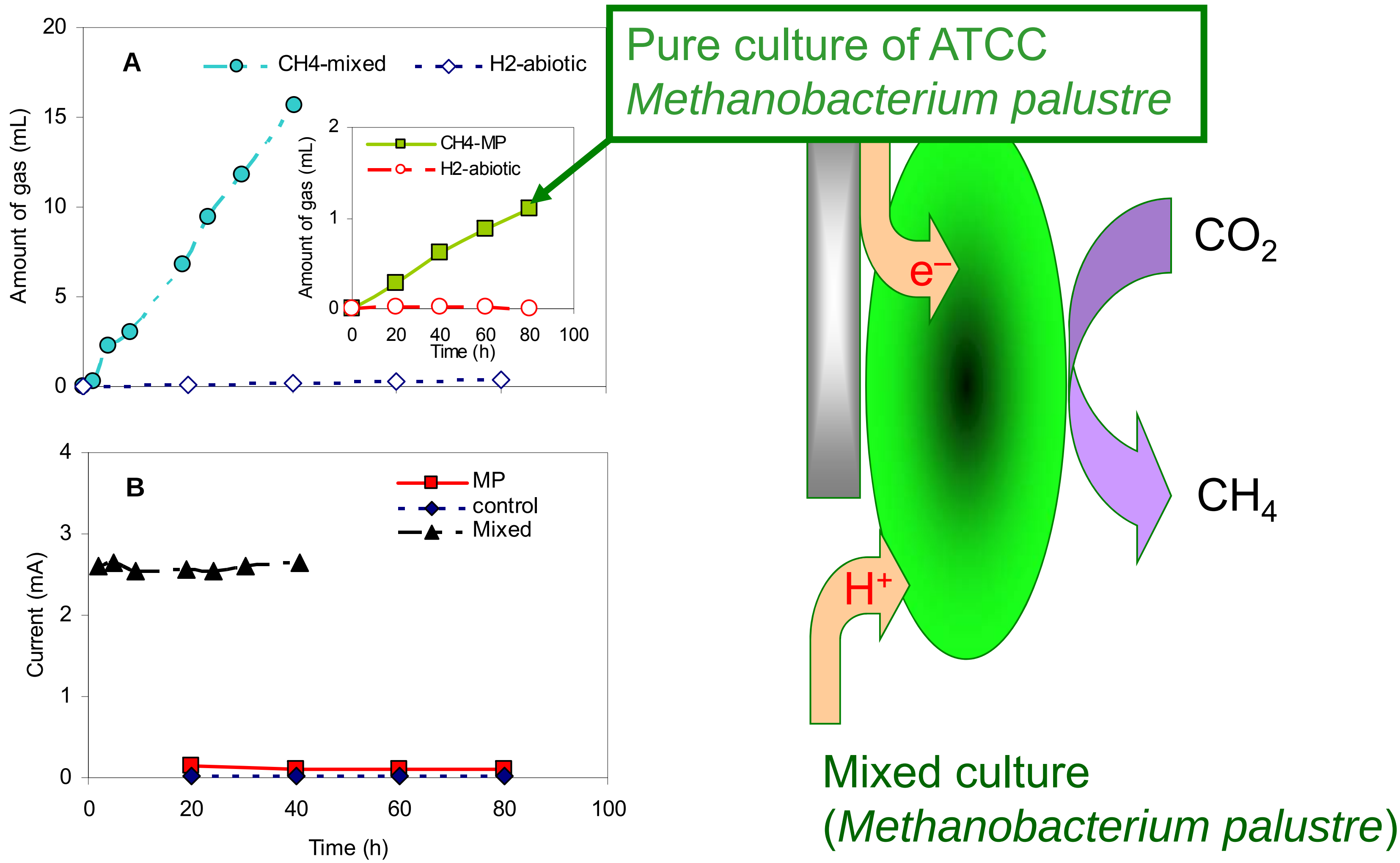
Figure source: Ishii et al. (2005) *Appl. Environ. Microbiol.*

Gorby & 25 others (2006) *Proc. Nat. Academy Sci.*

Electrotrophic Methanogens



Mixed culture
(*Methanobacterium palustre*)

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

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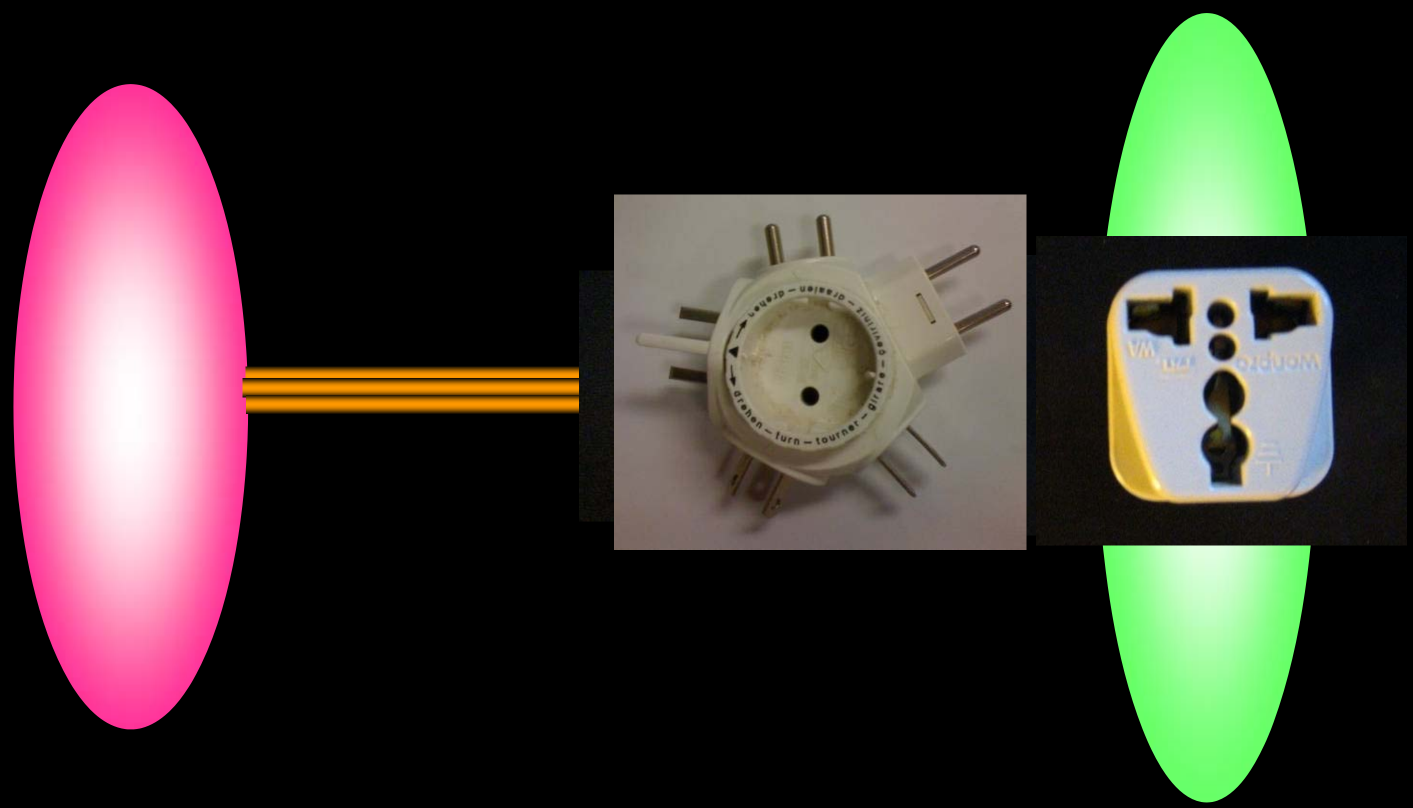
Connections between microbes- Specific or non-specific?



Exoelectro*gen*

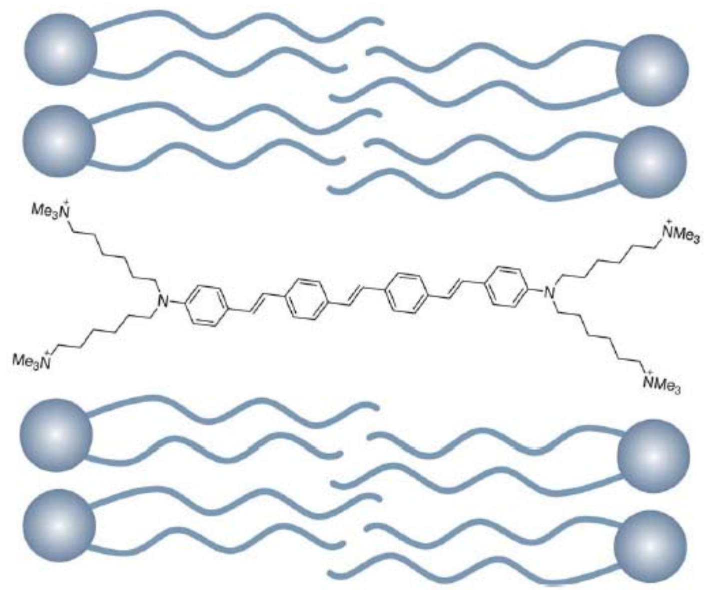
Exoelectro*troph*

Can “we” make artificial bio-nanowires?

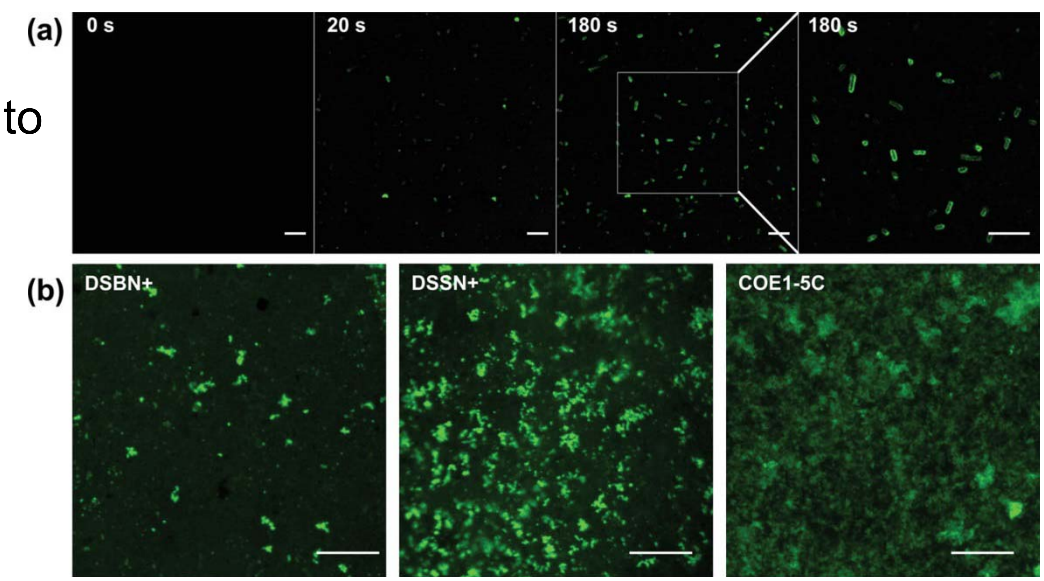
Yes!

“Conjugated oligoelectrolytes (COEs) are synthetic molecules described by a π -conjugated backbone bearing ionic pendant substituents.”

Research group: Guillermo (Gui) Bazan, University of California, Santa Barbara

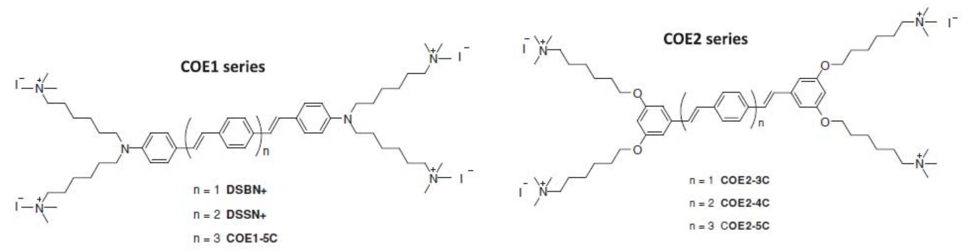


COEs spontaneously insert into the membrane, and fluoresce only when in the cells



Addition of COEs increase power production in *Escherichia coli*

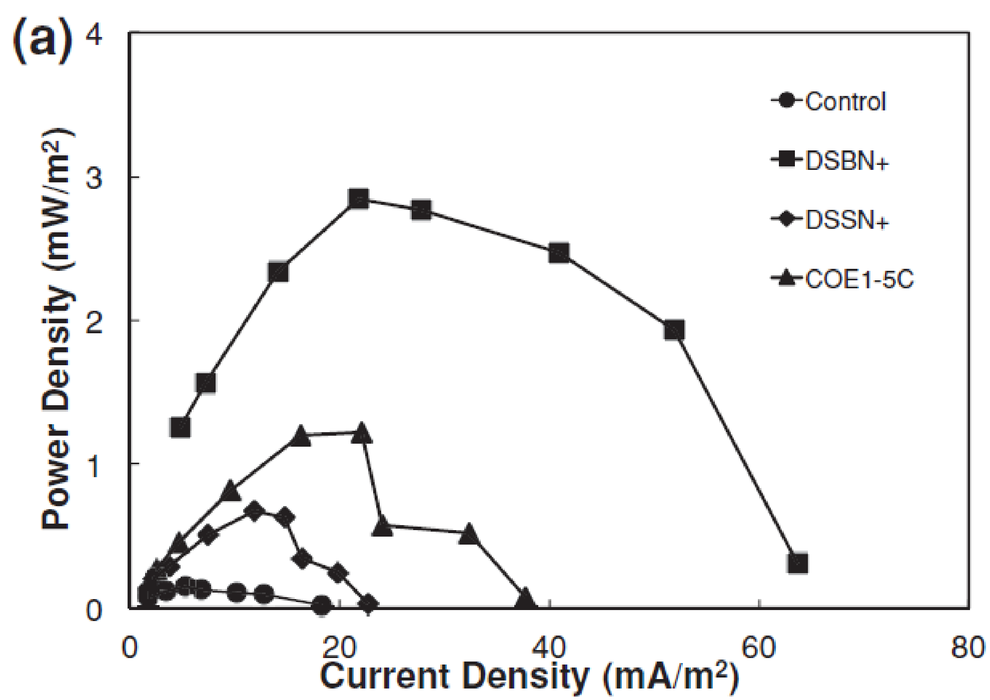
E. coli often used as a "negative control" as it produces little current in a microbial fuel cell.



Scheme 1. Molecular structures of conjugated oligoelectrolytes used in this study. COE1 series: DSBN+, DSSN+, and COE1-5C; COE2 series: COE2-3C, COE2-4C, COE2-5C.

Addition of 2 different COEs shown to increase power production (but power density is still relatively low)

Hou, Chen, Thomas, Catania, Kirchhofer, Garner, Han, and Bazan (2013) *Adv. Materials*



Scaling up MFCs

M**F**Cs= fuel cells, make electricity

Scaling up MECs

M**E**Cs= electrolysis cells, make H_2

How can we make large-scale MFCs?

- Reactor design- MFCs, MECs
- Materials and performance-- Costs are the key!

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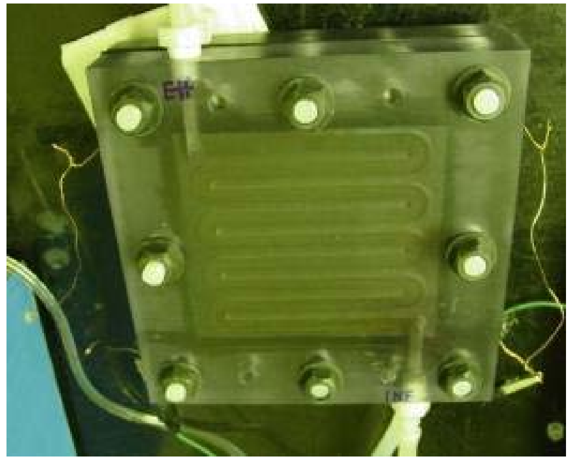
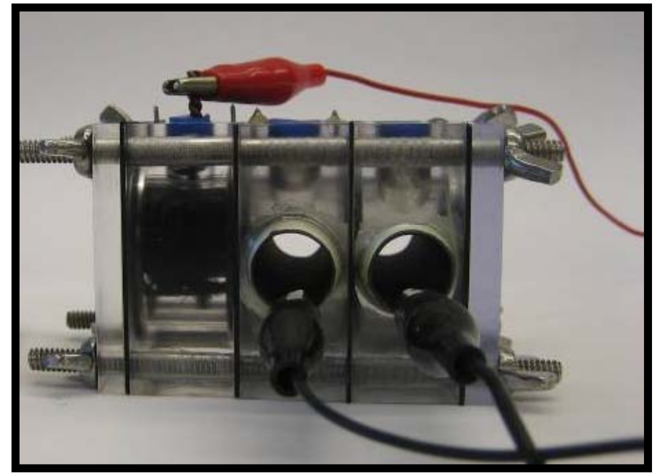
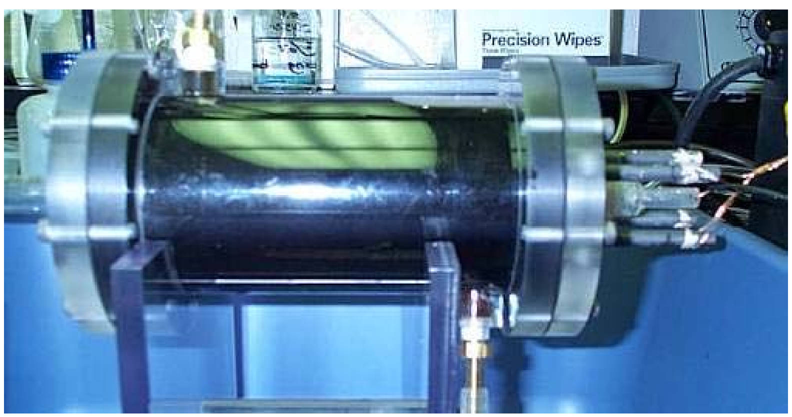
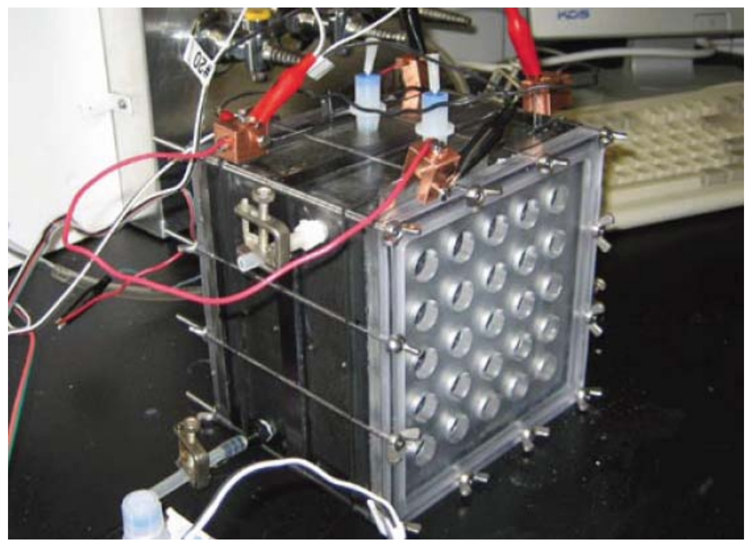
REACTOR ENGINEERING

Air cathode MFCs developed at Penn State









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MFC Architecture

Estimates for MFCs

- **100 € /m² or $130/m²**

Estimates for MECs

- **100 € /m² or $130/m²**

CHEMSUSCHEM

ChemPubSoc Europe

DOI: 10.1002/cssc.201100732

Bioelectrochemical Systems: An Outlook for Practical Applications

Tom H. J. A. Sleutels,[a] Annemiek Ter Heijne,*[b] Cees J. N. Buisman,[a, b] and Hubertus V. M. Hamelers[a, b]

Bioelectrochemical systems (BESs) hold great promise for sustainable production of energy and chemicals. This review addresses the factors that are essential for practical application of BESs. First, we compare benefits (value of products and cleaning of wastewater) with costs (capital and operational costs). Based on this, we analyze the maximum internal resistance (in $m\Omega m^2$) and current density that is required to make microbial fuel cells (MFCs) and hydrogen-producing microbial electrolysis cells (MECs) cost effective. We compare these maximum resistances to reported internal resistances and current densities with special focus on cathodic resistances. Whereas the current densities of MFCs still need to be increased considerably (i.e., internal resistance needs to be decreased), MECs are closer to application as their current densities can be increased by increasing the applied voltage. For MFCs, the production of high-value products in combination with electricity production and wastewater treatment is a promising route.

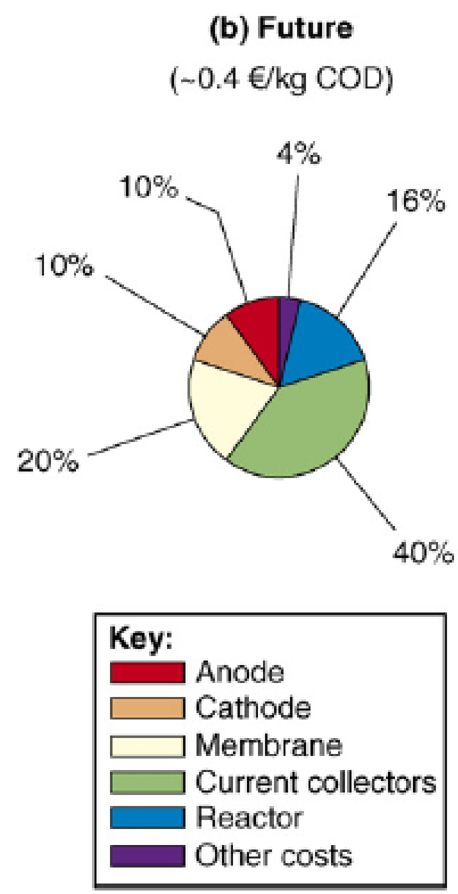
Review

Cell PRESS

Towards practical implementation of bioelectrochemical wastewater treatment

René A. Rozendal[1,2,3], Hubertus V.M. Hamelers[2], Korneel Rabaey[1], Jurg Keller[1] and Cees J.N. Buisman[2,3]

[1] Advanced Water Management Centre, The University of Queensland, St. Lucia, QLD 4072, Australia
[2] Sub-department of Environmental Technology, Wageningen University, Bomenweg 2, P.O. Box 8129, 6700 EV Wageningen, The Netherlands
[3] Wetsus, Centre for Sustainable Water Technology, Agora 1, P.O. Box 1113, 8900 CC Leeuwarden, The Netherlands



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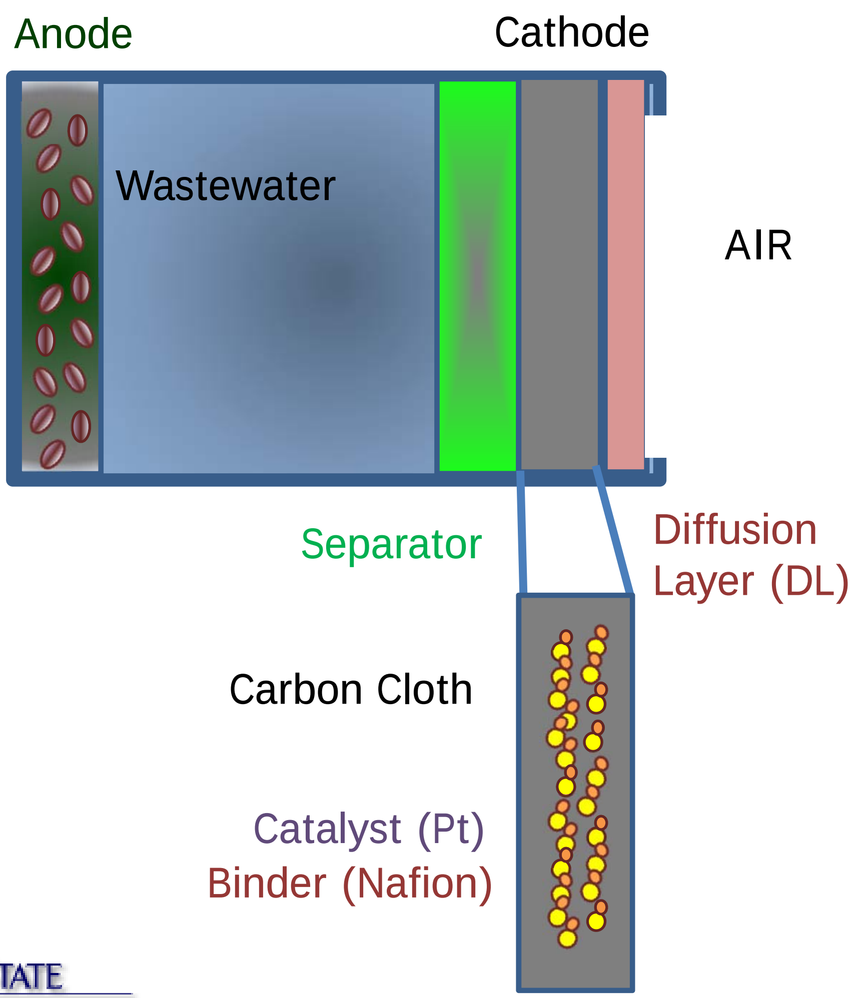
MFC Architecture



Original systems: $/m² (US)

- Carbon cloth~ $1,000
- Pt catalyst~ $ 500
- Binder~ $ 700
- DL (PTFE)~ $ 0.30
- Separator~ $ 1
- **TOTAL $2200**

New systems: $/m² (US)

- Anode $20
- Cathode $22
  - SS + CB= $20
  - Catalyst (AC)=$0.40
  - Binder= $1.5
  - DL (PDMS)= $0.15
- Separator $ 1
- **TOTAL $43**

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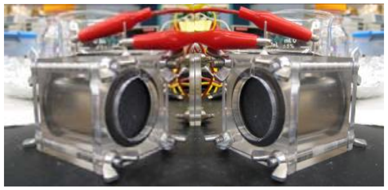
MFC Architecture



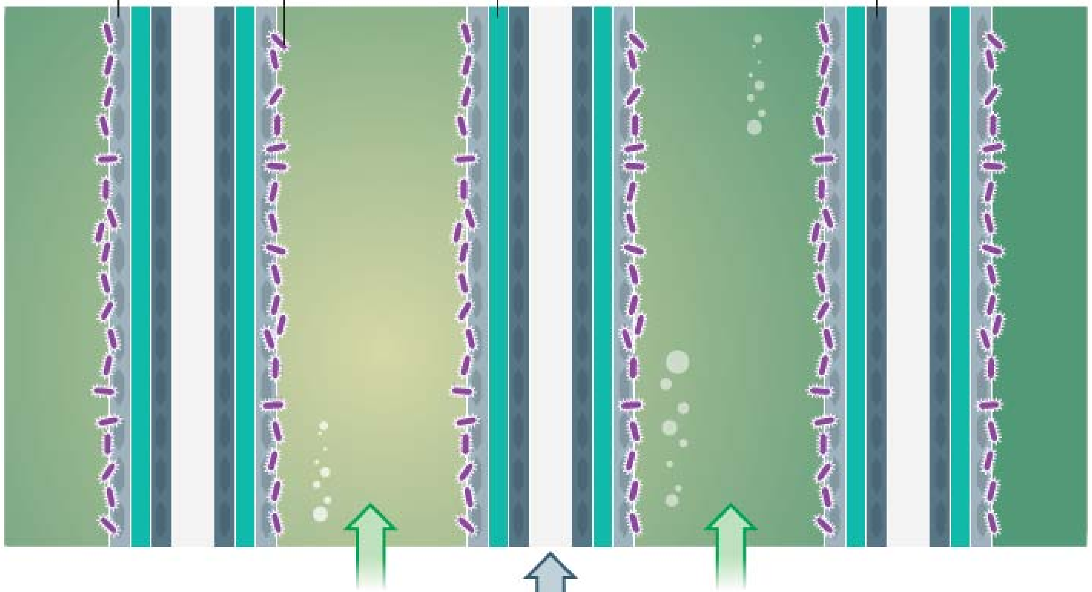
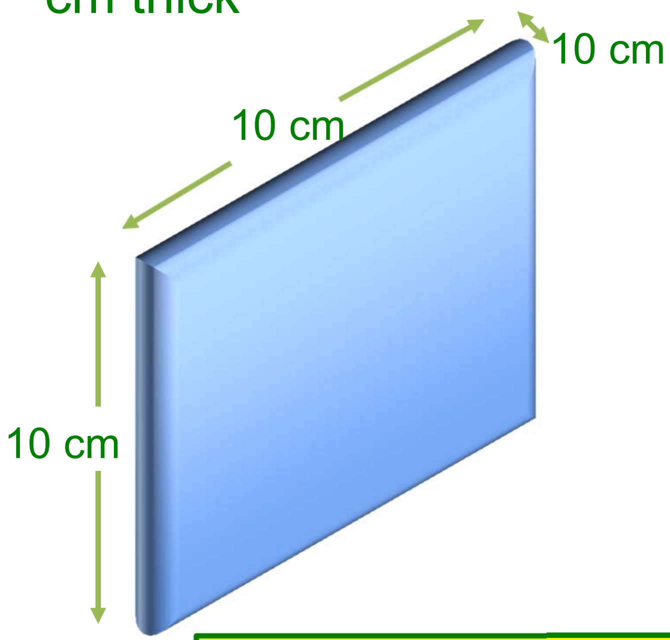


Figure 3 | An MFC stack. MFCs are arranged close together to reduce internal resistance and form compact reactors. Within the stack the electrodes consist of repeating units of an anode coated in a mat of bacteria, or biofilm, an insulating separator and a cathode. Waste water flows over the anodes and air over the cathodes. The individual anode and cathode are connected by a wire (not shown).

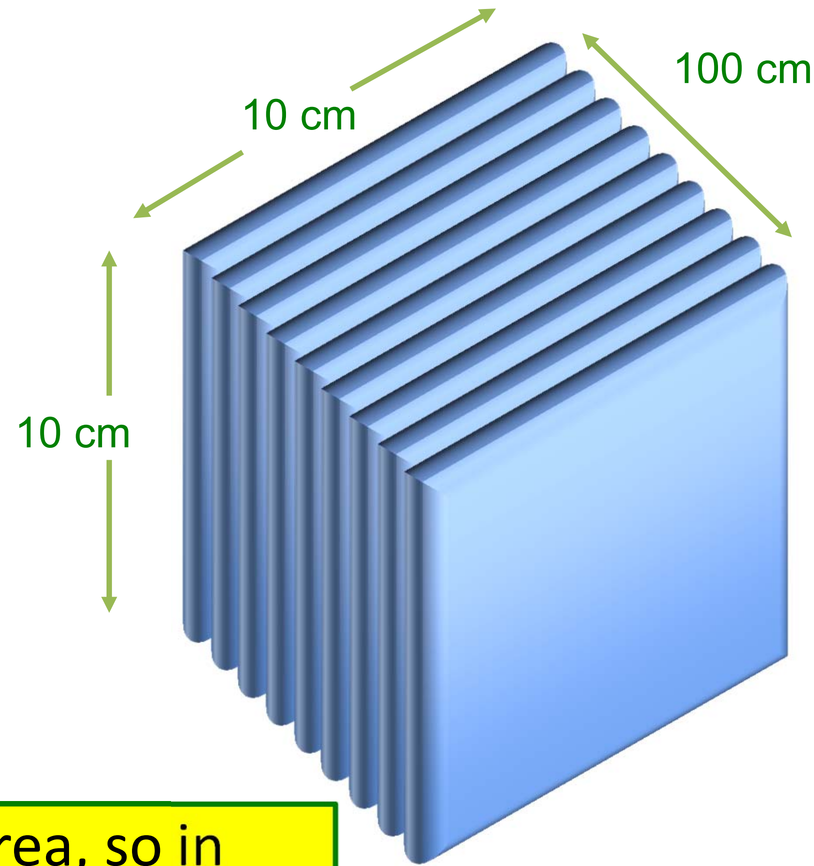
Logan & Elimelech (2012) *Nature*

Overall goal: compact reactor design

Assume: One anode-cathode module is 1 m^2 projected area (height x width) and 10 cm thick



Result: 10 modules = 10 m^2



Design: Limited by cathode area, so in this example we achieve 10 m^2/m^3

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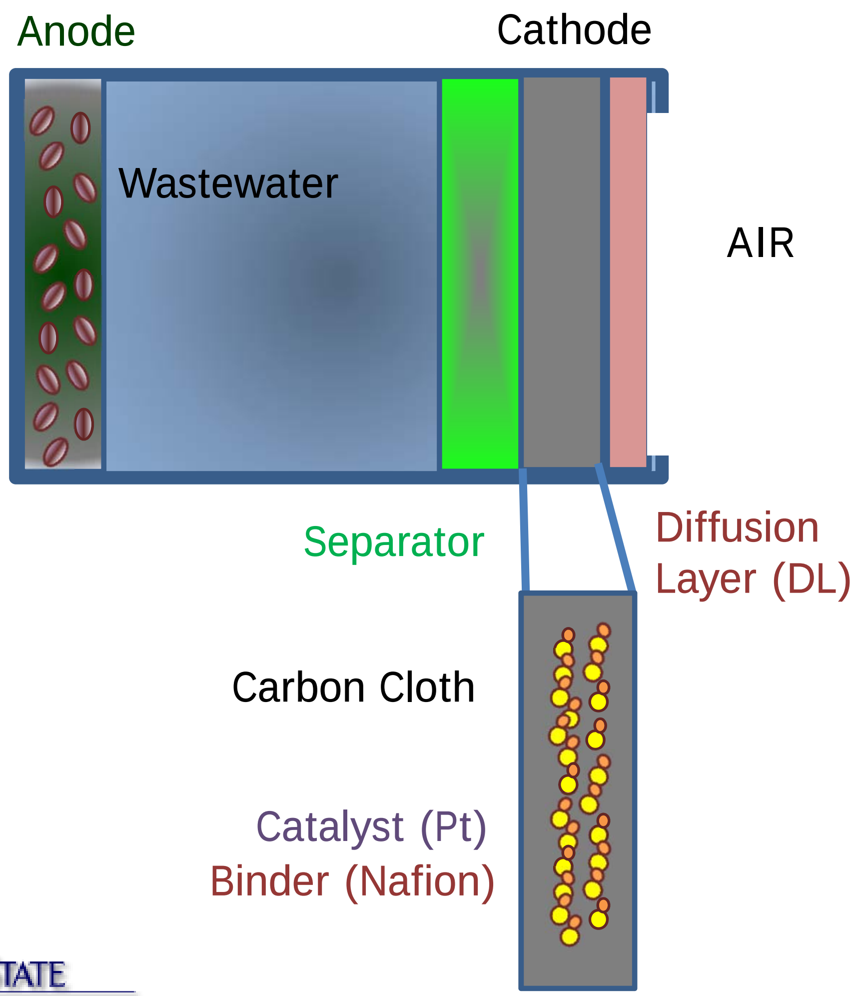
Logan (2012) *Chem. Sus. Chem.*

MFC Architecture



New systems: $/m² (US)

- Anode $20
- Cathode $22
  - SS + CB= $20
  - Catalyst (AC)=$0.40
  - Binder= $1.5
  - DL (PDMS)= $0.15
- Separator $ 1
- **TOTAL** **$43**

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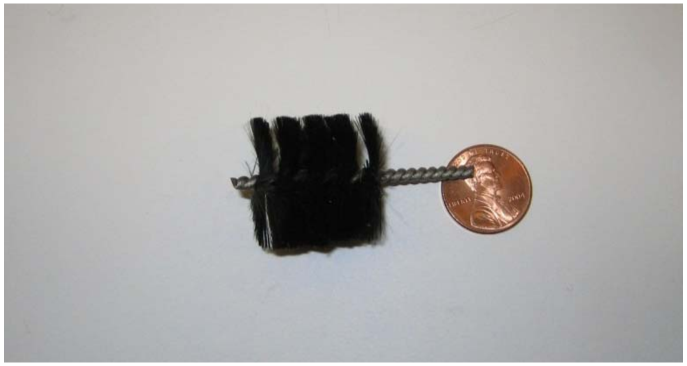
MFC Materials

Anode: Graphite brush electrode

- Graphite fibers commercially available (used in tennis rackets, airplanes, etc.)
- Easy to manufacture
- Fiber diameter- 6-10 μm a good match to bacteria (~1 μm)
- High surface area per volume- Up to 15,000 m^2/m^3



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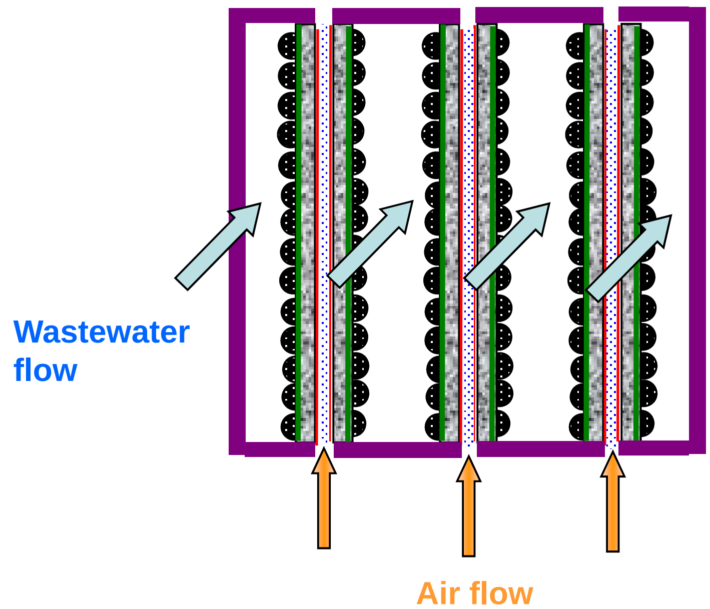
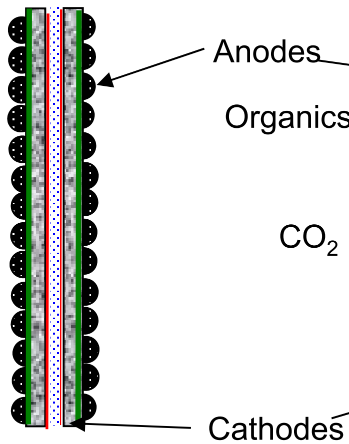
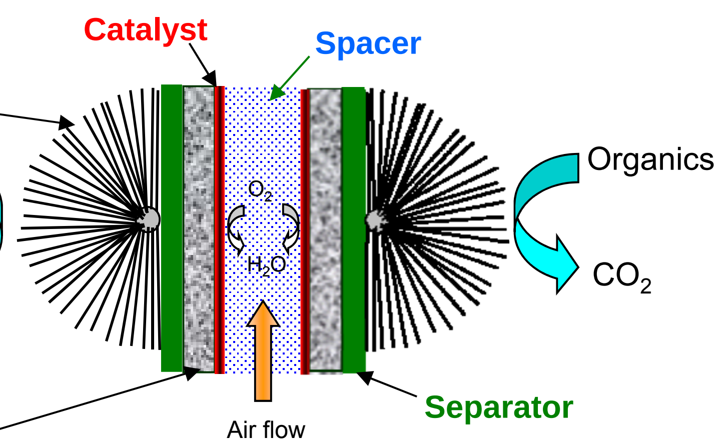
Logan et al. (2007) *Environ. Sci. Technol.*

Brush Module Design



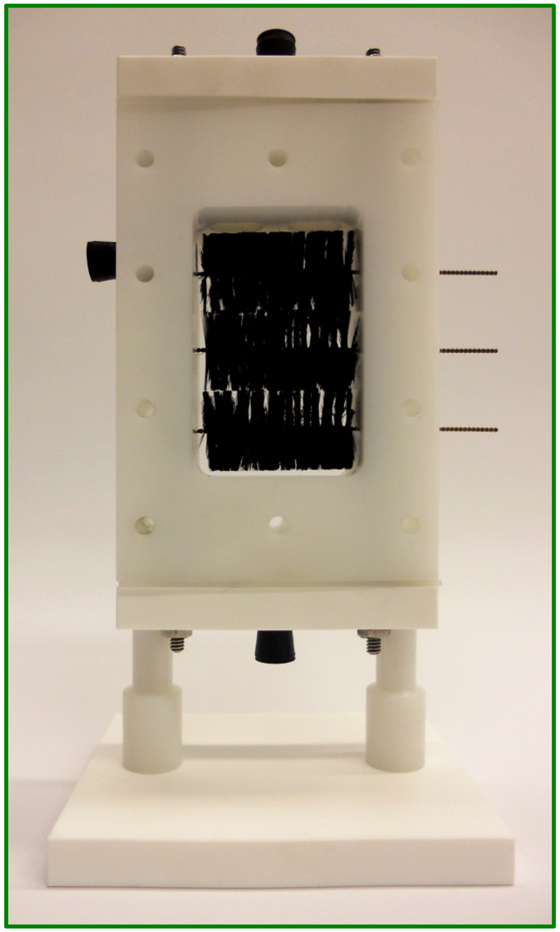




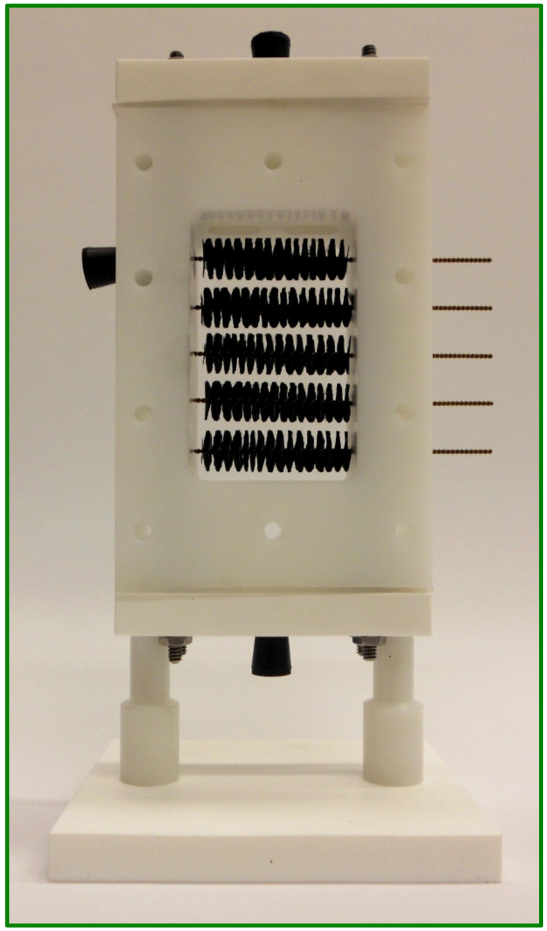
Side View

Close up view

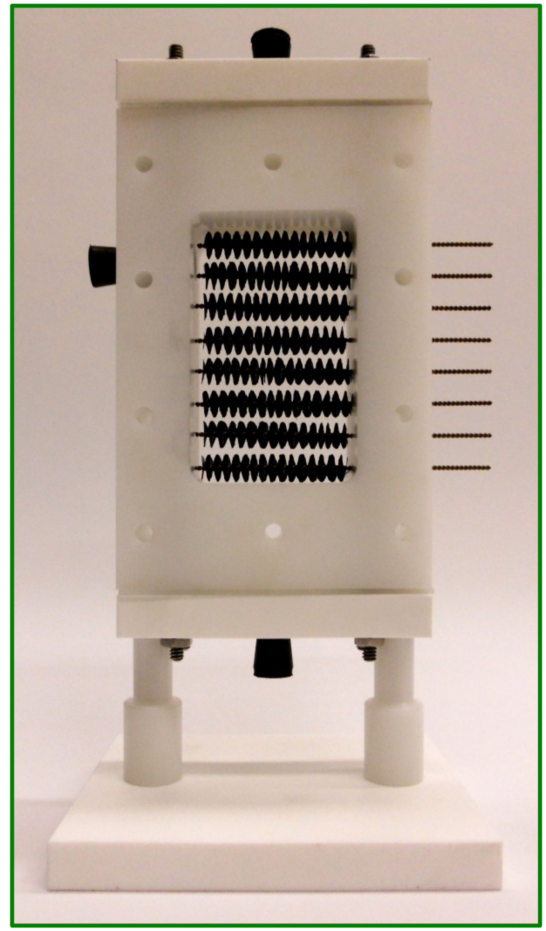
Multi-electrode MFCs



3 brushes (**R3**)
3500 m^2/m^3



5 brushes (**R5**)
2800 m^2/m^3



8 brushes (**R8**)
2900 m^2/m^3

Electrode area (2.5 cm diameter brush/chamber width = 40 m^2/m^3

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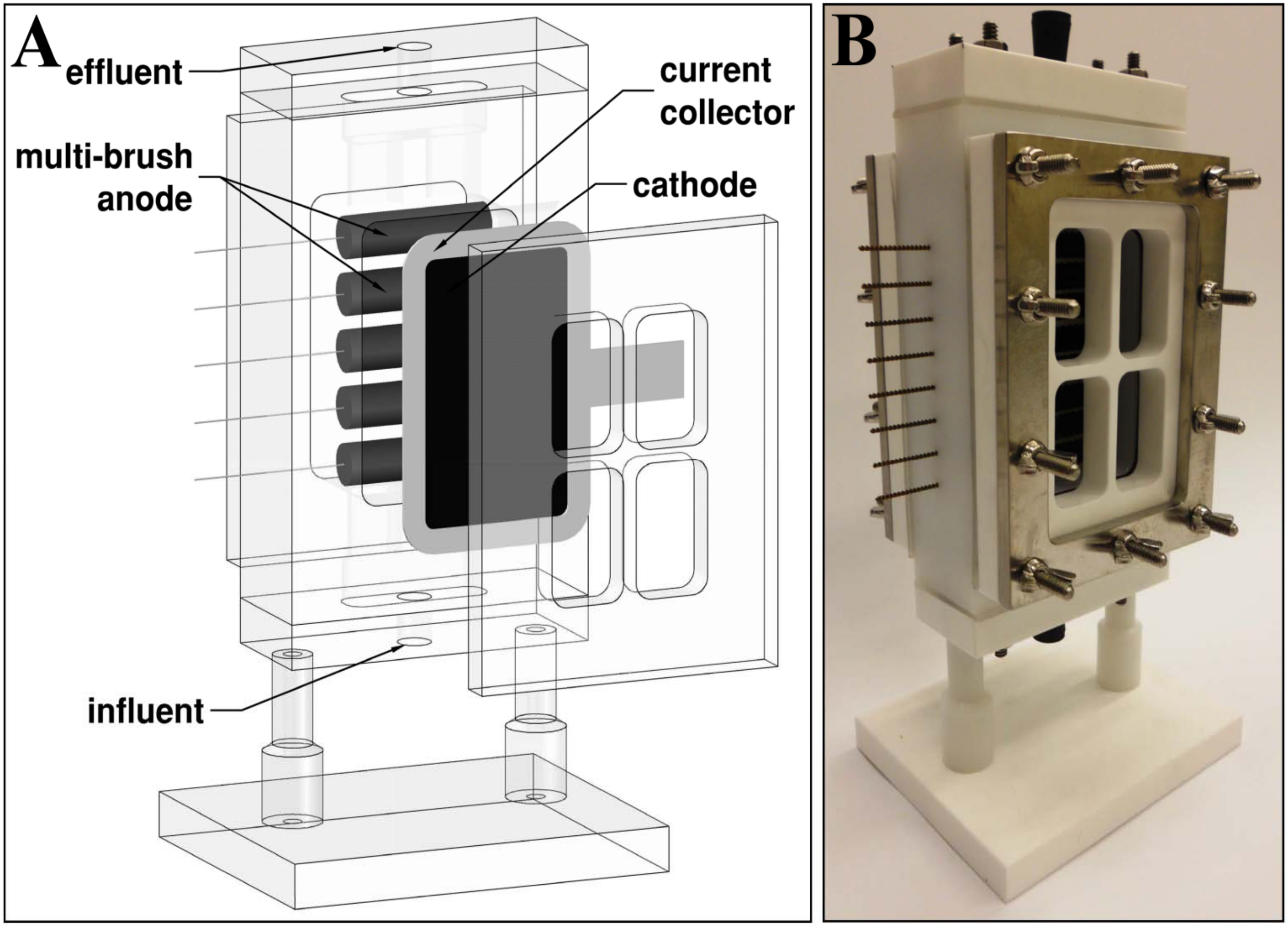
Lanas & Logan (2013) *Journal Power Sources*

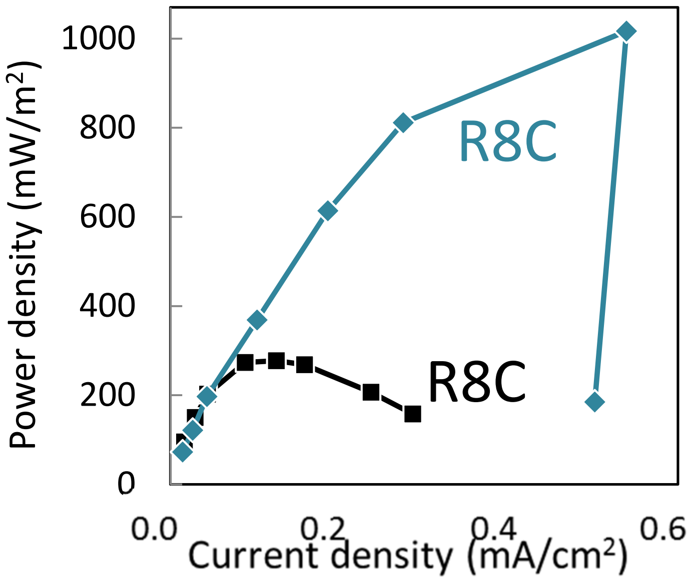
MFCs with 5 (left) or 8 anodes (right)

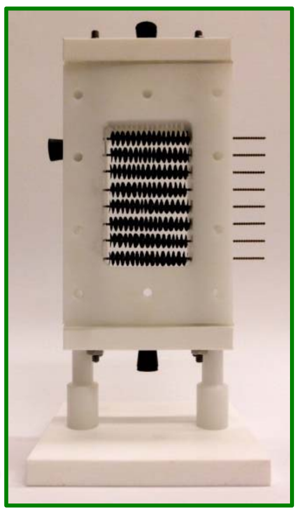


Lanas & Logan (2013) *Journal Power Sources*

Smaller, closer brushes work best

(Continuous flow, acetate in buffer)





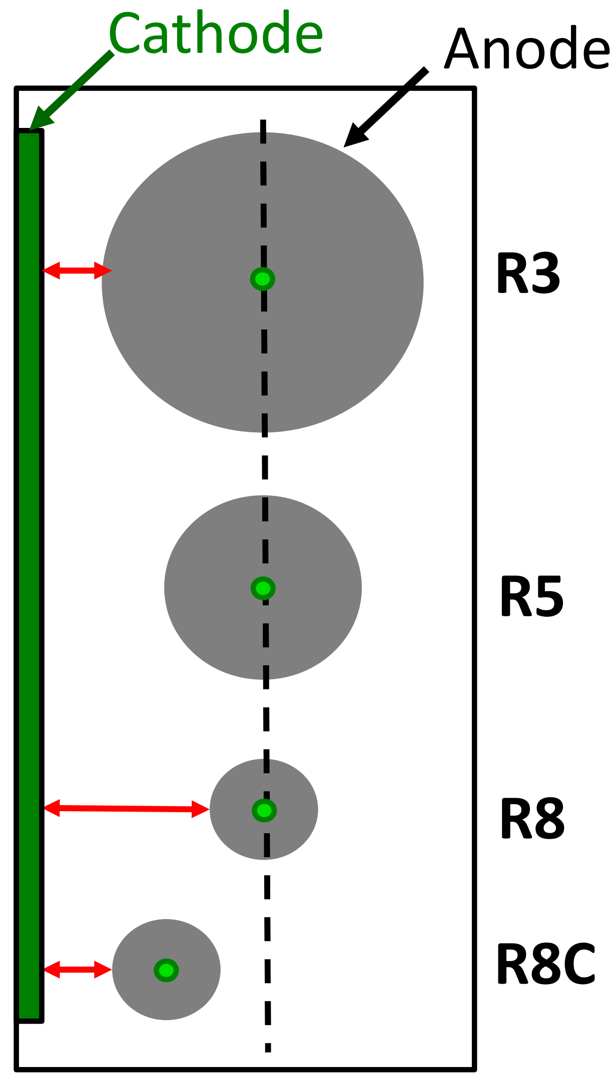
Maximum power densities

R8C= 1020 mW/m²

R8= 280 mW/m²

(R3= 560 mW/m²)

(not shown)



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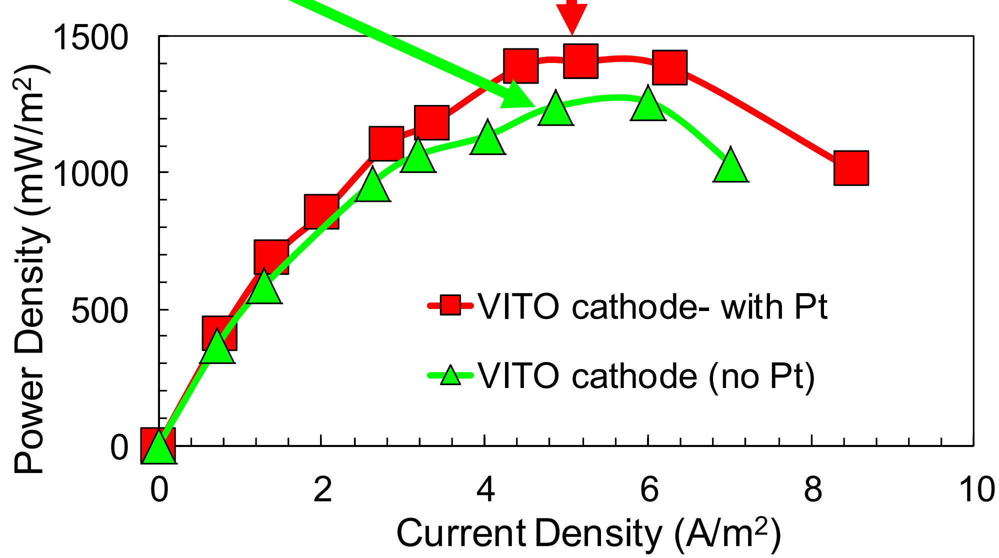
Lanas & Logan (2013) *Journal Power Sources*

Cathode: Activated Carbon Catalysts

VITO cathode (no Pt)

Carbon cloth with Pt

Activated carbon cathode works almost as well as Pt catalyst



Zhang, Cheng, Van Bogaert, Pant & Logan (2009) *Electrochem. Commun.*

Catalytic Activity of ACs

Precursor	Sample
Hardwood	**W1-** MWV1500
Phenol resin	**R1-** Kuraray RP-20
Peat	**P1-** Norit SX1
Peat	**P2-** Norit SX Plus
Peat	**P3-** Norit SX Ultra
Coconut shell	**C1-** Kuraray YP-50
Coconut shell	**C2-** CR8325C
Coconut shell	**C3-** ACP1250
Bituminous Coal	**B1-** CR325B

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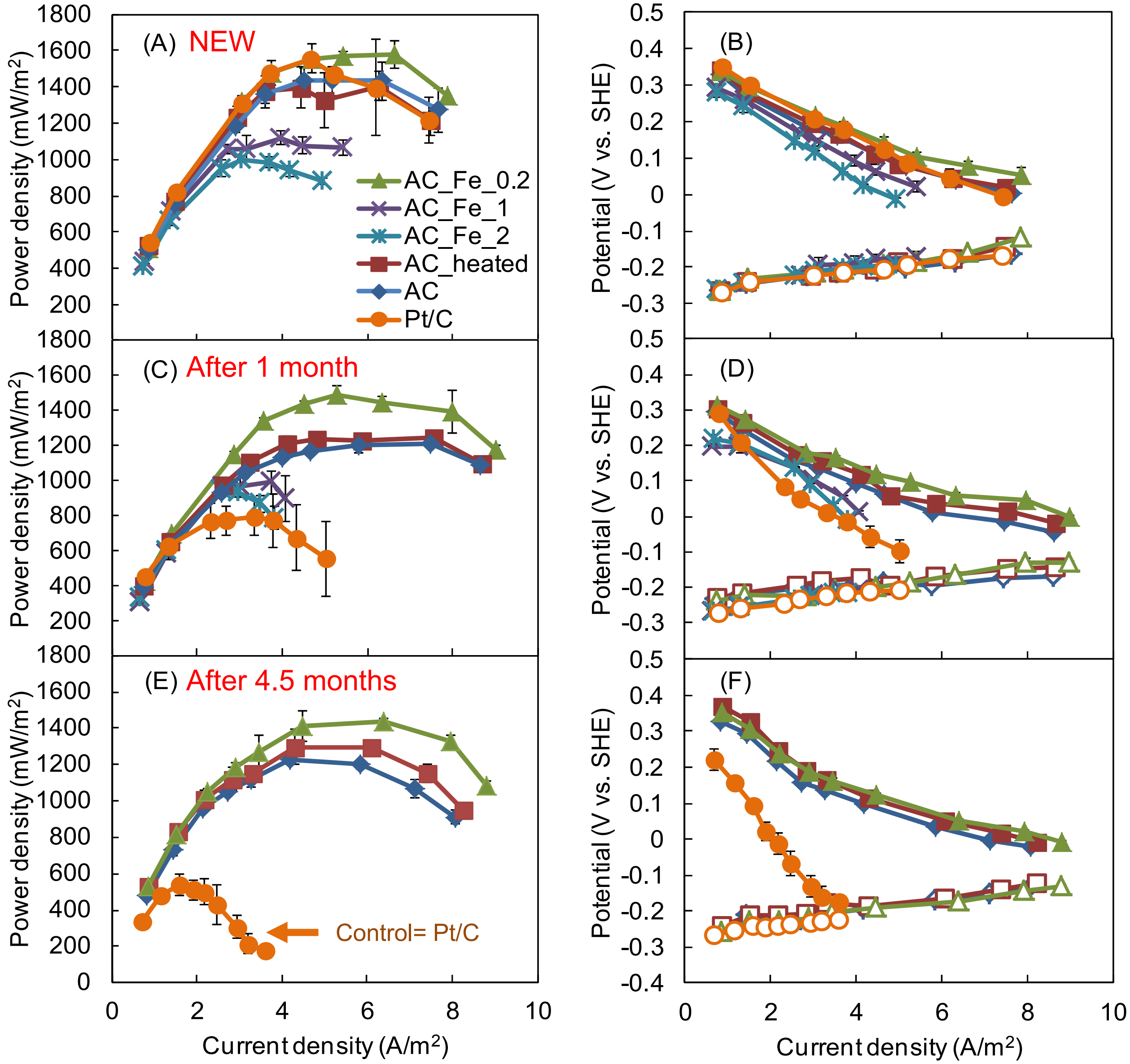
Watson & Logan (2013) ES&T

Activated Carbon Cathodes- improved longevity



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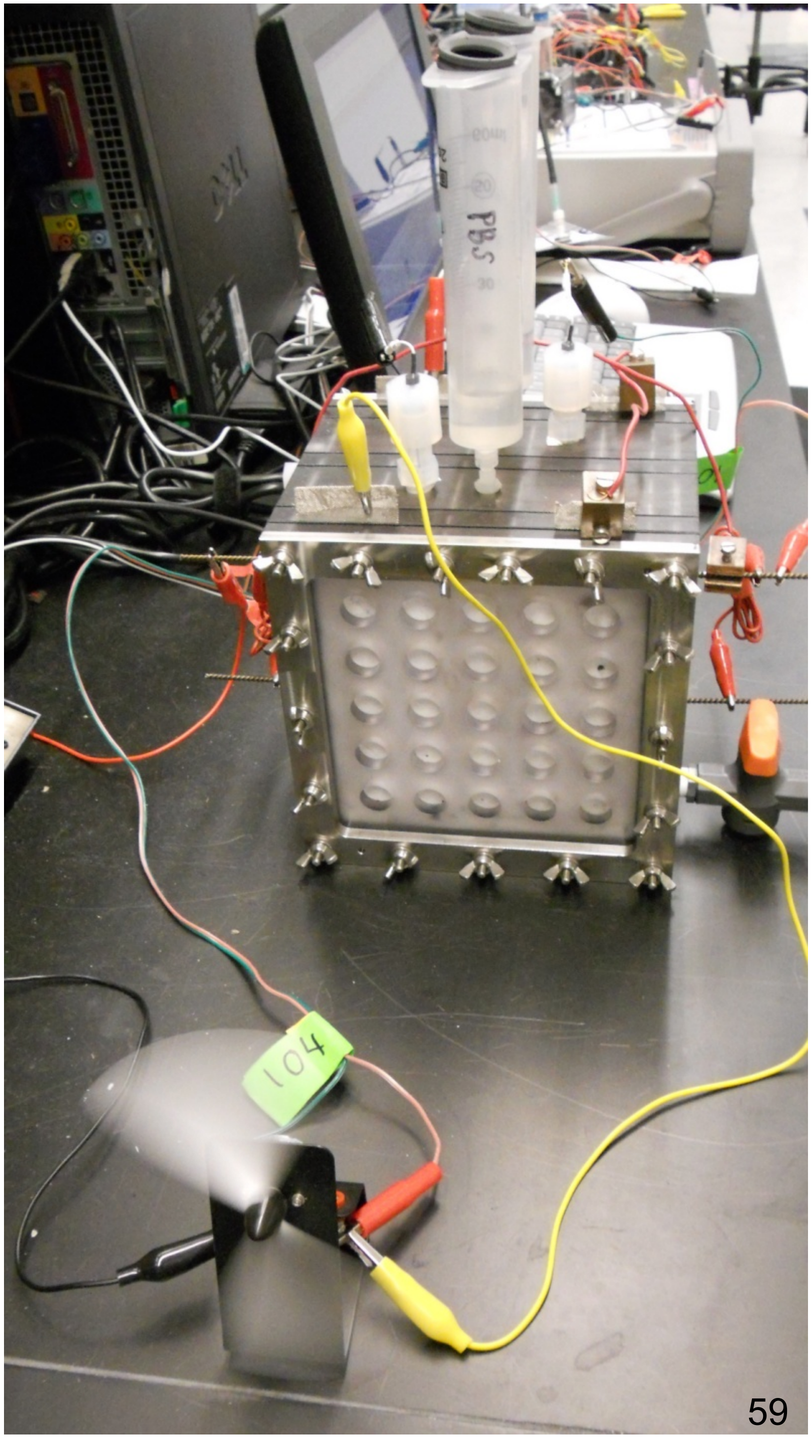
Xia, Zhang, Huang & Logan (2013) *ACS Materials Inter. Science*

Scaling up MFCs

MFCs= fuel cells, make electricity

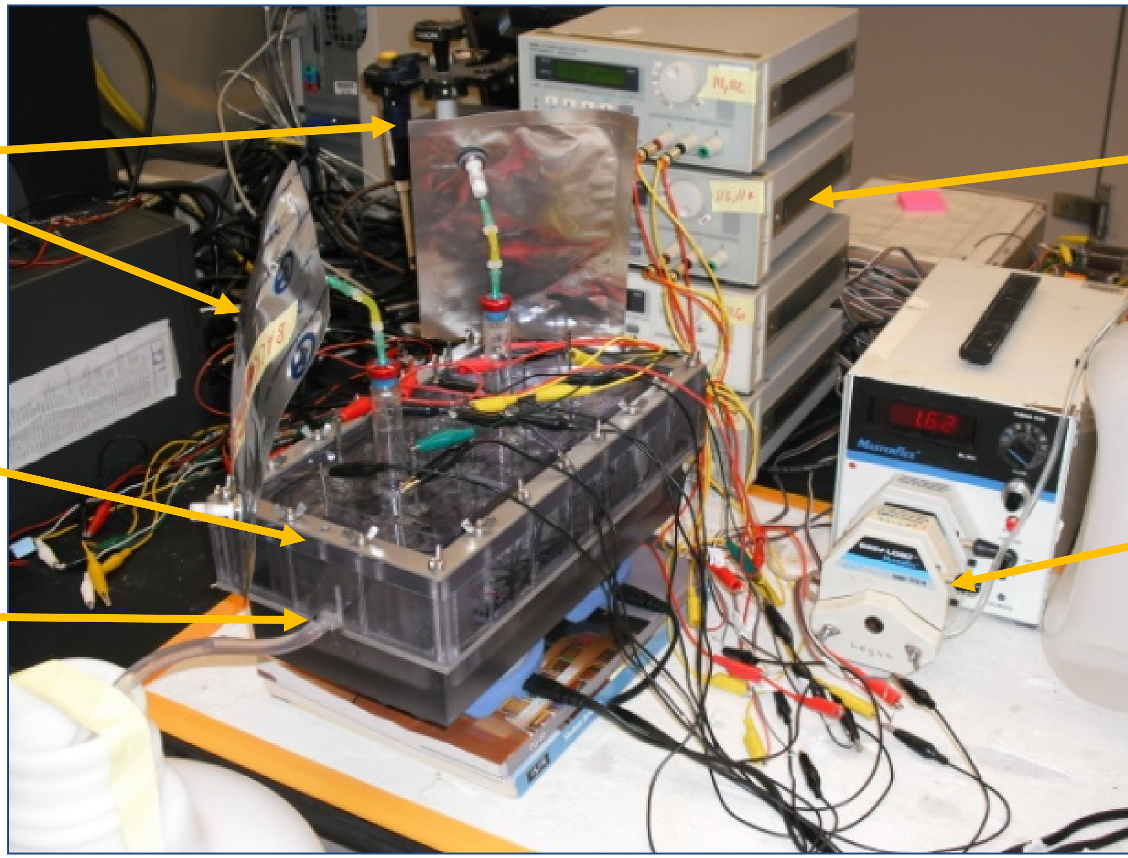
This **2-Liter** MFC has been "viewed by the public for several years:

- See the MFC webcam (live video of an MFC running a fan)
  - www.engr.psu.edu/mfccam
- Display at the London Science museum (2012), with the help of:
  - KAUST (Saudi Arabia)
  - University of Newcastle (UK)
  - VITO (Belgium)



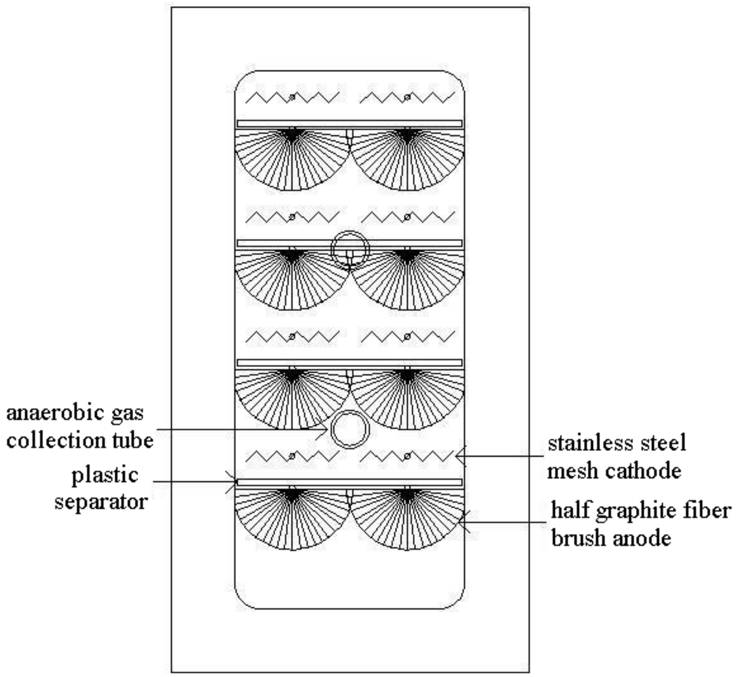
Scaling up MECs

MECs= electrolysis cells, make H_2

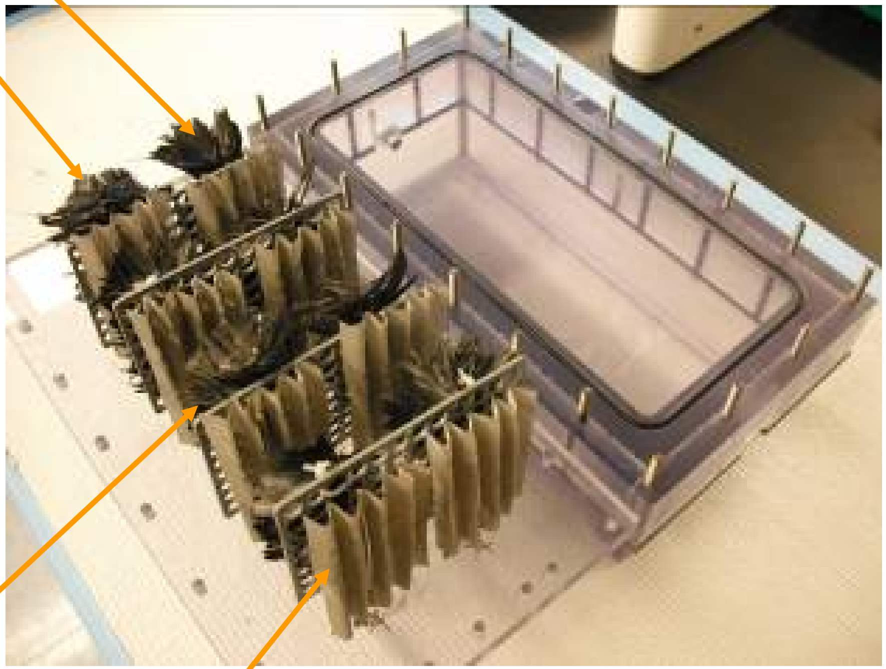


MEC components (2.5 L reactor)

Schematic



Half Graphite Fiber Brush Anodes



Plastic Separator

Stainless Steel Mesh Cathodes

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Rader & Logan (2011) *Int. J. Hydrogen Energy*

MEC Reactor that has 24 modules with a total of 144 electrode pairs (1000 L)

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

Wastewater Evaluation for Pilot-Scale Tests: Choosing the best WW

Four Waste Waters:

1. Domestic (MFC, MEC)
2. Winery (MFC, MEC)
3. Dairy (MFC)
4. Potato Chip (MFC)

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

Summary of Results

Waste Water	COD (g/L)	Power Density (mW/m^2)	MFC CE (%)	Q (m^3/m^3-d)	MEC CE (%)
Domestic	0.32	147	13	0.16	35
Winery	2.5	260	18	0.35	26
Dairy	2.8	189	12	--	--
Potato Chip	7.7	217	21	0.48 0.74	50 78

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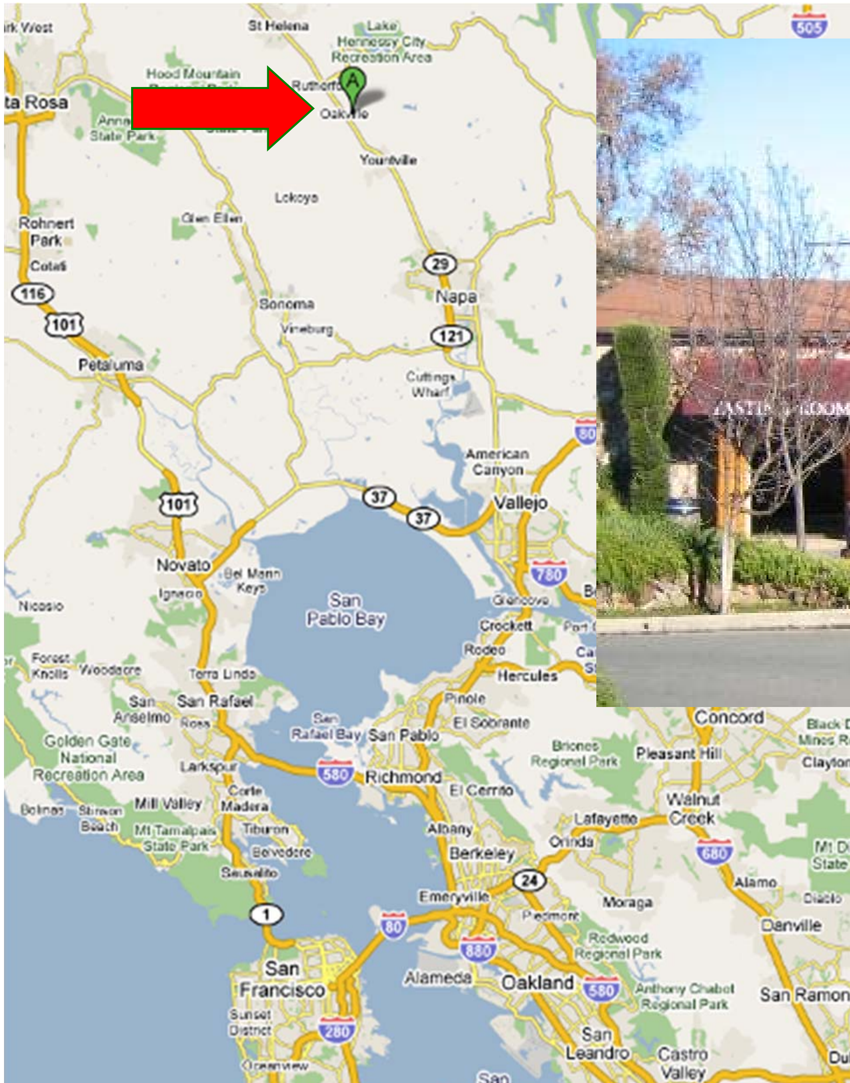
Cusick et al. (2011) *Appl. Microbiol. Biotechnol.*

MEC Field test :

Penn State University @ Napa Wine Company



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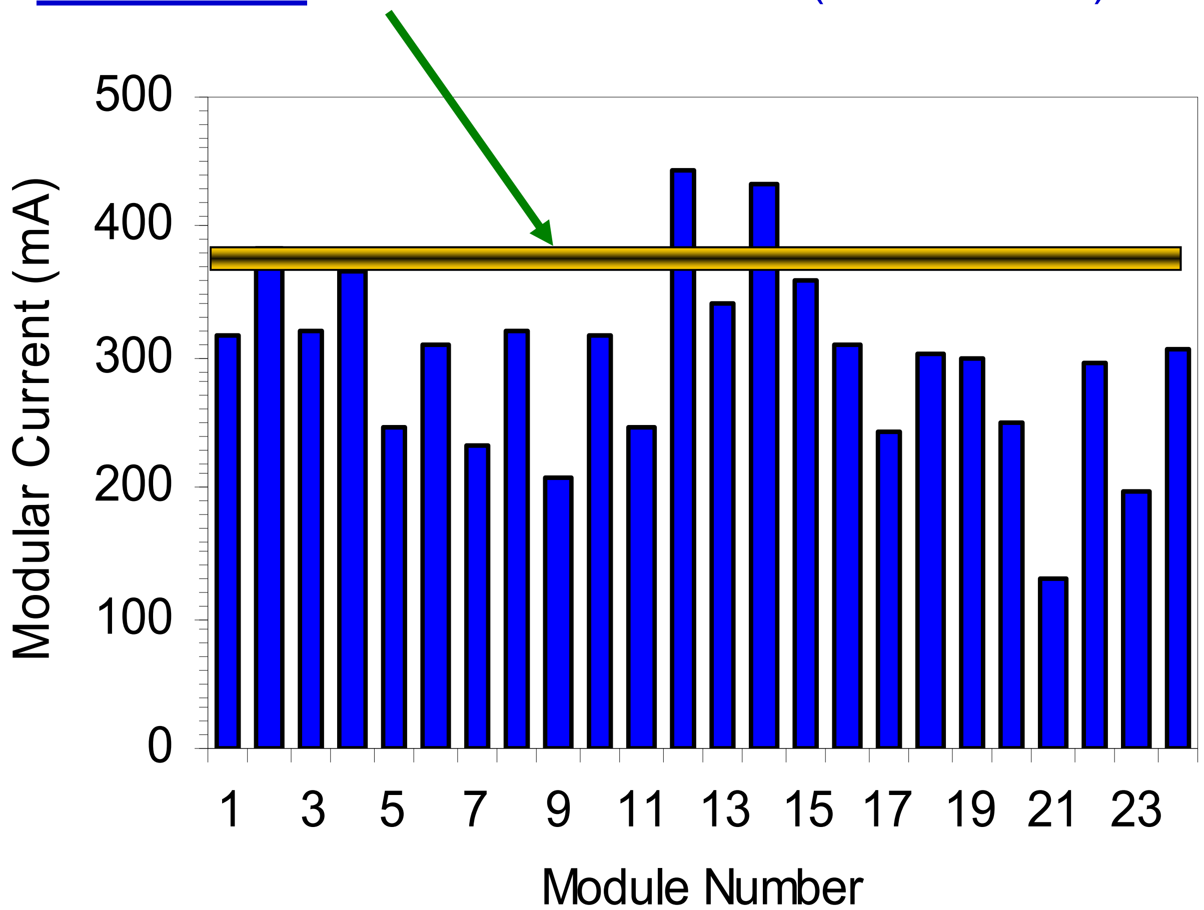
Individual module performance of the MEC treating Wastewater

<u>*Predicted*</u>*:* 380 mA/module (total of 9.2 A)



H_2 intially produced, but it all was converted to CH_4

Elec. Energy input= 6 W/m³
Energy Out = 99 W/m³

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

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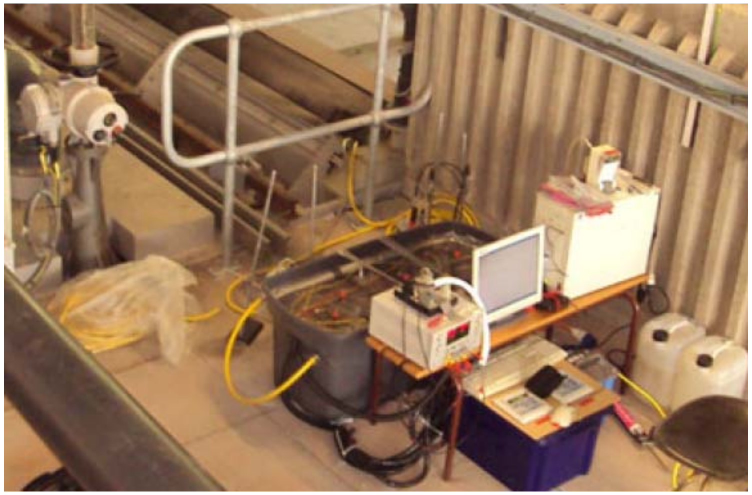
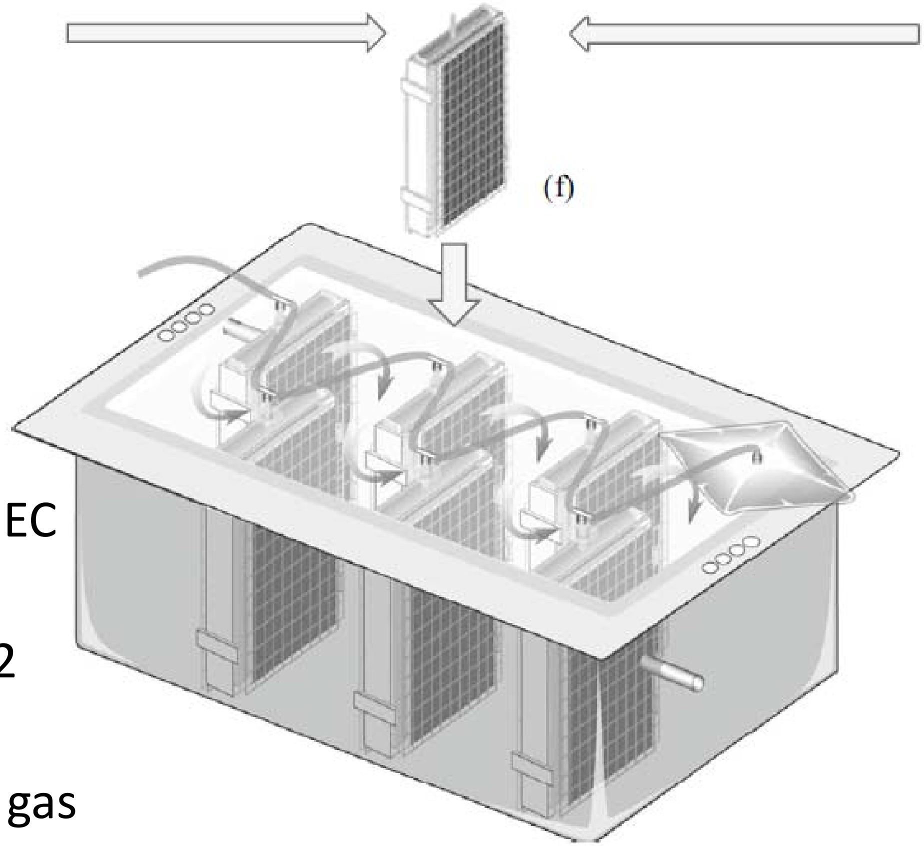
Cusick et al. (2011) *Appl. Microbiol. Biotechnol.*

MEC at a Domestic WWTP (120 L)

(University of Newcastle, UK)





- Produced pure H_2 using 2-chamber MEC cassettes
- 2.3 kJ/gCOD used compared to 2.5-7.2 kJ/gCOD for activated sludge
- Recovered ~70% of energy used in H_2 gas
- Incomplete COD removal

Heidrich et al. (2012) *Appl. Microbiol. Biotechnol.*

Other Microbial Electrochemical Technologies

- MDCs: Microbial desalination cells
  [for water desalination without electrical grid energy]

- MSCs: Phosphorus (struvite) recovery from wastewaters

- MES: Electrofuels and organic substrates
  [Microbial ElectroSynthesis]

- Energy production from salinity gradient and waste heat energy using MRECs and MRFCs

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New Energy Sources Available using Microbial Electrochemical Technologies (METs)

- **Wastewater** : Organic matter in water (USA)
  - **17 GW** in wastewater

    (Save 45 GW energy/yr used + produce 17 GW = 62 GW net change)
- **Cellulose Biomass Energy**: Get biomass→ water
  - **600 GW** available (based on 1.34 billion tons/yr of lignocellulose)

    (this is how much electrical power is produced in USA)
- **Salinity Gradient Energy-** Salt & Fresh-waters (global values)
  - **980 GW** (from the 1900 GW available from river/ocean water)

    (20 GW available where WW flows into the ocean)
- **Waste Heat Energy**→ Capture heat in "water" (USA)
  - **500 GW** from industrial "waste heat"
  - **1000 GW** from power plant waste heat

    (Does not include solar and geothermal energy sources)

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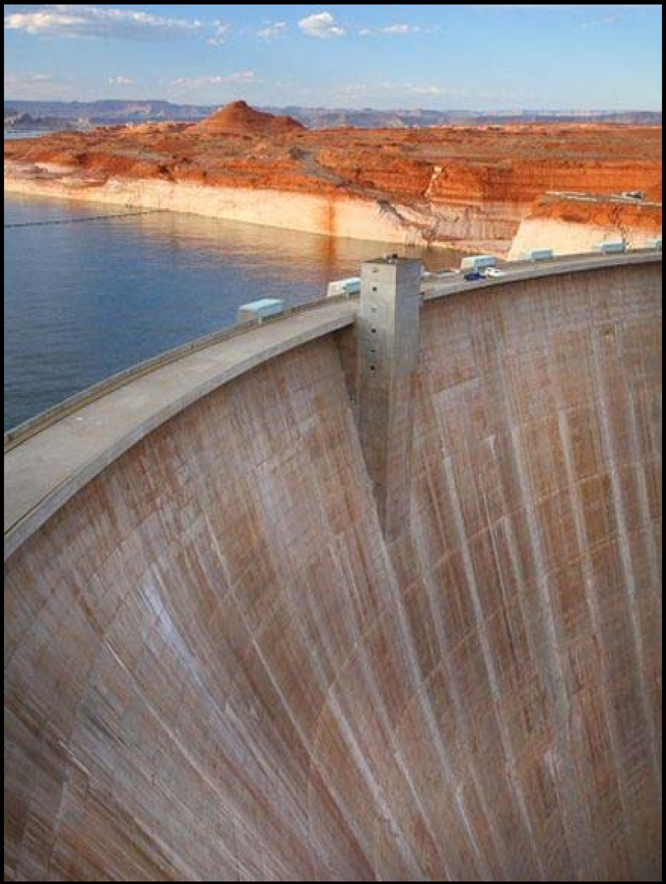
Logan and Rabaey (2012) *Science*
Logan and Elimelech (2012, *Nature*

Salinity Gradient Energy

+

=



270 m of
Hydraulic Head

Oceanside WWTPs and Rivers could produce 980 GW

3 Methods to capture Salinity Gradient Energy

1) Pressure retarded osmosis (**PRO**)
2) Reverse electrodialysis **(RED)**
3) Capacitive layer expansion ("**Capmix**")

   (Variation uses battery like reactions, "Battmix")

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Combining MFCs with salinity gradient energy technologies??

- MFC + PRO = MOFC (Microbial osmotic fuel cell)
  - (Envisioned more for water desalination than power generation)
- MFC + RED = MRFC (Microbial reverse electrodialysis fuel cell)
  - Single circuit enhanced power
- MFC + CapMix = CMFC (CapMix MFC)
  - Two circuit system for energy capture

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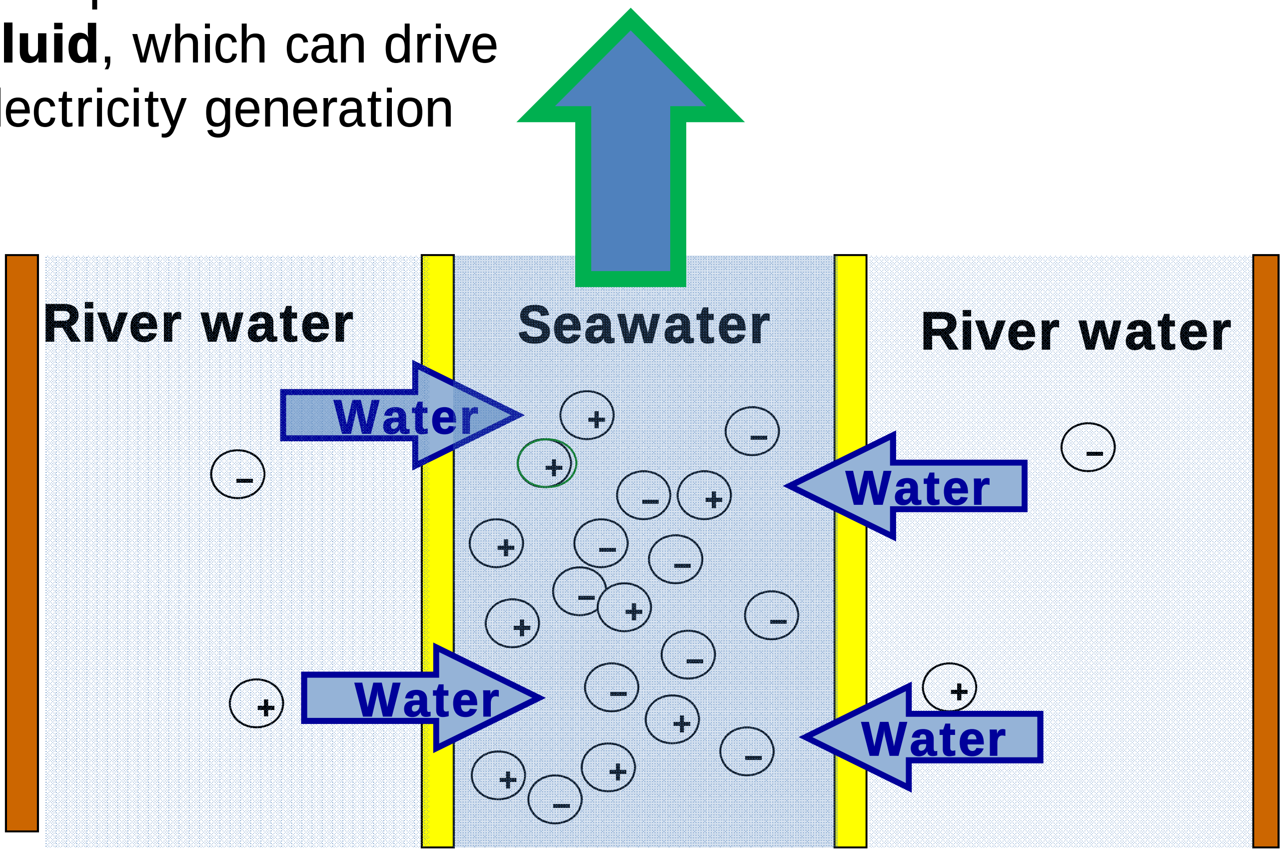
#1- Pressure Retarded Osmosis (PRO)

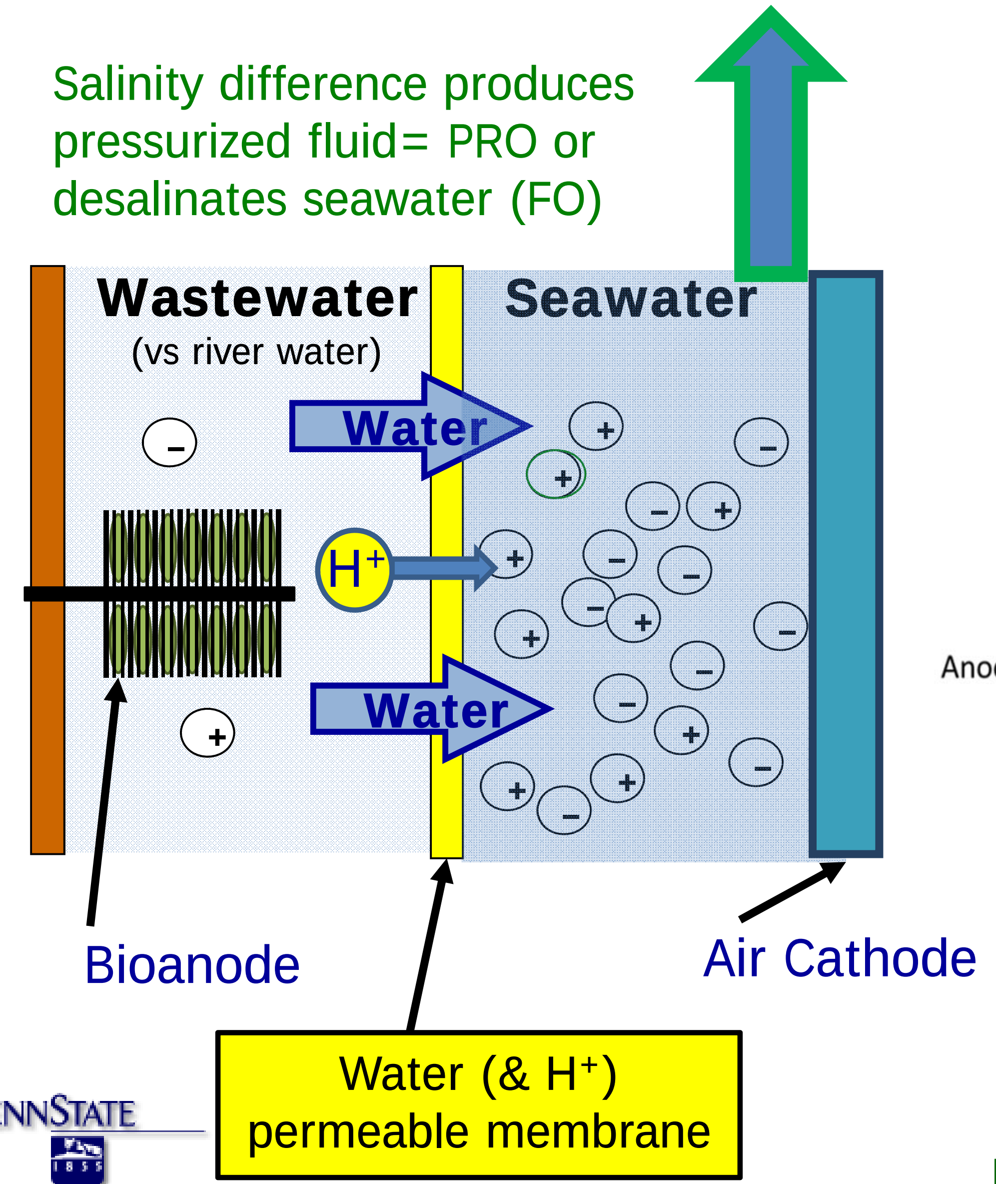
Salinity difference produces **pressurized fluid**, which can drive a turbine for electricity generation

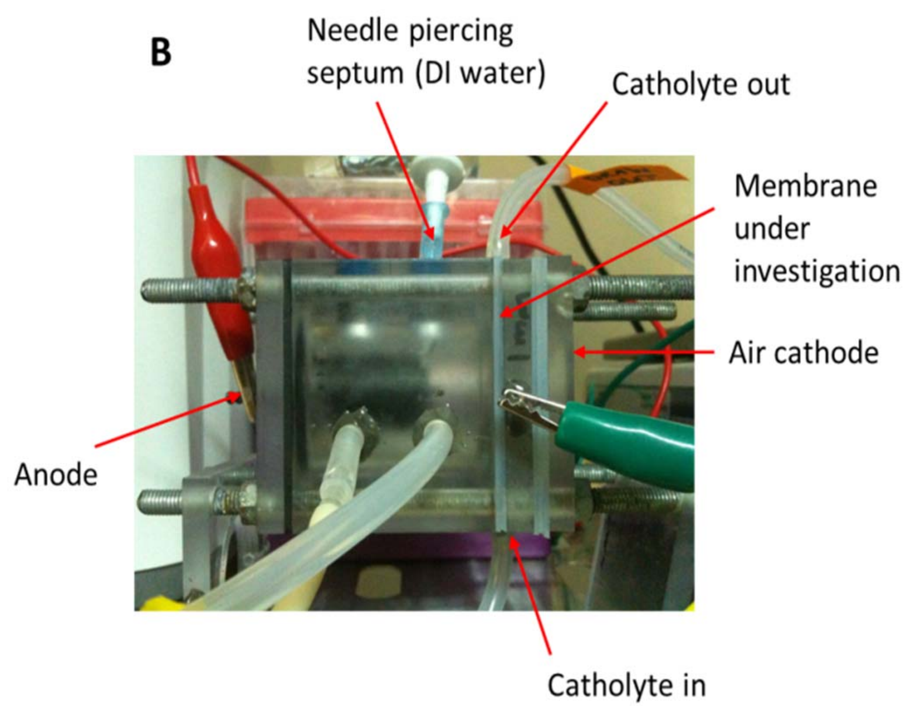


Water permeable membranes- "Forward Osmosis" (FO)membrane

MFC + PRO = MOFC (Microbial Osmotic Fuel Cell)

Salinity difference produces pressurized fluid= PRO or desalinates seawater (FO)



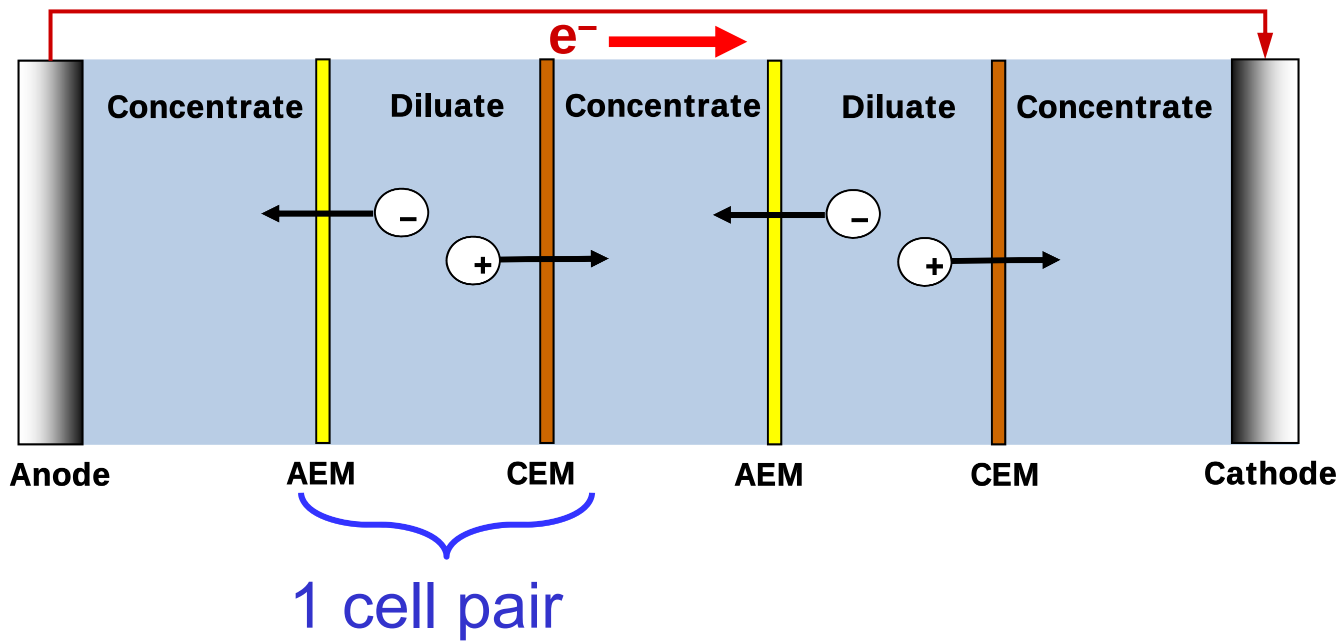


Werner, Logan, Saikaly, Amy (2013) *J. Membrane Res.*

#2- Reverse Electrodialysis (RED)

What is Electrodialysis (ED)?

Method to use electricity to desalinate water

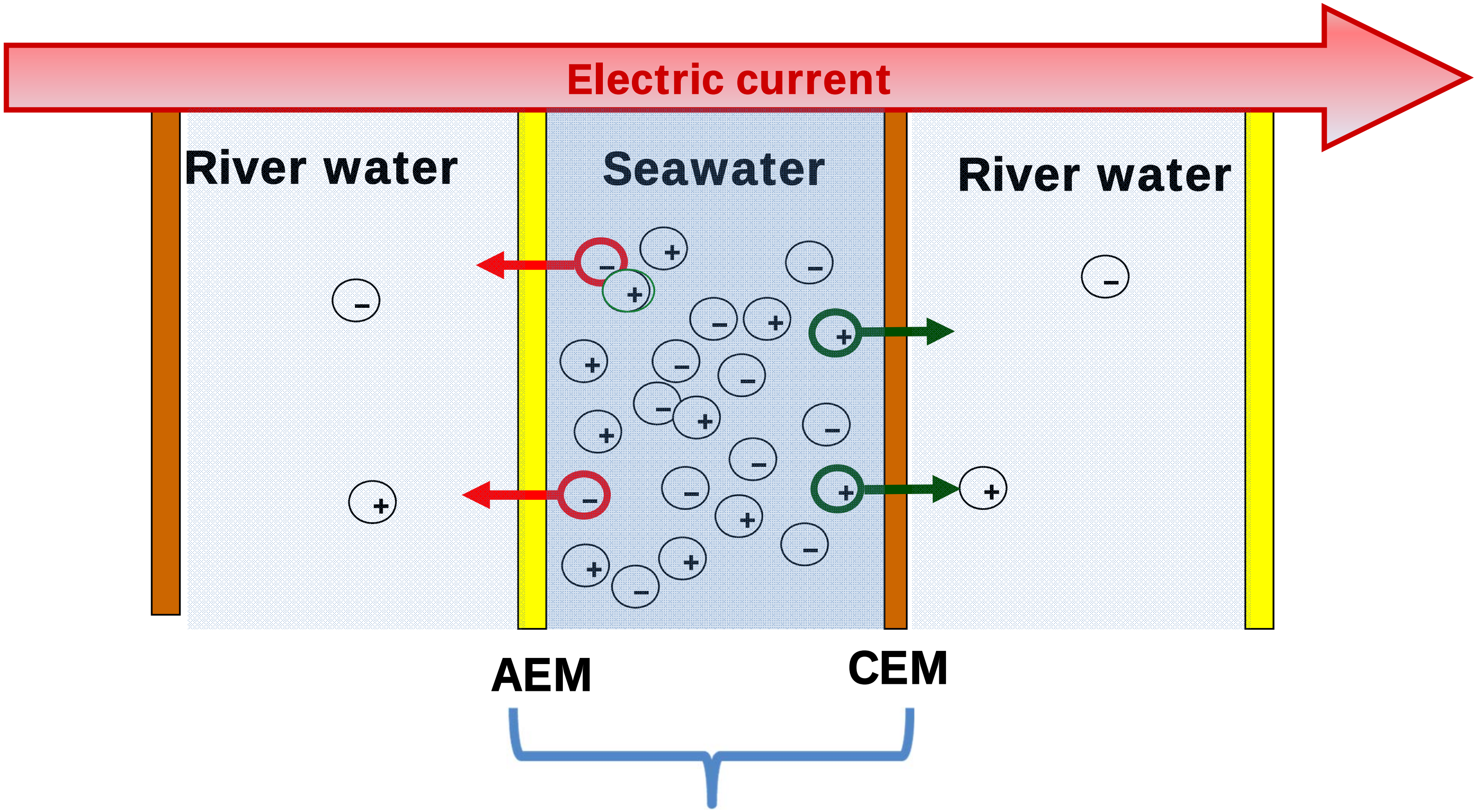


1-cell pair system: 1 e⁻ → 1 cation and 1 anions

2-cell pair system: 1 e⁻ → 2 cations and 2 anions

Reverse electrodialysis (RED)

Salinity difference **produces** electrical current



Each pair of seawater + river water cells→ **~0.1 – 0.2 V**

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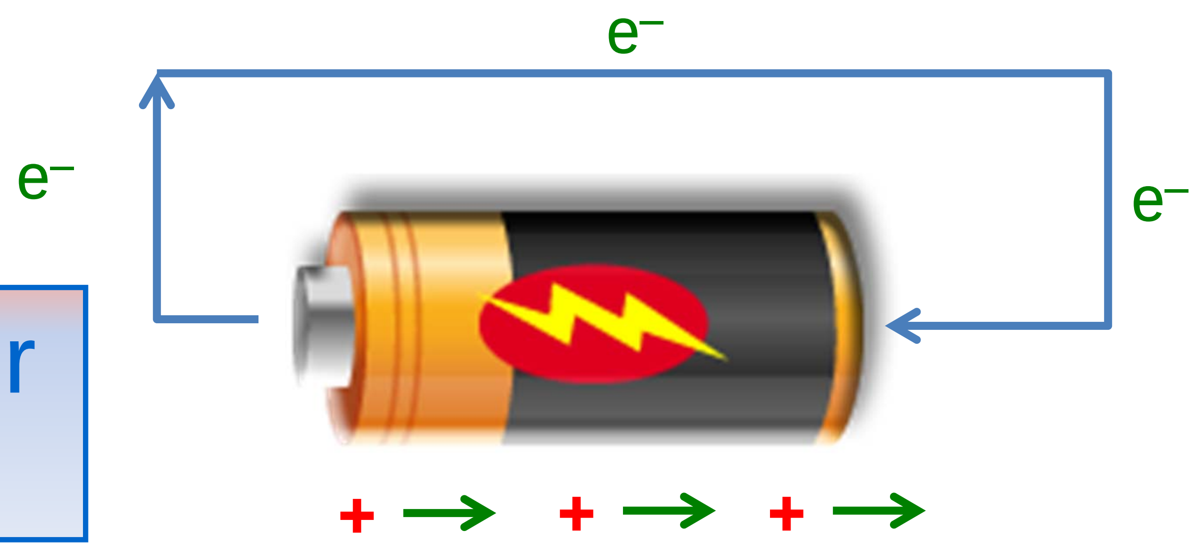
Batteries = motion of ions & electrons



1.5 V per battery

6 V (4 batteries)

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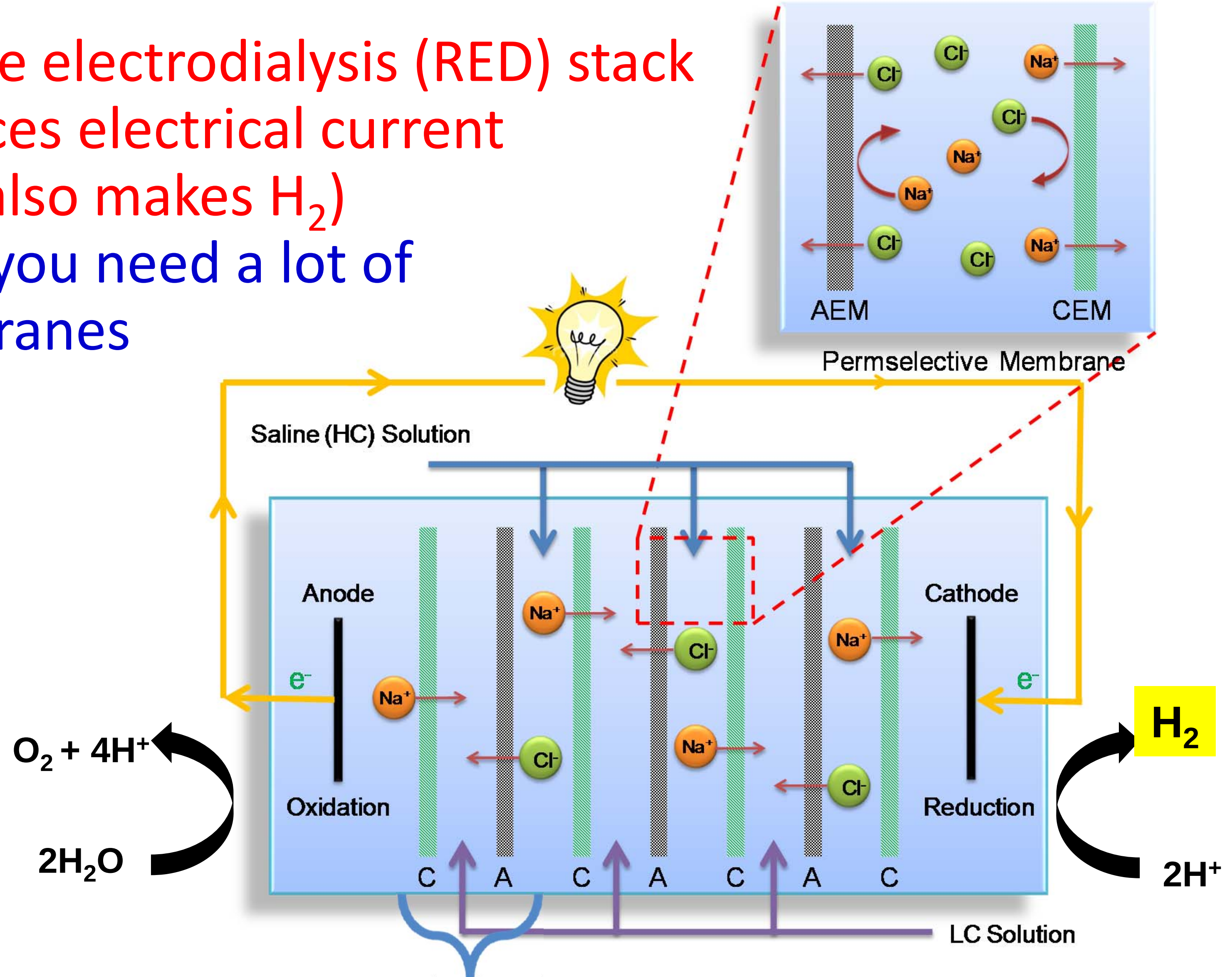
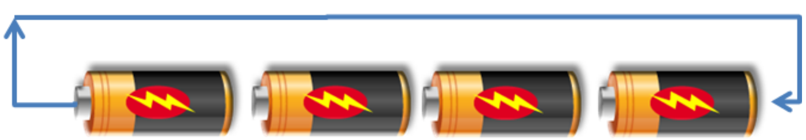
Reverse electrodialysis (RED) stack produces electrical current (here also makes H_2)

… but you need a lot of membranes



Each pair of high salt (HC) + low salt (LC) cells = **~0.1 – 0.2 V**



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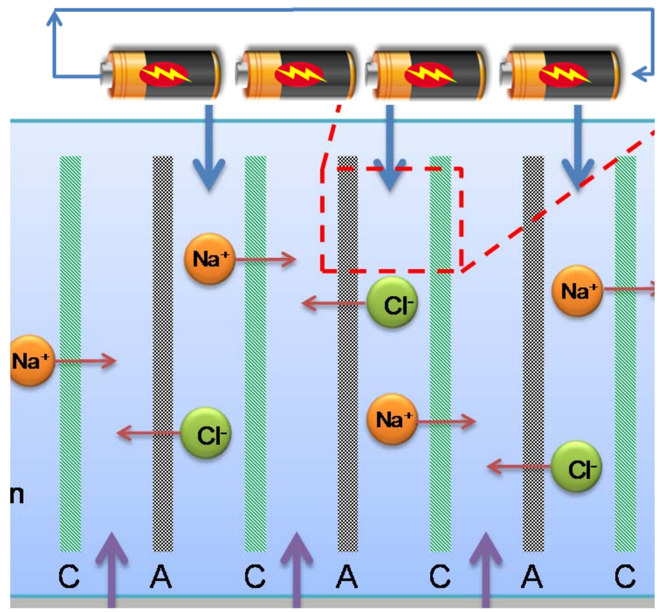
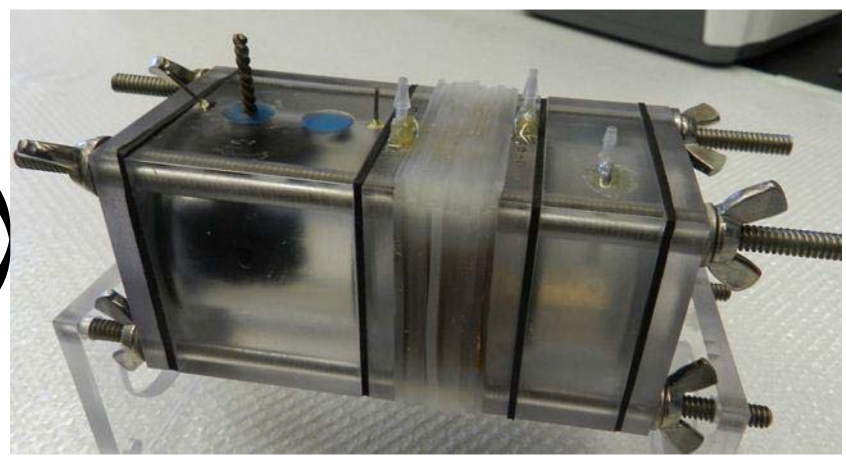
Logan and Elimelech (2012) Nature

What if we move the RED stack into an MFC?



Organic matter

CO_2 & H^+



$O_2 + 4H^+$

$2H_2O$

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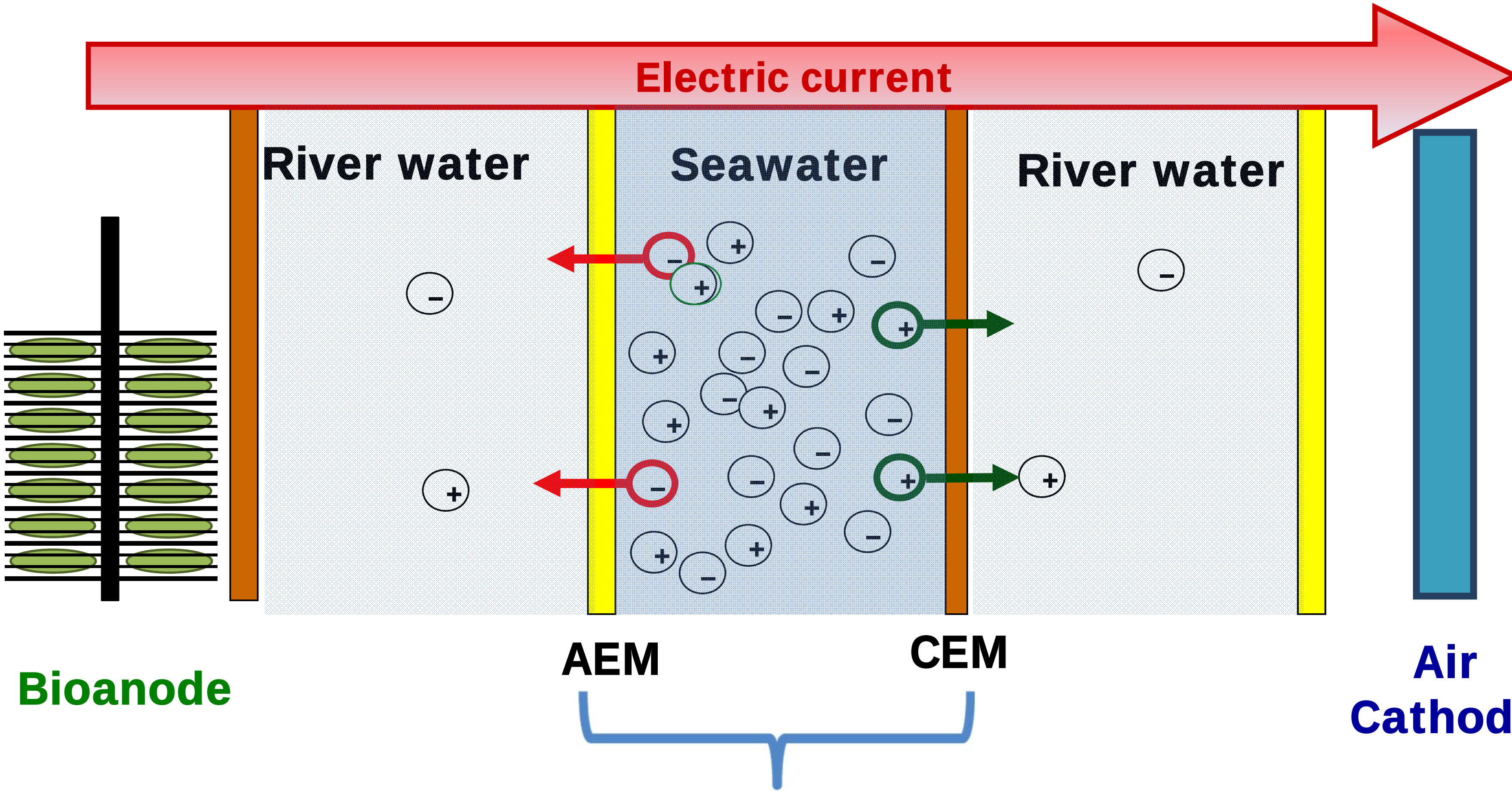
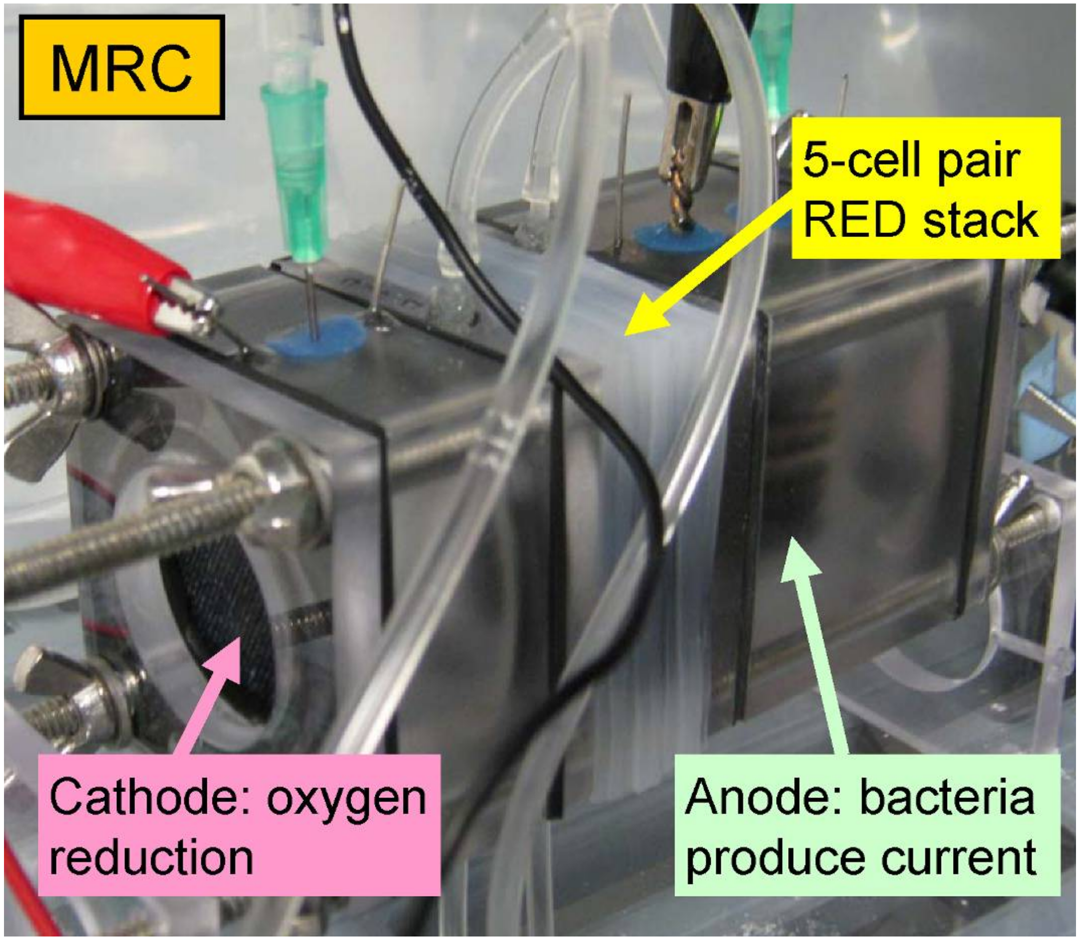
Reverse electrodialysis (RED)

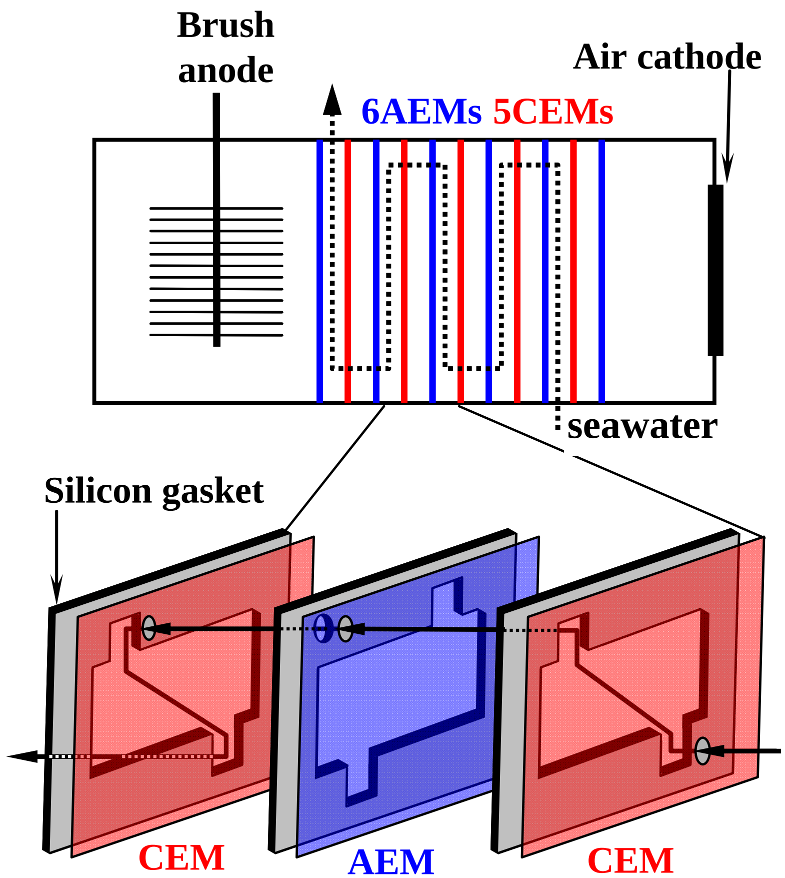
Salinity difference **produces** electrical current



Each pair of seawater + river water cells→ **~0.1 – 0.2 V**

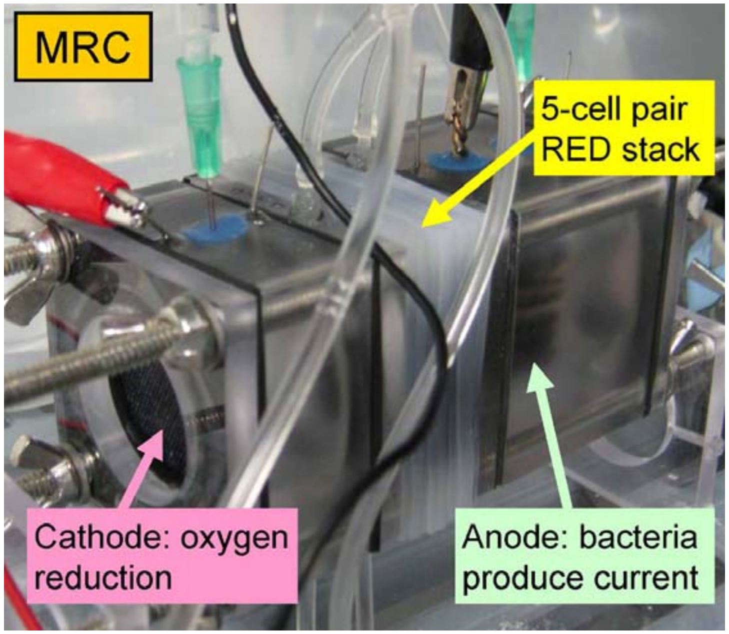
MFC + RED = MRFC (Microbial RED Fuel Cell)





Kim & Logan (2011) *ES&T* (MRCs)

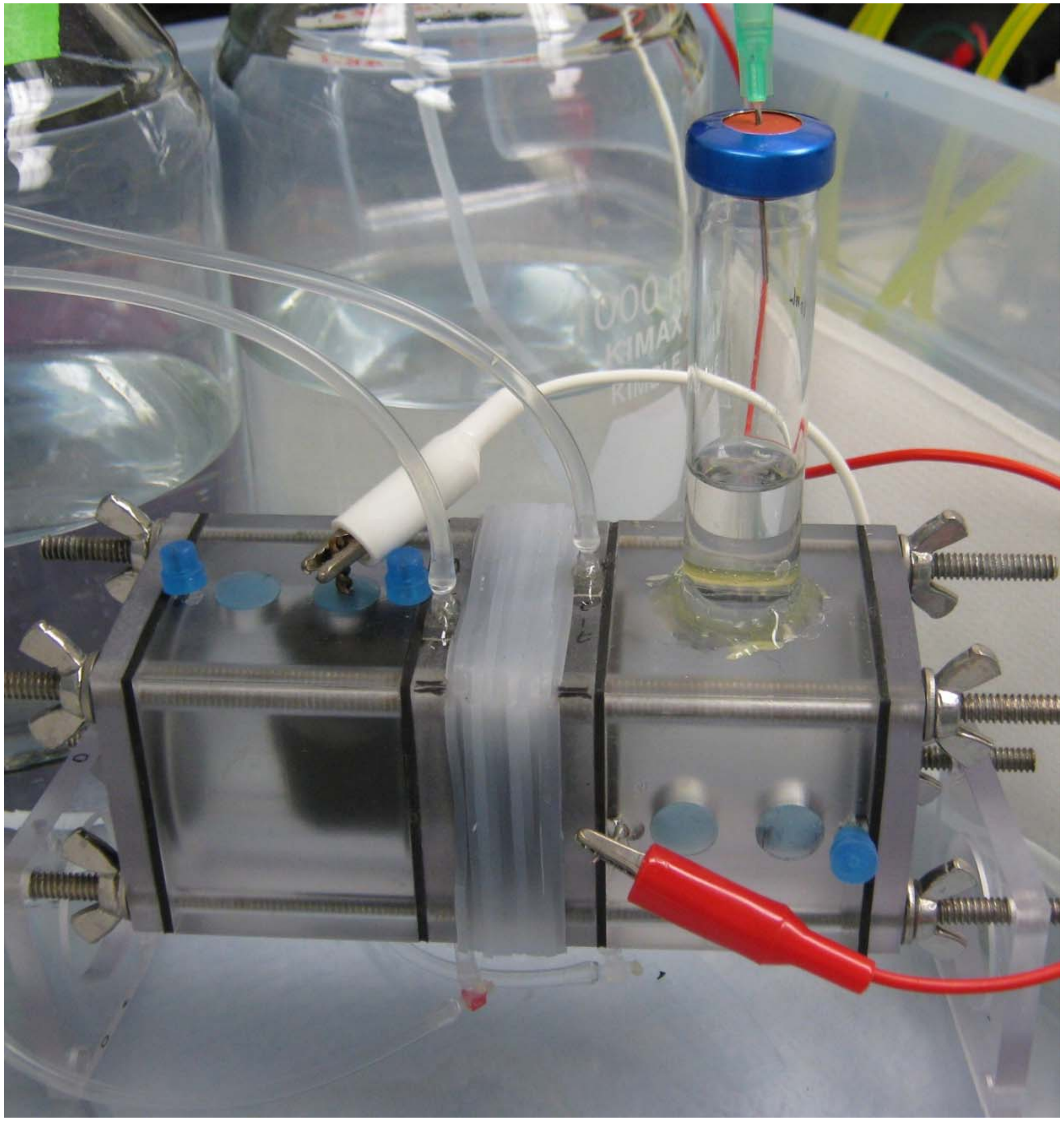
MRFC performance

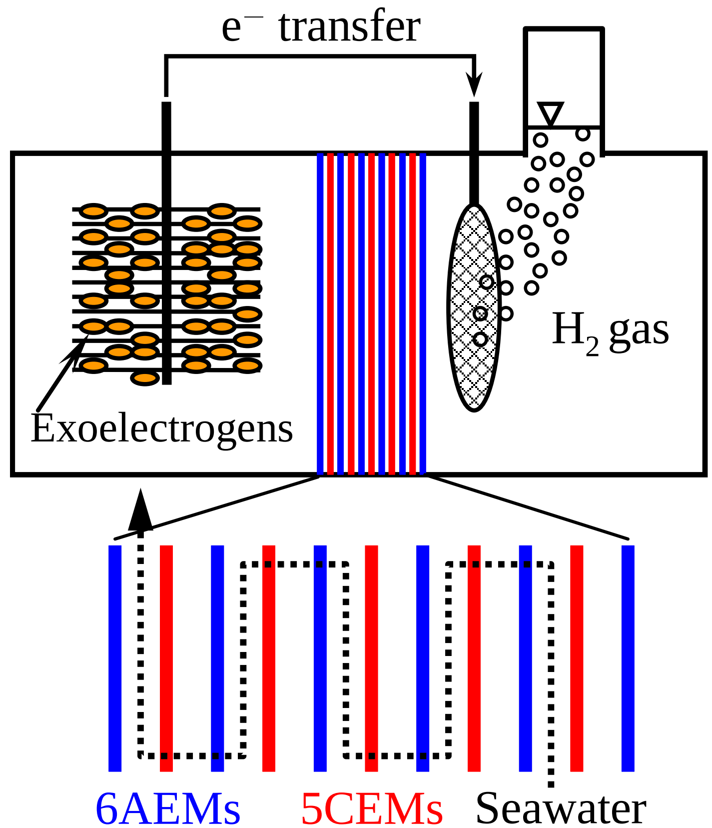


- Higher voltages
  - 1.3 V (vs. MFC alone = 0.5 V)
- Higher power
  - 4.3 W/m^2 (vs. MFC = 0.7 W/m^2 + RED <0.15 W/m^2)
- Higher energy efficiency
  - 42% (obtained vs entering and *leaving)*:

Kim & Logan (2011) *ES&T* (MRCs)

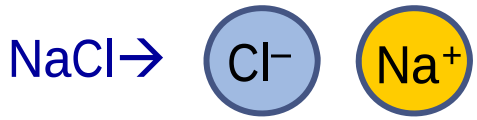
MEC + RED = MREC (Microbial RED Elec. Cell)





Kim & Logan (2011) *Proc. Nat. Academy Sci.*

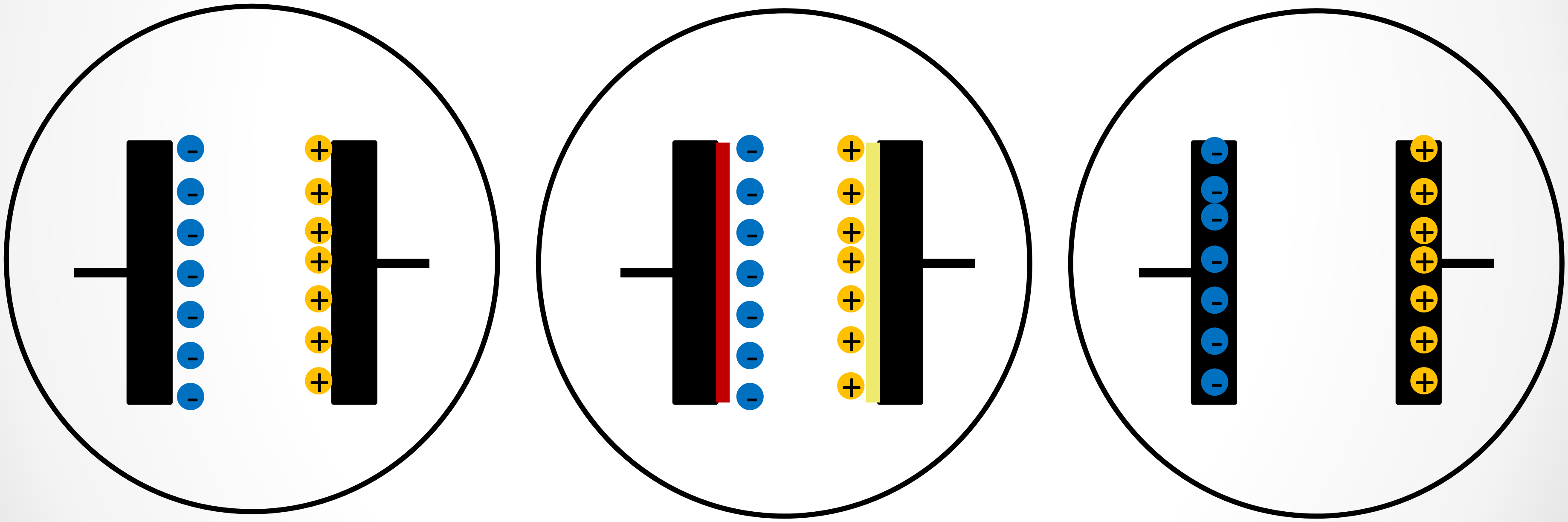
#3- Capacitive/Battery Mixing Techniques



Capacitive energy extraction through Double Layer Expansion

Capacitive energy extraction based through Donnan Potential (*membranes*)

Battery-like energy extraction with oxidation/reduction (intercalation based) electrodes



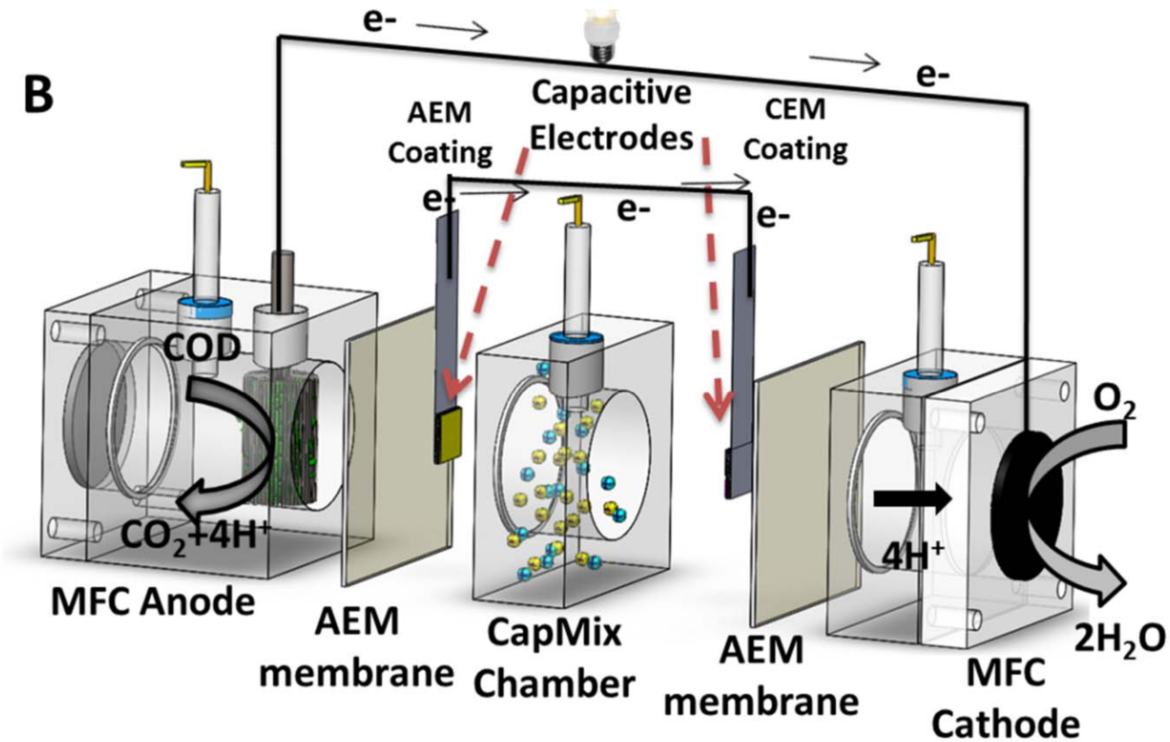
Capmix CDLE:
Capacitive- Double Layer Expansion

Capmix CDP:
Capacitive- Donnan Potential

Battmix:
Battery reactions or an entropy battery

MFC + CapMix = CMFC

- Two separate circuits are used to capture energy from the MFC circuit, and separately from the CapMix circuit
- The central chamber is cycled with seawater and freshwater.
- Insertion of electrodes in MFC (CMFC) increased energy capture 65×, power production 46× compared to CapMix alone (up to ~1 W/m^2 based on CapMix electrodes)



Hatzell et al. (2013) *Submitted*

New Energy Sources Available using Microbial Electrochemical Technologies (METs)

- **Wastewater** : Organic matter in water (USA)
  - **17 GW** in wastewater

    (Save 45 GW energy/yr used + produce 17 GW = 62 GW net change)
- **Cellulose Biomass Energy**: Get biomass→ water
  - **600 GW** available (based on 1.34 billion tons/yr of lignocellulose)

    (this is how much electrical power is produced in USA)

- **Salinity Gradient Energy-** Salt & Fresh-waters (global values)
  - **980 GW** (from the 1900 GW available from river/ocean water)

    (20 GW available where WW flows into the ocean)
- **Waste Heat Energy**→ Capture heat in "water" (USA)
  - **500 GW** from industrial "waste heat"
  - **1000 GW** from power plant waste heat

    (Does not include solar and geothermal energy sources)

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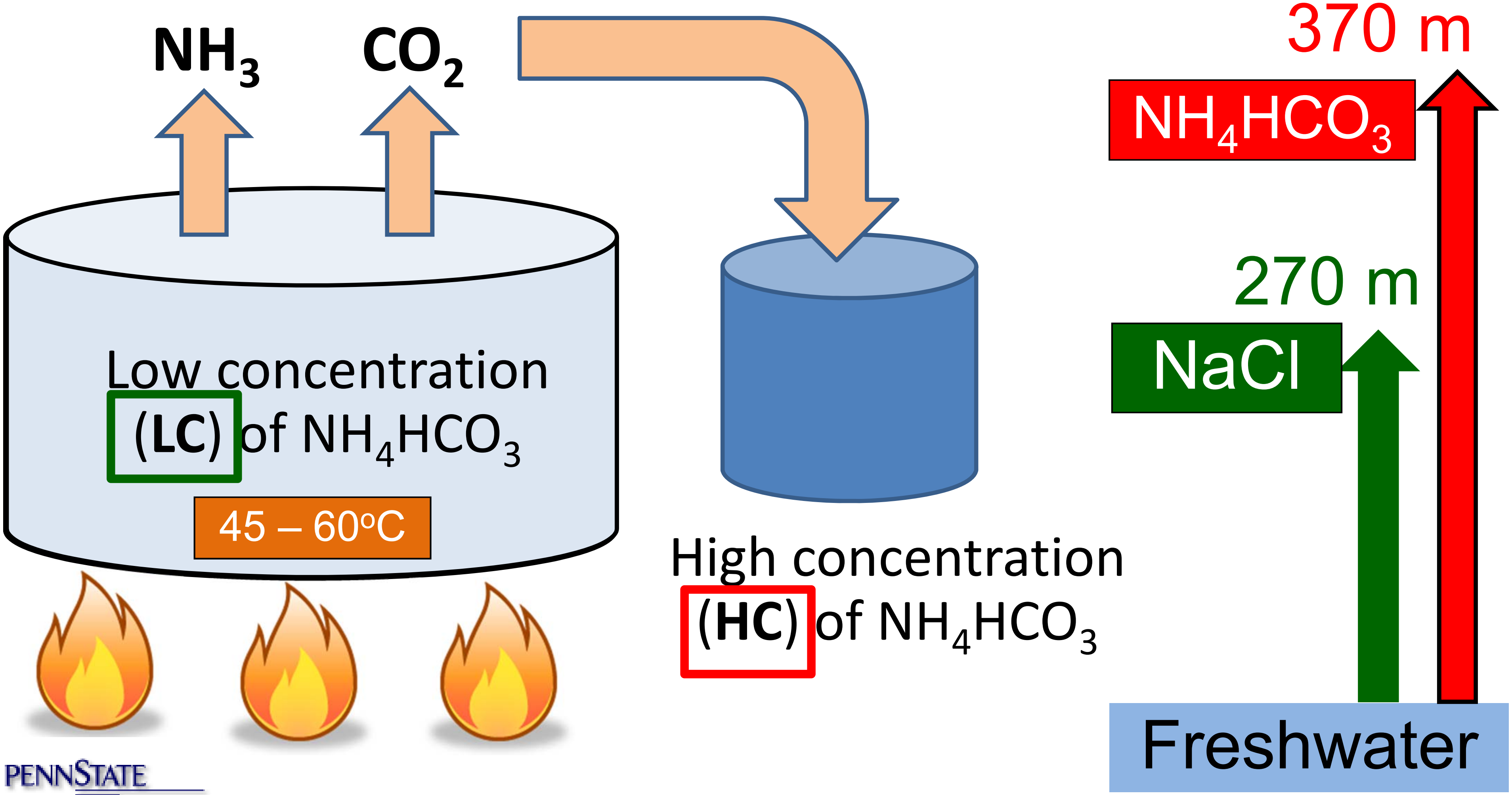
Logan and Rabaey (2012) *Science*
Logan and Elimelech (2012, *Nature*

Use waste heat to create artificial "salintity gradient" energy using ammonium bicarbonate



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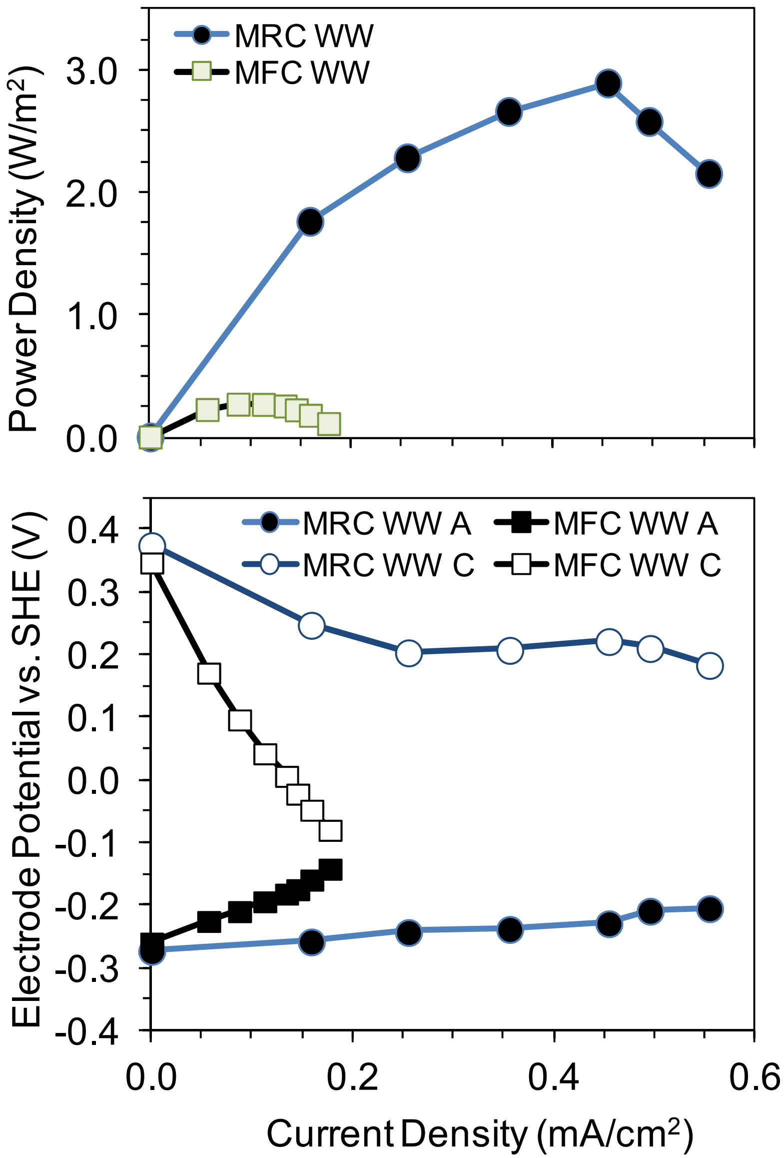
Cusick, Kim & Logan (2012) *Science*

MRFC with: Domestic Wastewater, AmB

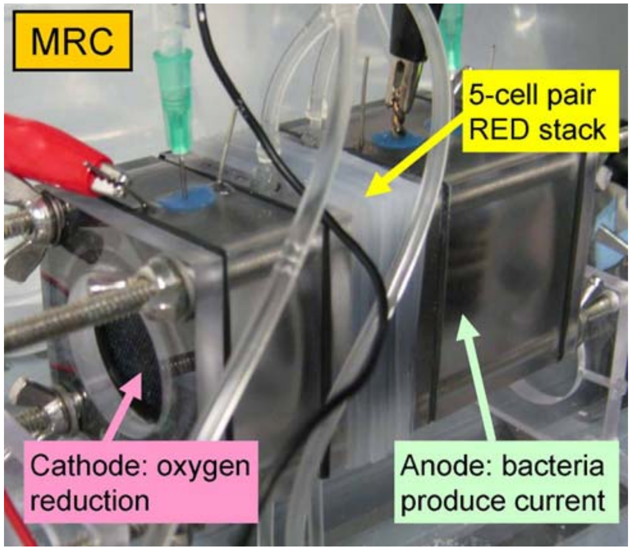


MHRC Peak Power = 2.8 W/m²

= **10×** versus **MFC with wastewater**

Electrodes: 1.8 W/m²

RED: 1.0 W/m²



Cusick, Kim & Logan (2012) *Science*

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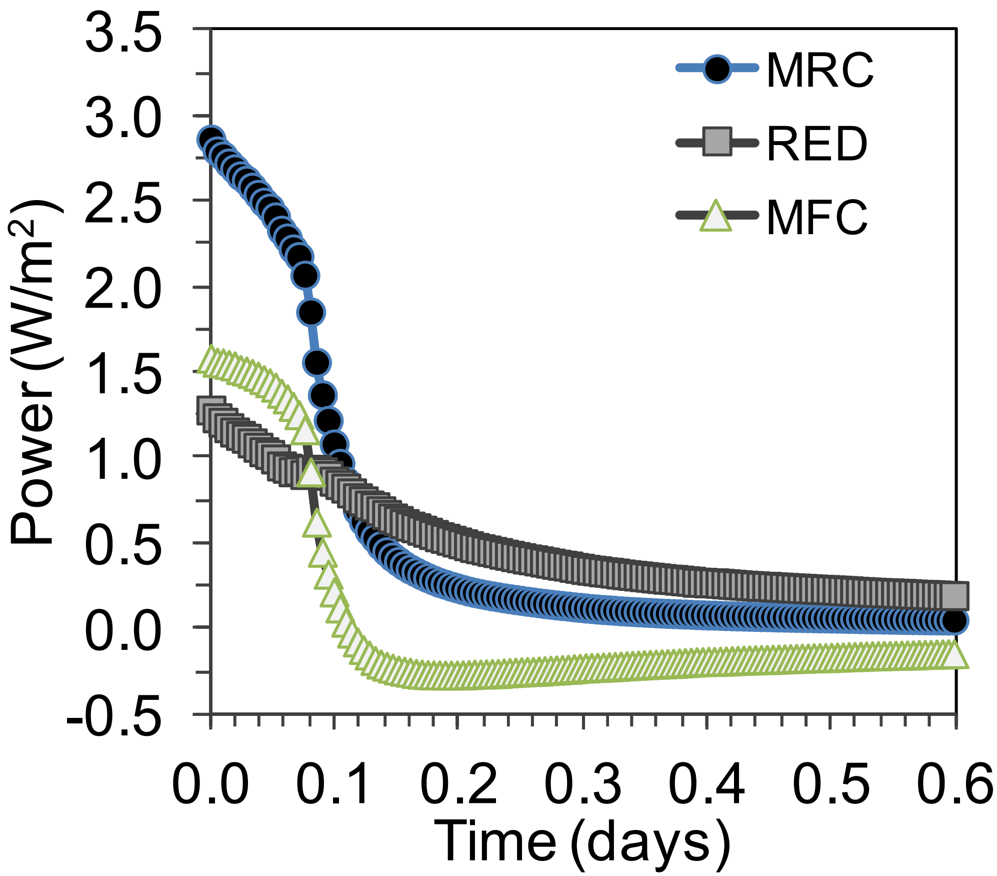
Improved performance with Domestic Wastewater
Time for treatment greatly reduced



<u>Short Cycle Time:</u>

- 40% COD removal per cycle
- 25% COD removal in 2 hrs
  (suggests only sCOD removal)
  (typical of biofilm processes)

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Cusick, Kim & Logan (2011) *Science*

Conclusions

- New renewable energy technologies can be created using electro-active microorganisms:
  - Exoelectrogens- make electrical current
  - Electrotrophs- consume electrons, make H_2 and CH_4
- METs
  - MFCs= electrical power
  - MECs= H_2 gas
  - MRCs = Just add (salt) water to supply extra power
  - CMFCs= Using electrochemical fields to enhance energy production
- Pilot scale METs
  - MECs= it worked! (although CH_4 recovered not H_2)
  - MFCs- On the way…
  - MRCs- Still a bit in the future.
- Stay tuned!

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- My collaborators at the universities and institutes listed below

Additional Information

Email: blogan@psu.edu

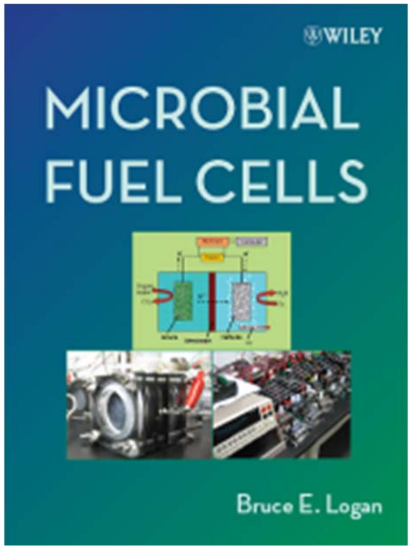
Logan webpage: www.engr.psu.edu/ce/enve/logan/

International MFC site: www.IS-MET.org

YouTube: YouTube/user/MFCTechnology
Twitter: MFCTechnology

MFC webcam: www.engr.psu.edu/mfccam

(live video of an MFC running a fan)



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