Microbial Fuel Cell and Wastewater Treatment

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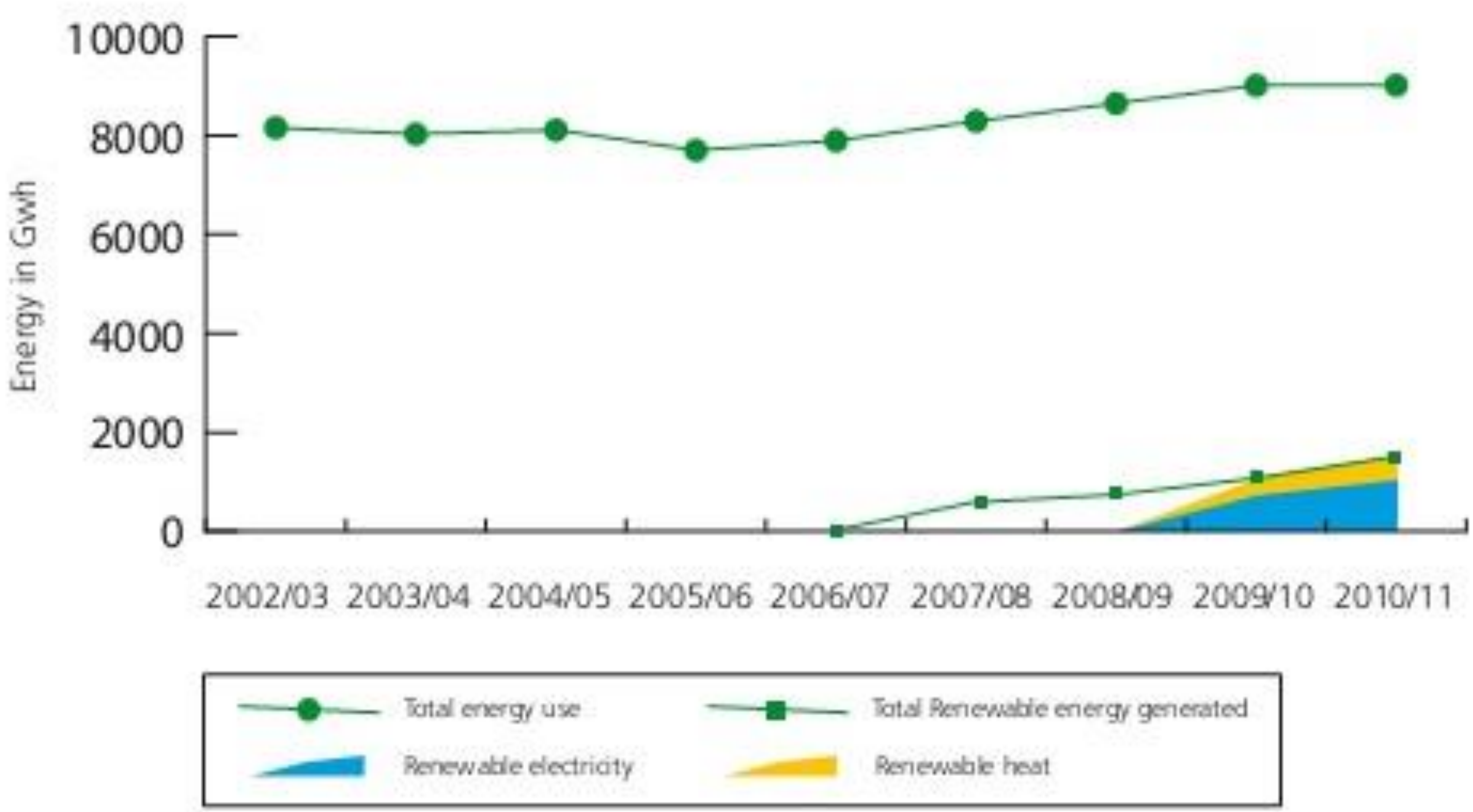
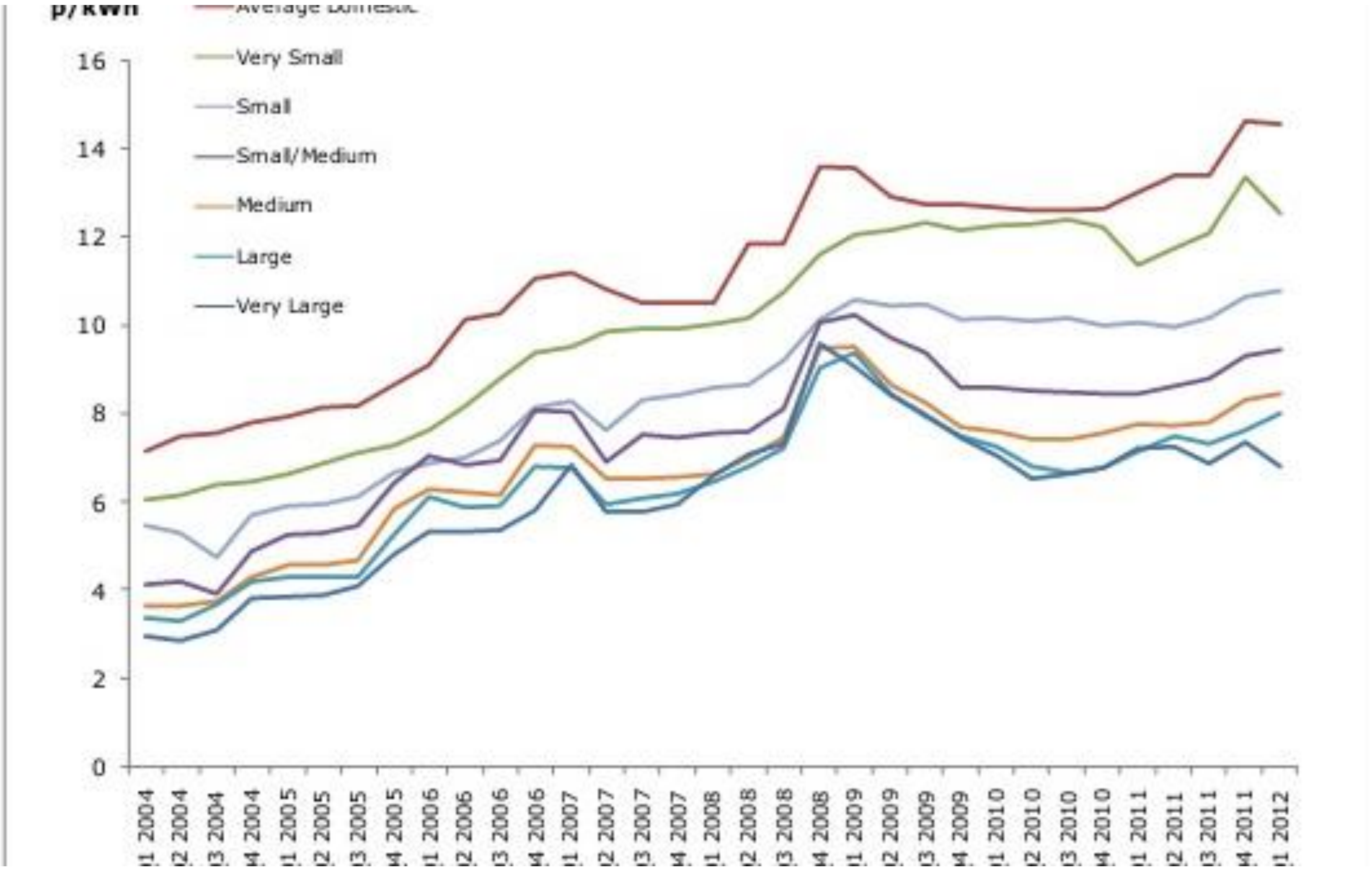
Inexorable Rise of Energy Use in The Water Industry



Inexorable Rise in Energy Prices



But there is Energy in Wastewater!

- Bomb Calorimetry
- Domestic wastewater contains
  - 7.6 kJ/L
  - 2000 kWh/ML
- Probably more..

Heidrich 2011

UK Domestic Supply

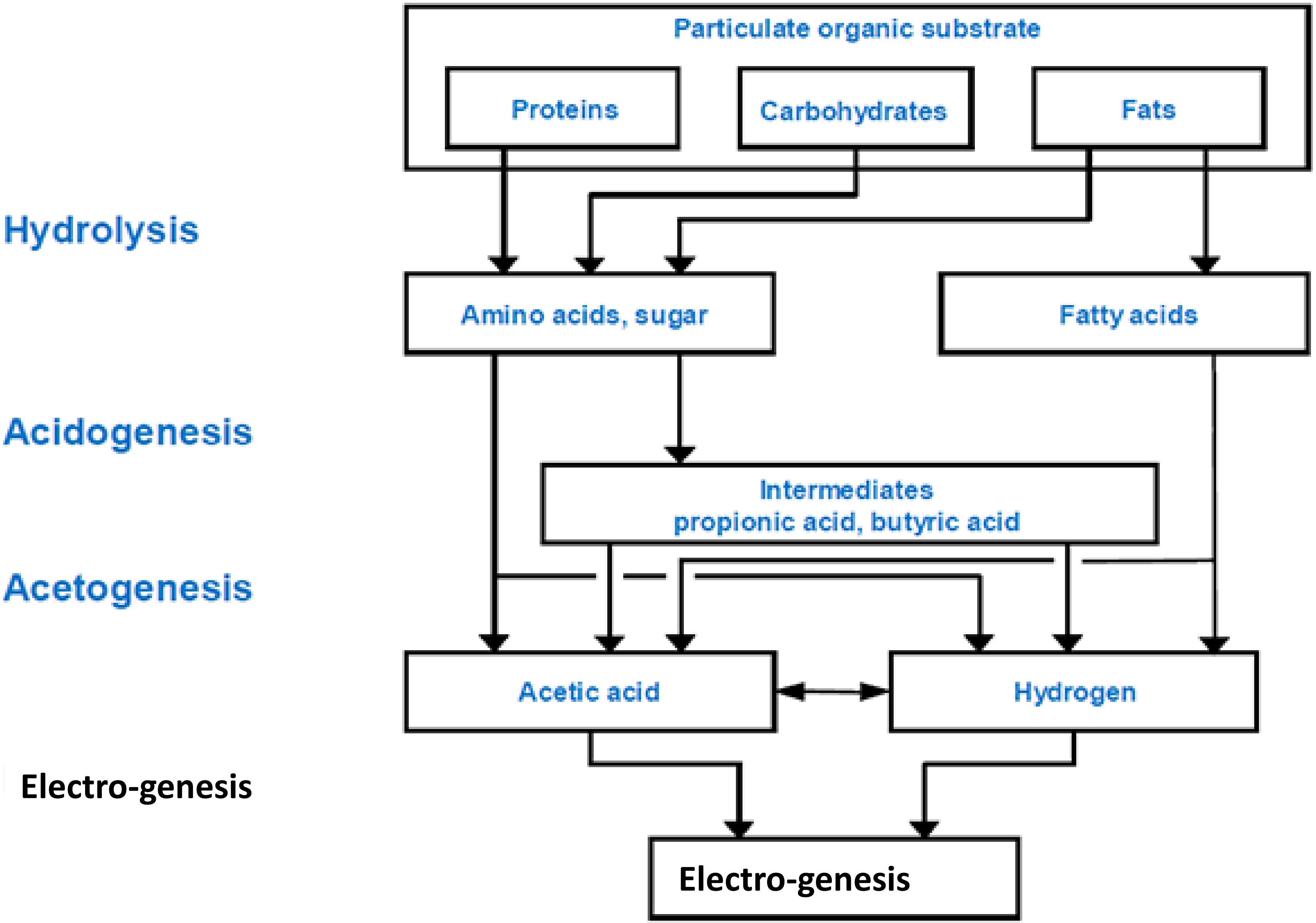
- 22 GWh/day energy in WW
- 6.34 GWh/day used to treat WW

NWL Domestic Supply (2010)

- 2.03 GWh/day energy in WW
- 0.45 GWh/day used for WW treatment

Intrinsic energy is 3-4 times the amount required for treatment

Anaerobic breakdown of complex wastes



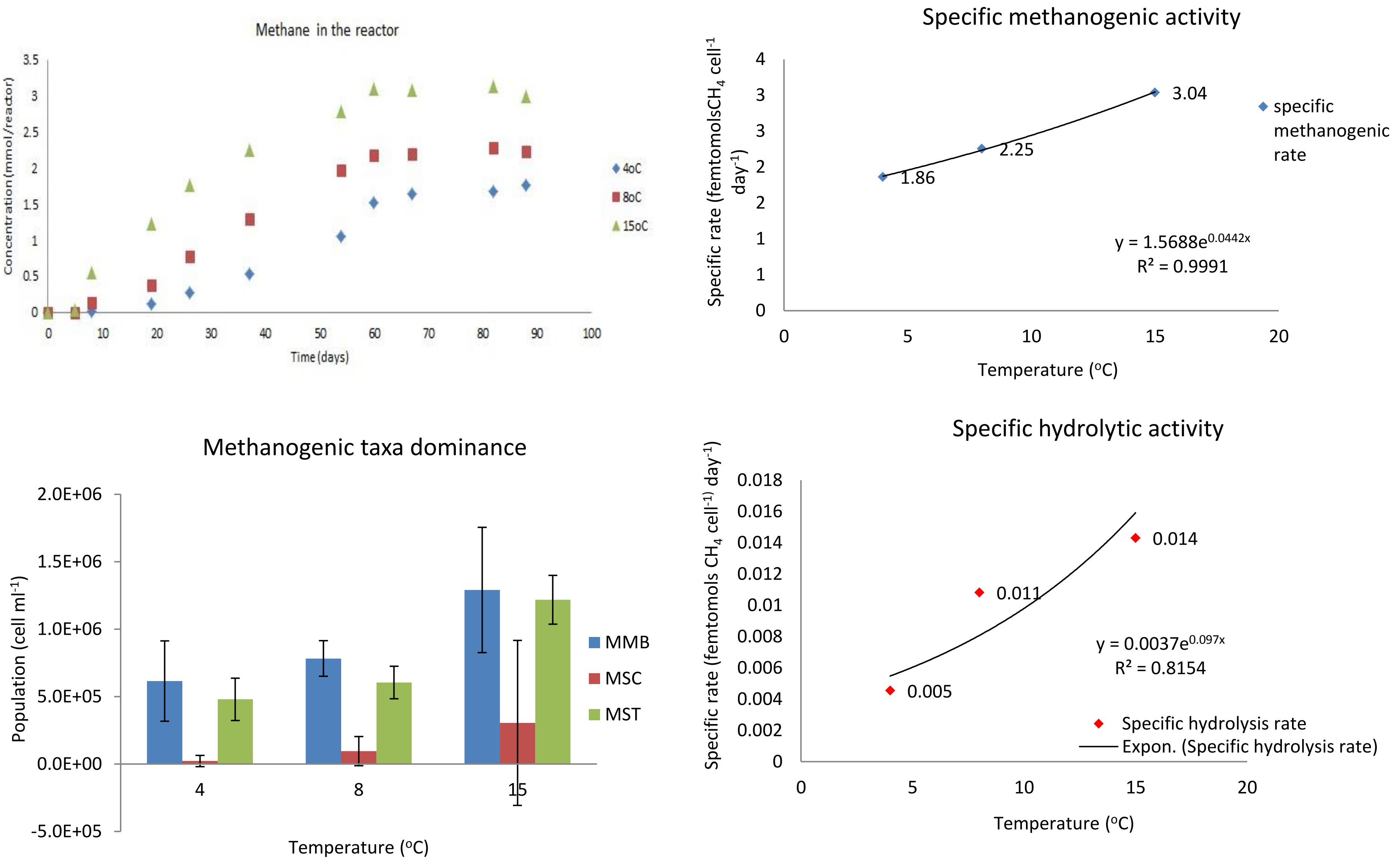
Domestic wastewater treatment in methanogenic reactors

Works well in S. America

- No 1º sedimentation tank
- Little sludge
- Lots of methane
- Up to 600,000 people

UASB treating domestic wastewater in NE Brazil

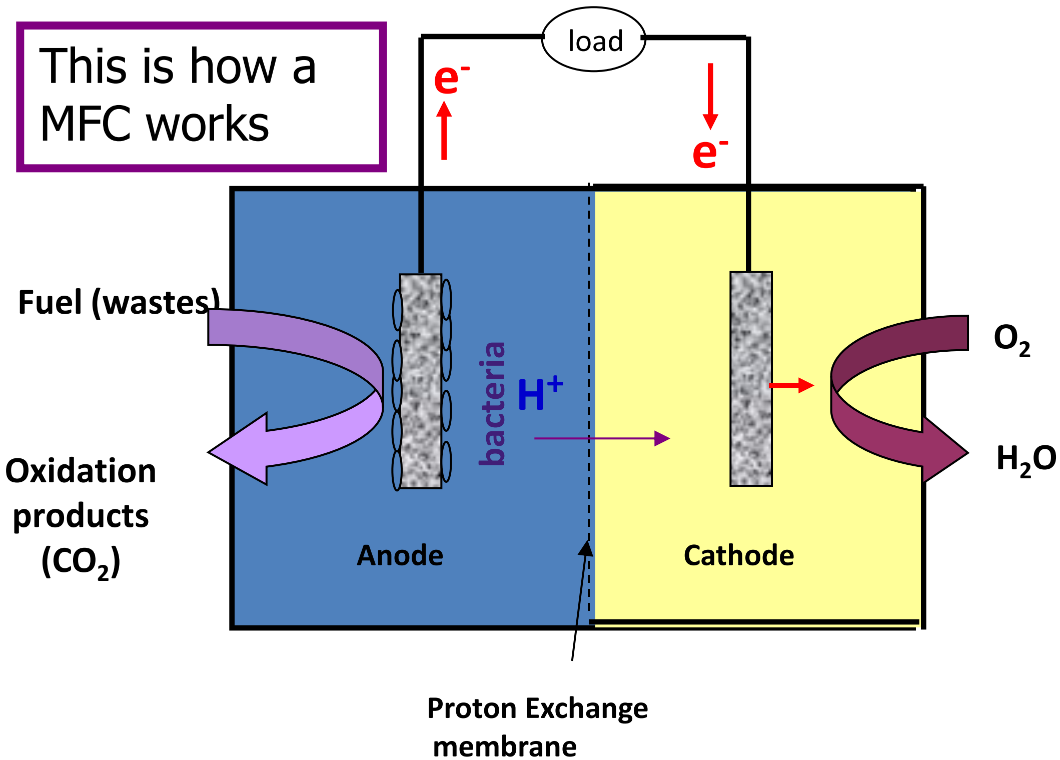
- Key interlinked problems
  - Temperature
  - Stability
  - Nutrients



a) Methane production versus time at all temperature; b) Methanogenic populations at all temperatures (the trend shows that the lower the temperature the higher the hydrogenotrophic:acetotrophic ratio – hydrogenotrophic methanogenesis is supported at low temperatures; c) Specific methanogenesis rates; d) specific hydrolysis rates; all images above describe anaerobic digestion of raw domestic wastewater at 4, 8 and 15°C.

A Microbial Fuel Cell

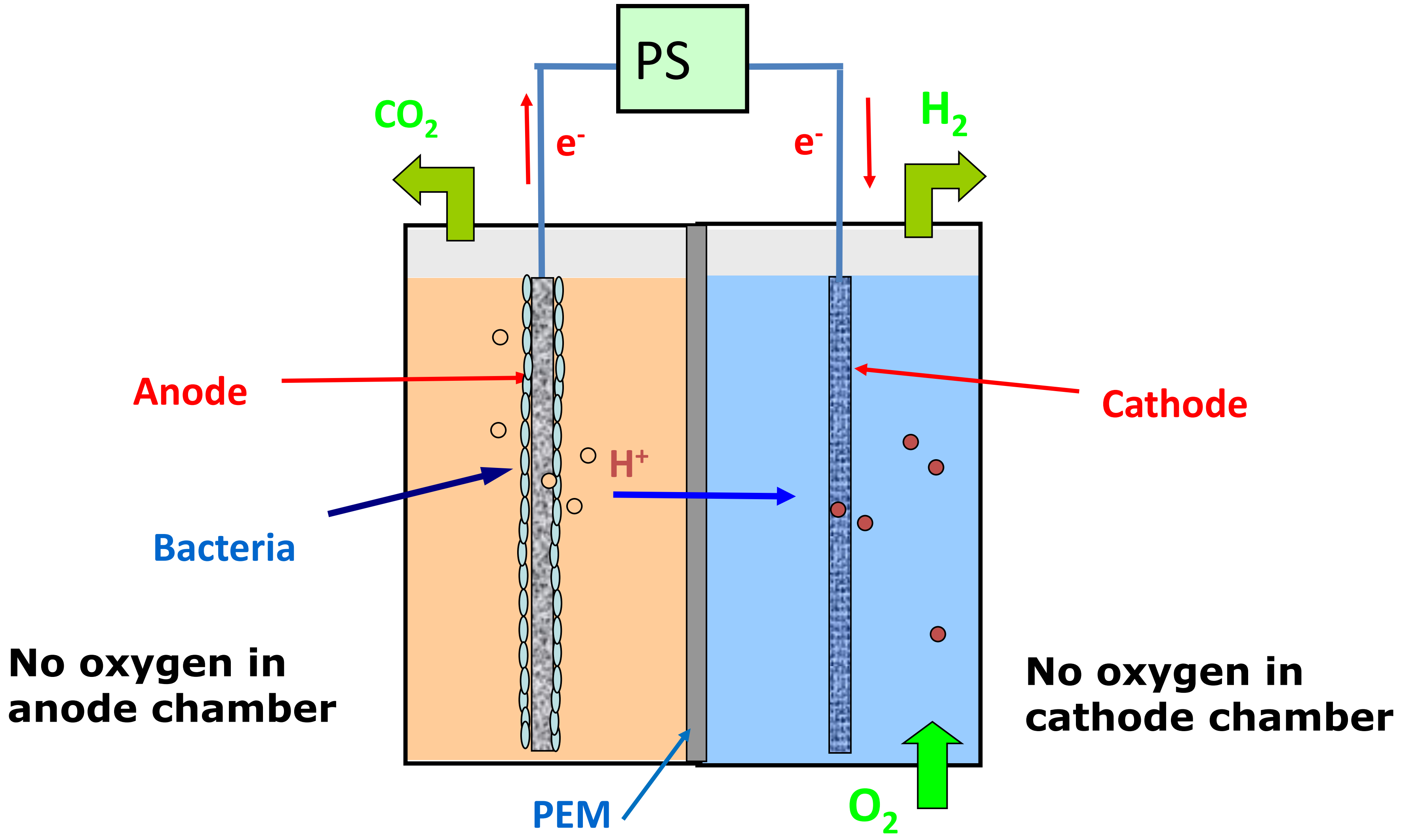
This is how a MFC works



A MFC is a device that uses bacteria to oxidize organic matter and produce electricity. The bacteria (attached to the anode) produce electrons that travel to the cathode (current).

Source: Liu et al., *Environ. Sci. Technol.*, (2004)

A Microbial Electrolysis Cell



0.25 V needed (vs 1.8 V for water electrolysis)

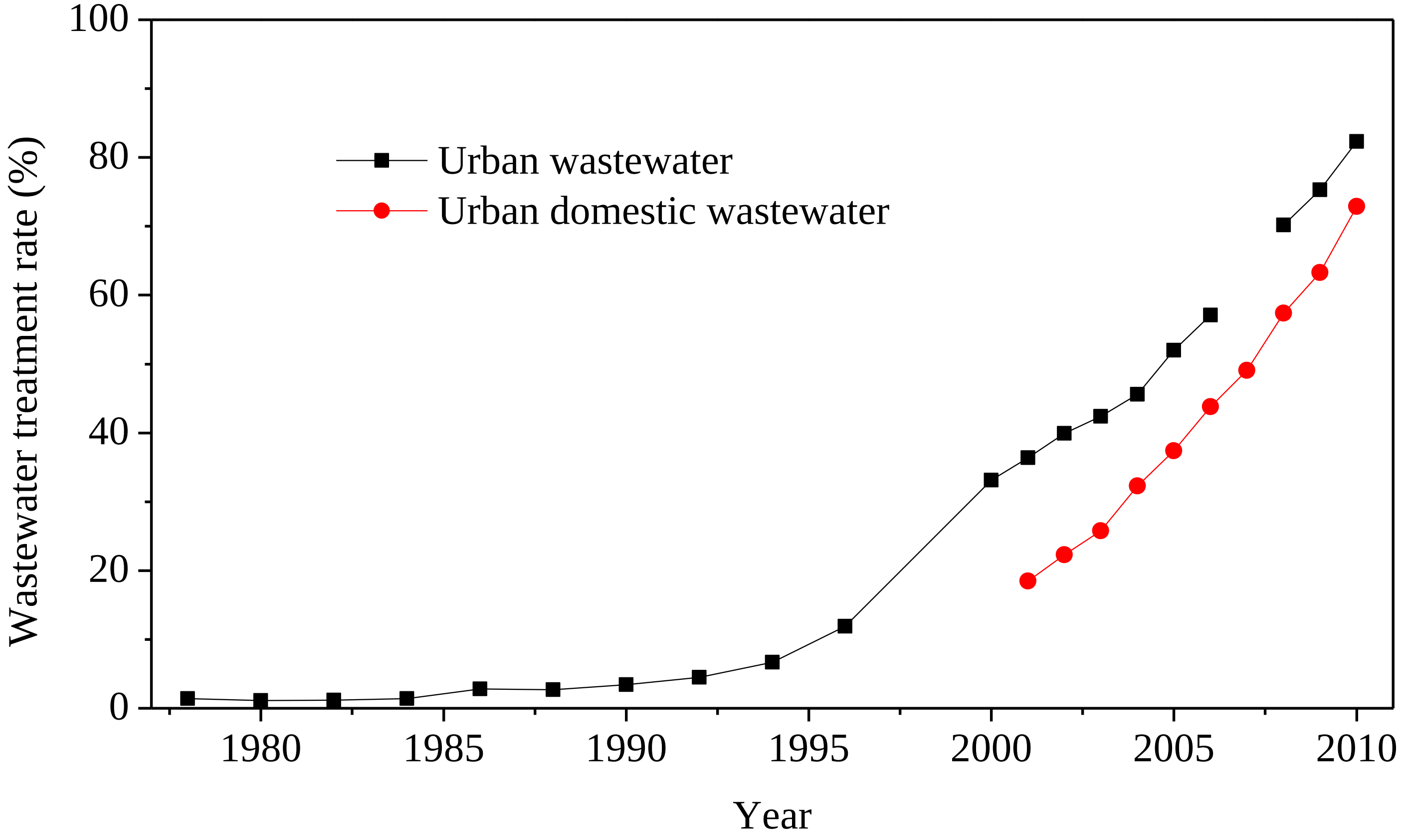
Anaerobic technologies for wastewater treatment

	MFC	MEC	Anaerobic Digestion
Temperatures	7.5 – 45 ^{o}C	4.5 – 40 ^{o}C	> 20 ^{o}C
Process control	limited	possible	limited
Retrofittable	unlikely	possible	possible
Organic Load	low- high	low - high	high

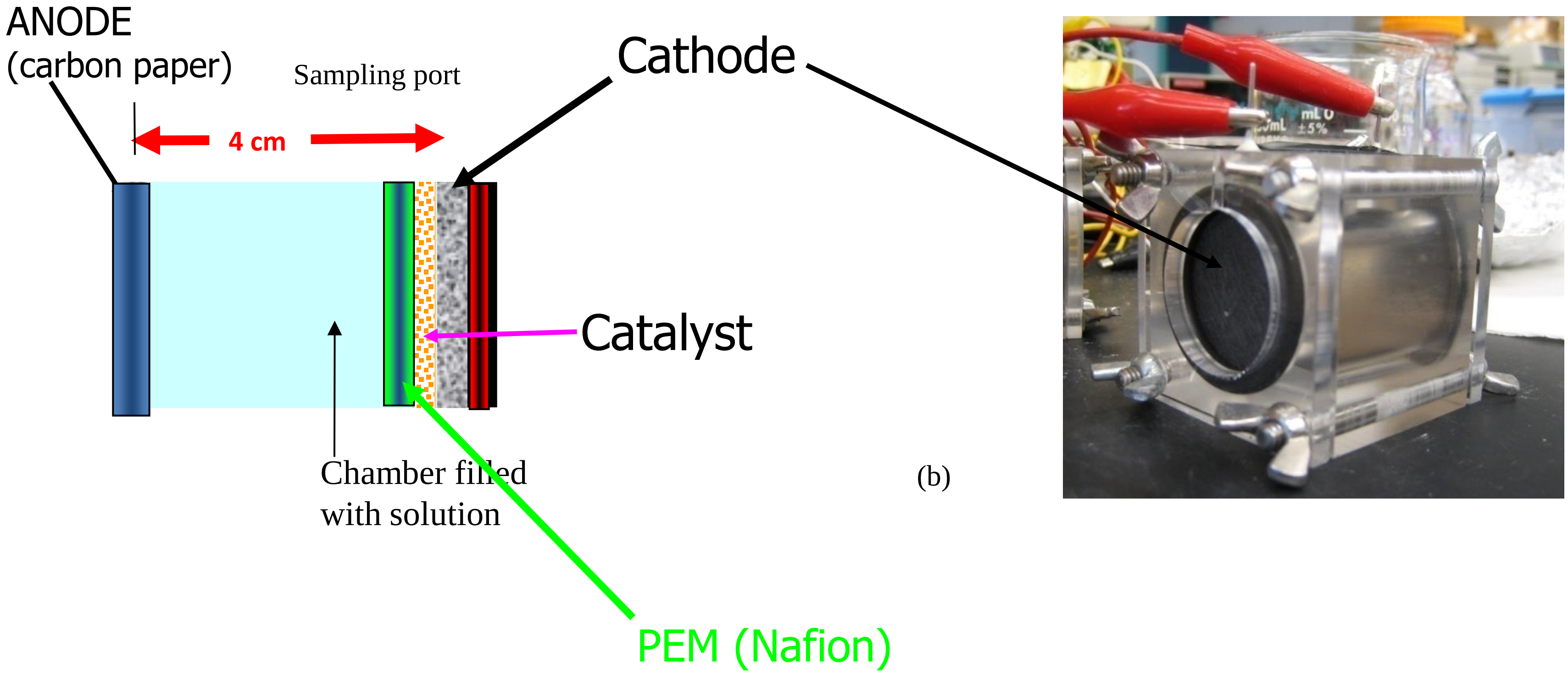
Why retrofitting is important

- Pie chart of your water bill
  - 30% Water
  - 40% Wastewater
  - 30% Financing cost:
    - 25 years for fixtures
    - 50 years for concrete!

Municipal Wastewater Treatment Rates In China



Most Research is Small Scale



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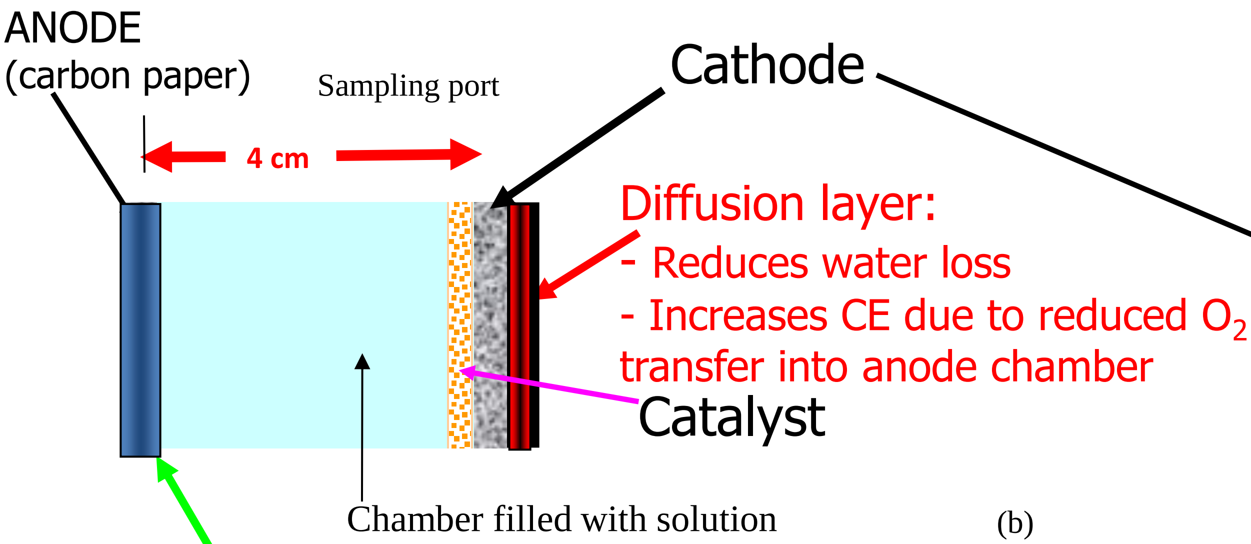
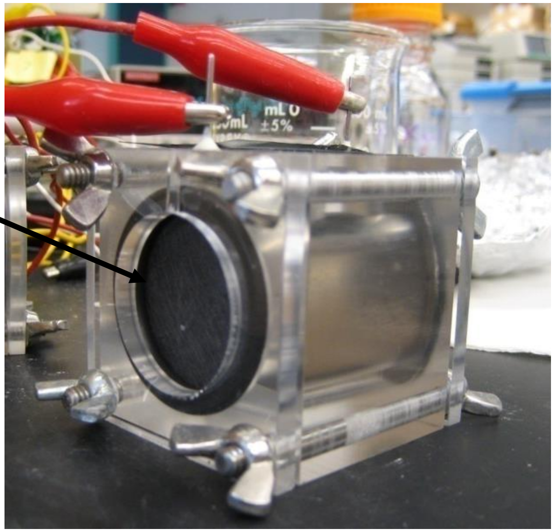
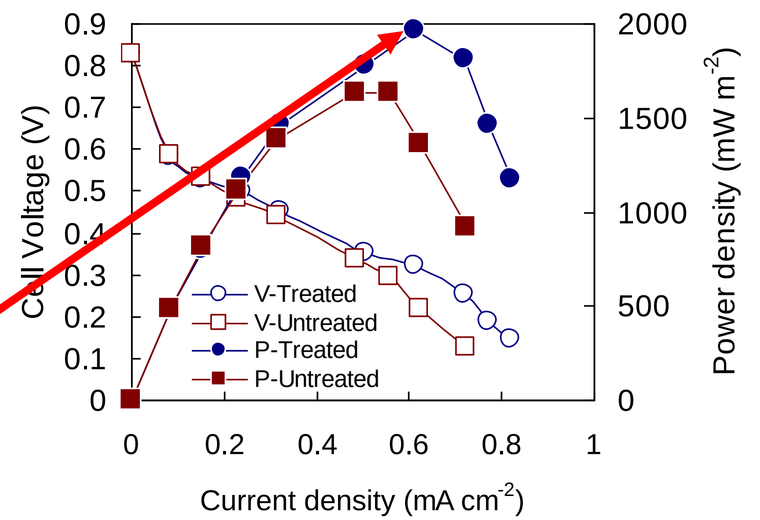




The PEM can be omitted, increasing power generation

Ammonia-gas treatment of anode increases power



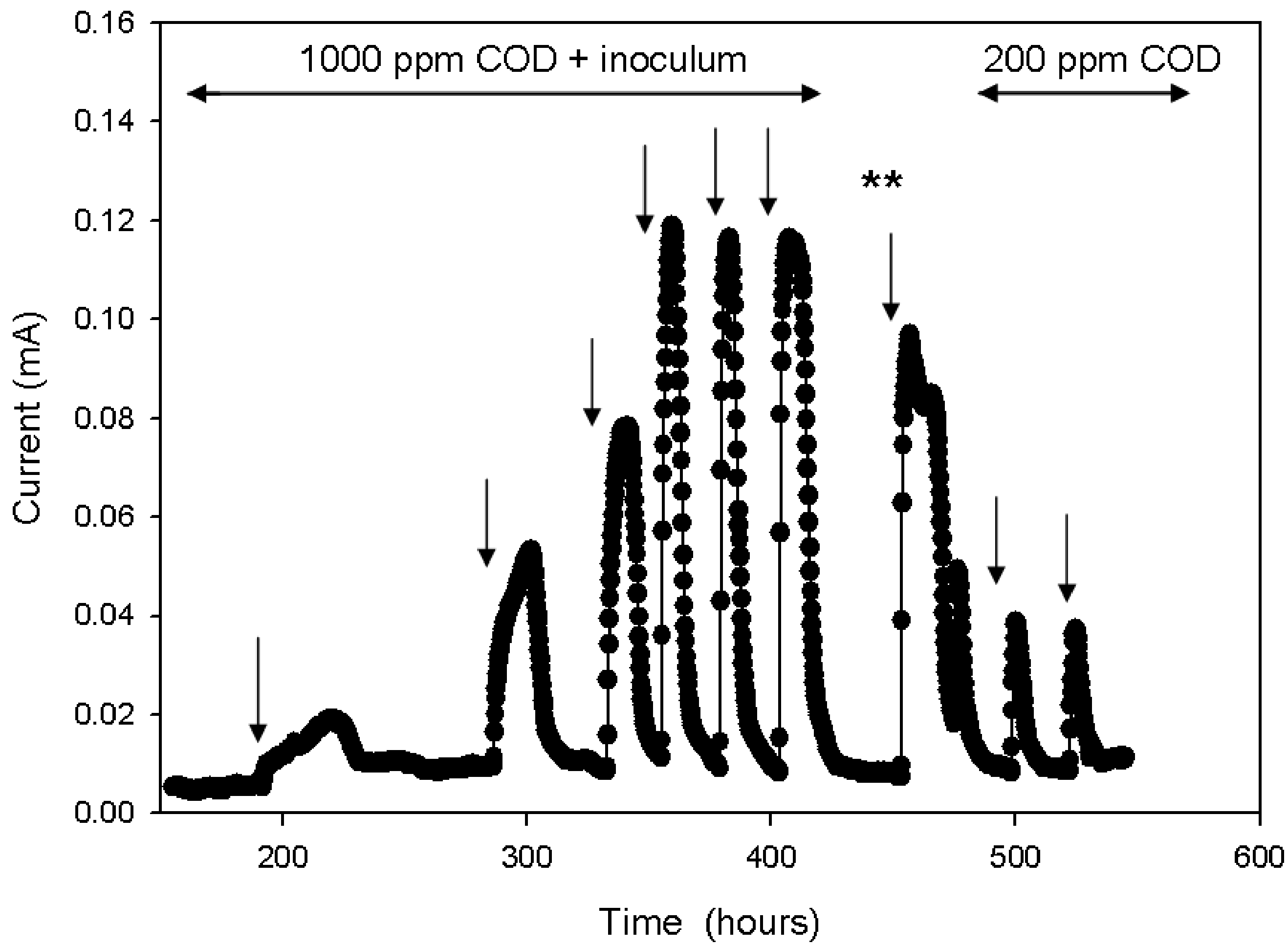
Power = 1970 mW/m^2 (acetate)
= 115 W/m^3

Where are the microbes in a Microbial Fuel Cell?

Thick biofilm on wastewater fed microbial fuel cell

- Microbes accept electrons from organic matter
  - Electron donors
- Microbes donate electrons to reducible chemicals
  - Electron Acceptors
    - e.g. oxygen
    - Iron (oxides)
- In MFC anode is an electron acceptor
- Microbe breath anode!

Maturing anode community increases current



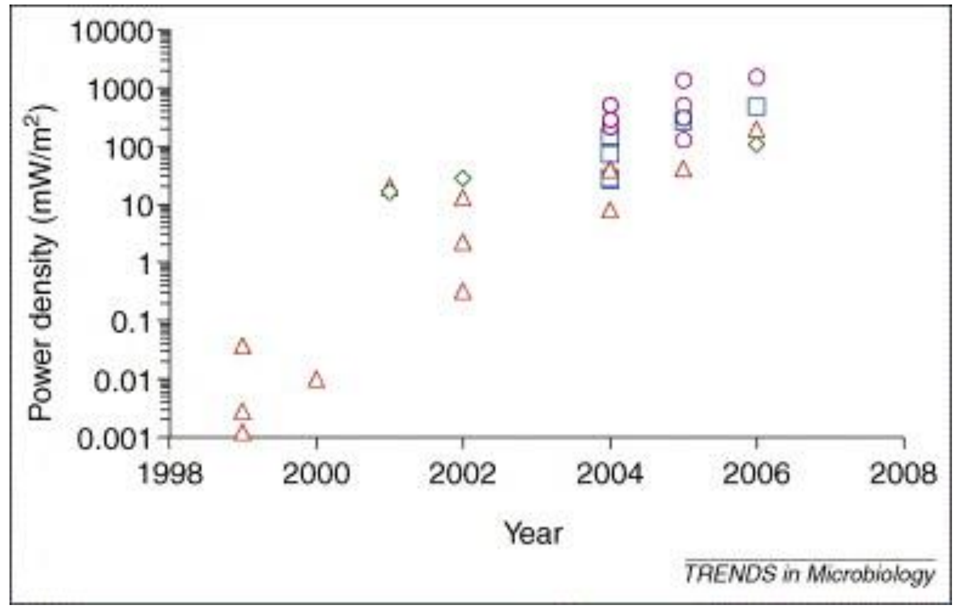
Voltages are modest

- Anode
  - Acetate oxidation
    - $2HCO^{-}_{3} + 9\ H^{+} + 8e^{-} \Rightarrow CH_3COO^{-} + 4H_2O$
      - -0.300V
- Cathode
  - Oxygen reduction
    - $O_2 + 4\ H^{+} + 4\ e^{-} \rightarrow 2\ H_2O$
      - 0.805V IN THEORY
      - ~0.200V In practice

$$E'_{emf} = 0.200\text{-}(-300) = 0.500V$$

Power is increasing year on year

- Power increasingly expressed / m^3
- May also / m^2
  - Anode
  - Cathode
  - Membrane



Logan & Regan, 2006. Trends in Microbiology. 14, 512-518

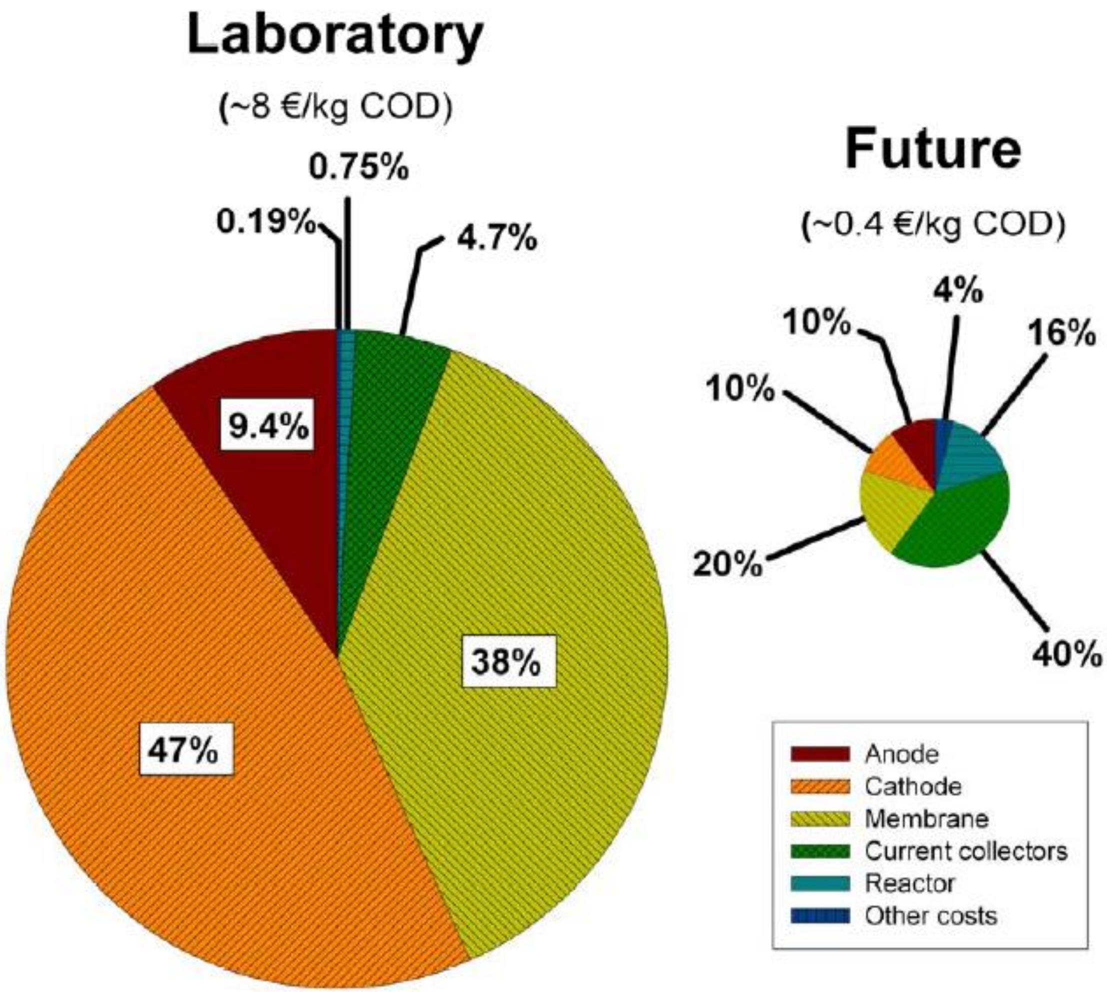
Most Researchers "cheat"

- Use
  - Acetate or sucrose instead of wastewater
  - Warm rooms instead of ambient
  - High conductivity buffer instead of wastewater
  - Expensive materials instead of cheap ones
  - Short runs at small scale instead of long ones at large scale

Research Challenges in Newcastle

- Scale
- Materials
- Coulombic efficiency
- Length of operation
- Valorisation
- Retrofitability

Capital costs



Rozendaal TIB 2008

Tentative costs WWT: anaerobic and MEC look best.

System	Product	Capital costs (Euros/kg COD)	Product Revenue (Euros/kg COD)	Net Revenue (Euros/kg COD)
Activated sludge	N/A	0.1	-0.3	-0.3
Anaerobic Digestion	CH_4	0.01	0.1	0.1
MFC	Electricity	0.4	0.2	-0.2
MEC	H_2	0.4	0.6	0.2

Rozendaal TIB 2008

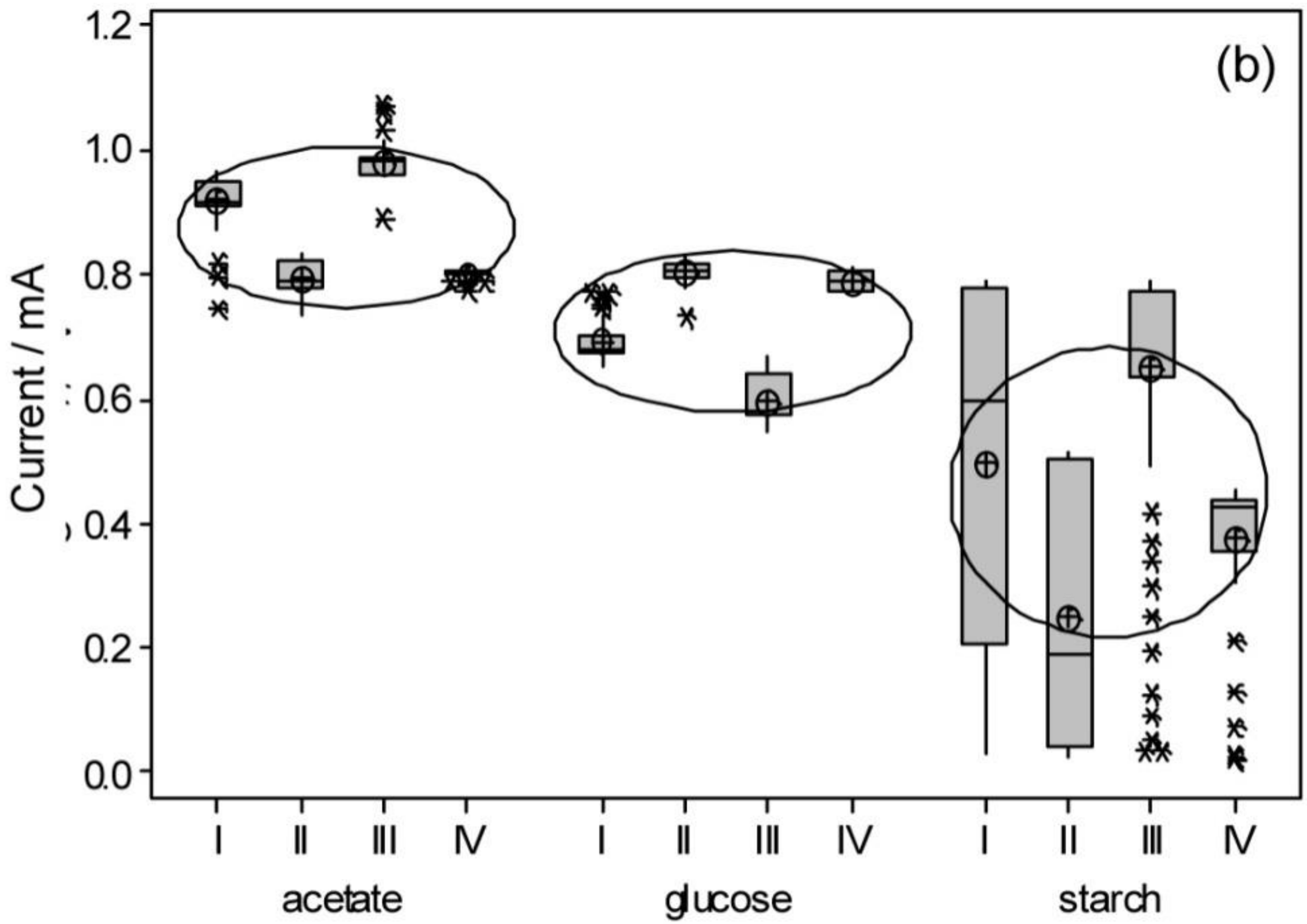
Materials: Evaluation on Cost vs Performance

Table 1: Cost-performance ratio for the different membrane materials. Cost was linked to power density and coulombic efficiency.

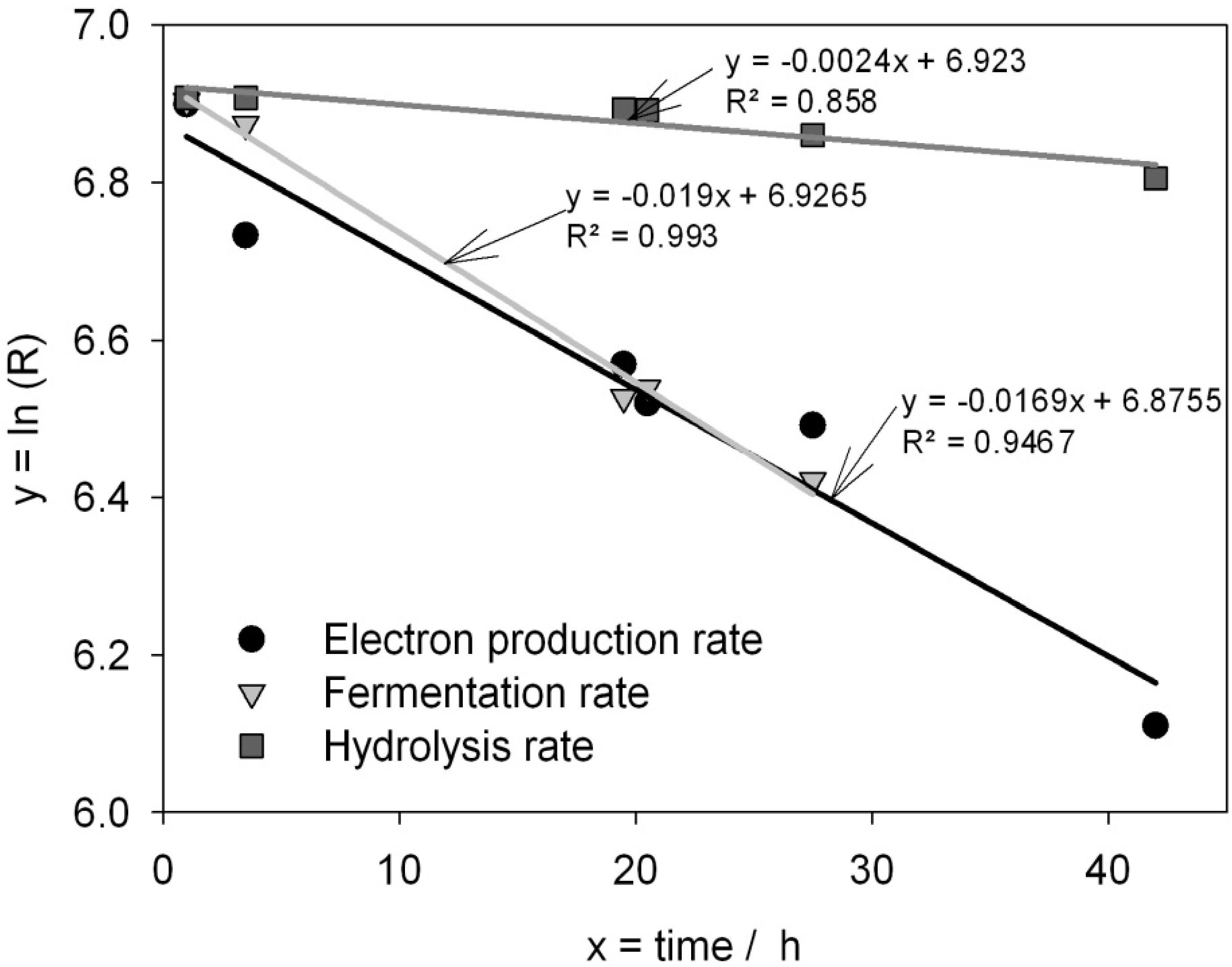
	Cost /£ m^{-2}	P /mW m^{-2}	Cost/P £ mW^{-1}	CE /%	Cost/%CE /£ m^{-2} $\%^{-1}$	Energy generated over a lifetime of 10 years / kWh m^{-2}	Total income generated over 10 years / £
CP	105	24±0.02	4.4	68±11	1.5	2.1	0.17
RH	1.5	14±2.2	0.11	63±8	0.02	1.2	0.10
Nafion	506	29±2.6	17.5	71±12	7.1	2.5	0.20
ETFE	3	29±3.4	0.10	92±6	0.03	2.5	0.20
PVDF	2	11±0.5	0.18	66±20	0.03	1	0.08

Christgen 2013

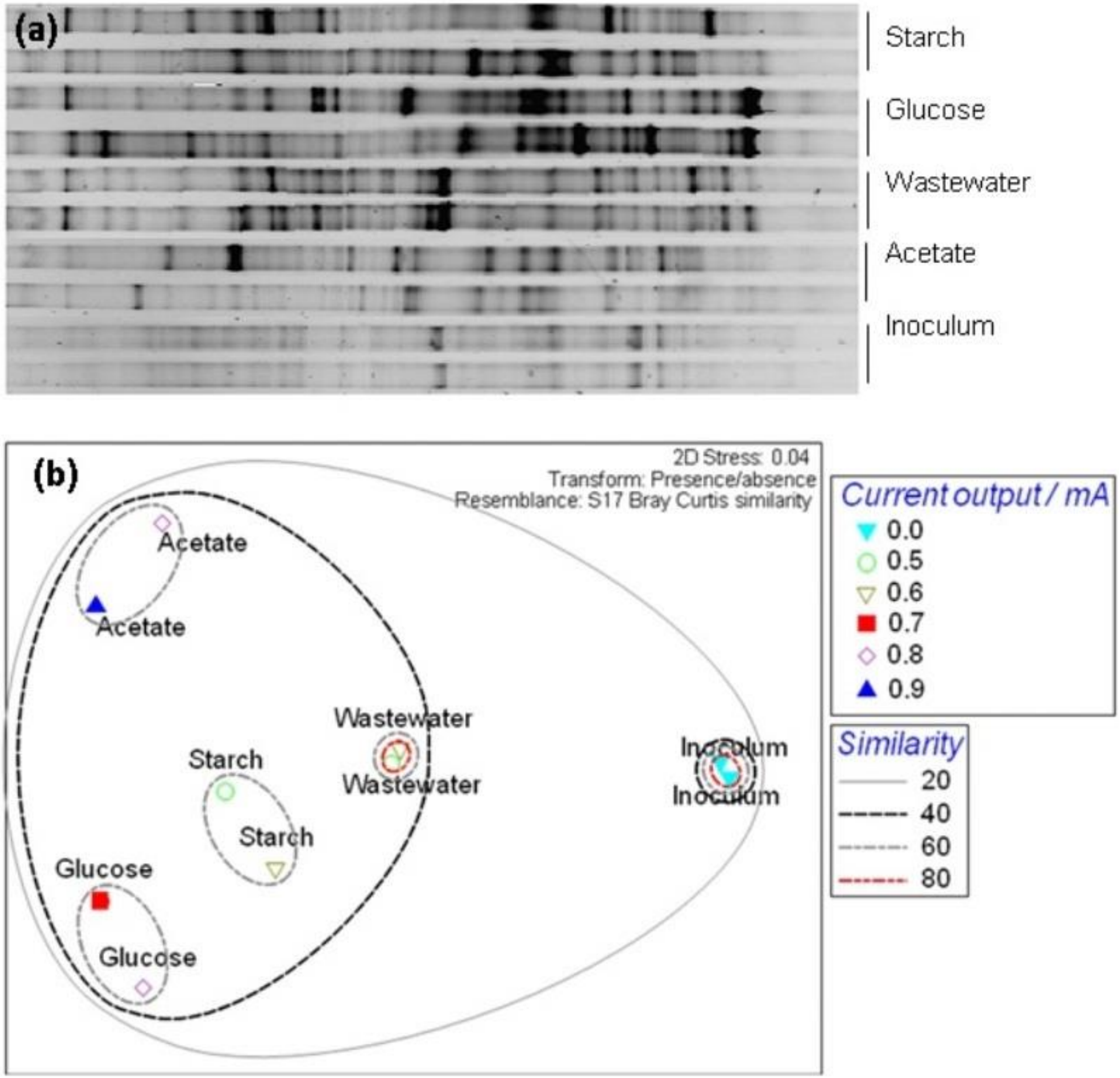
Less Current From Complex Wastes



Hydrolysis the rate limiting



Distinct communities

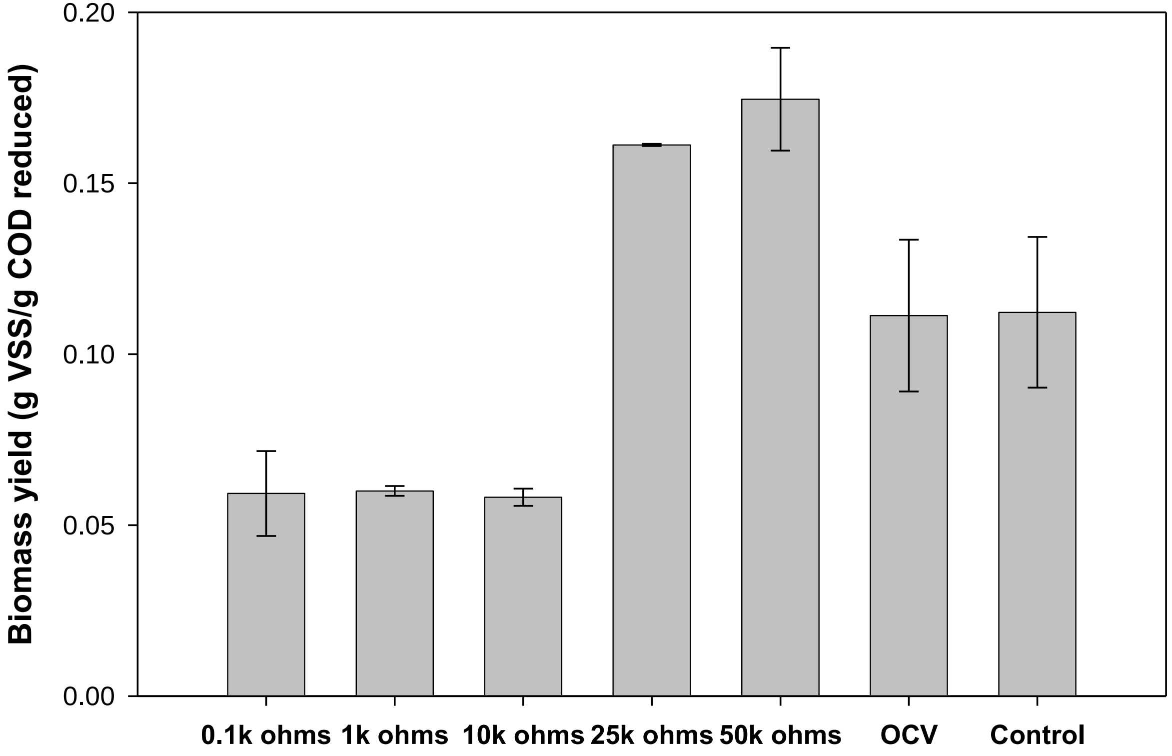


MEC performance on real wastes

- Research remains sparse, energy recovery often not reported, widely variable.

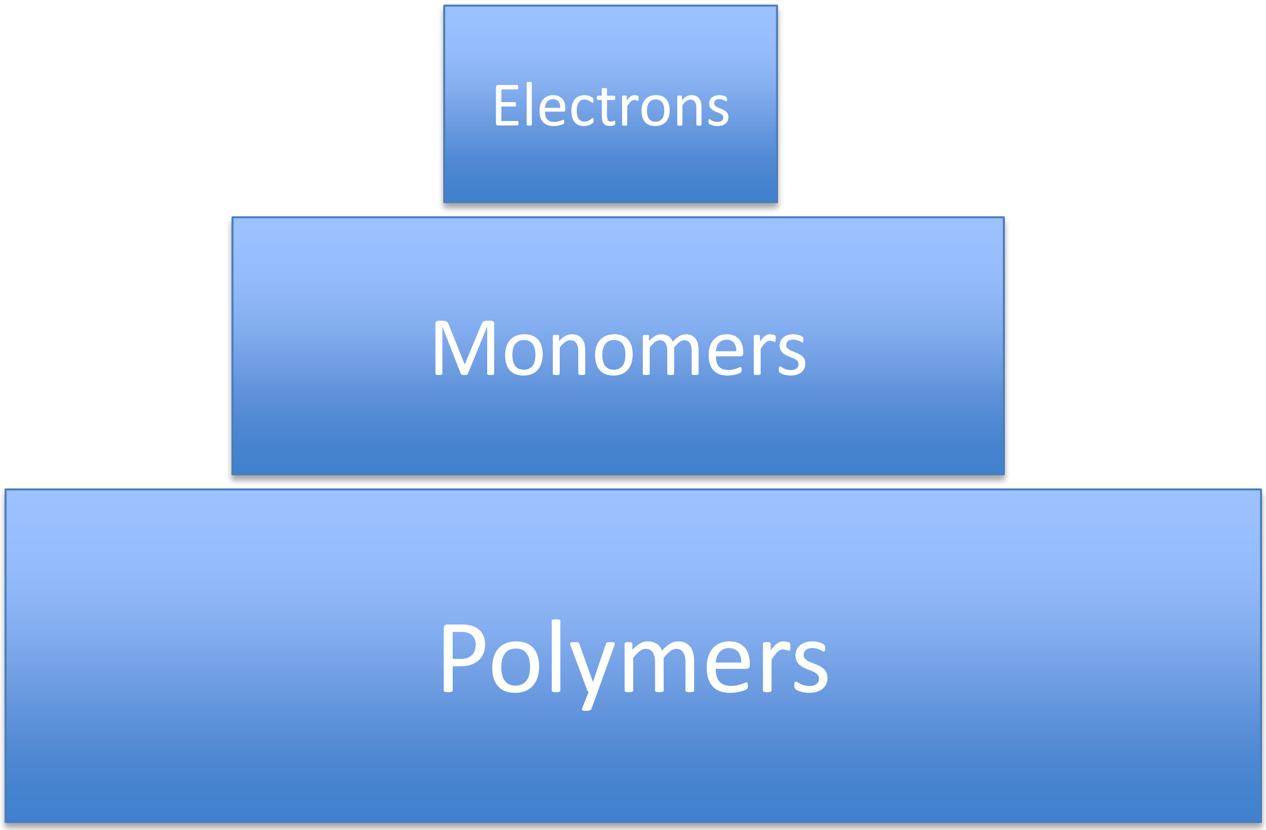
Paper	Substrate	Reported Energy recovery
Ditzig 2007	Domestic wastewater	< 1%
Wagner 2009	Swine wastewater	179%
Cusick 2011	Winery wastewater (acetate supplement)	If methane yield used “energy would exceed electrical input”
Escapa 2012	Domestic wastewater	“energy consumption comparable to aerobic treatments”
Jia 2012	Piggery wastewater	Input electricity efficiency 124% - term not defined

Low Yields imply large energy losses: possible uncoupling



Katuri 2007

Losing energy in the food chain?



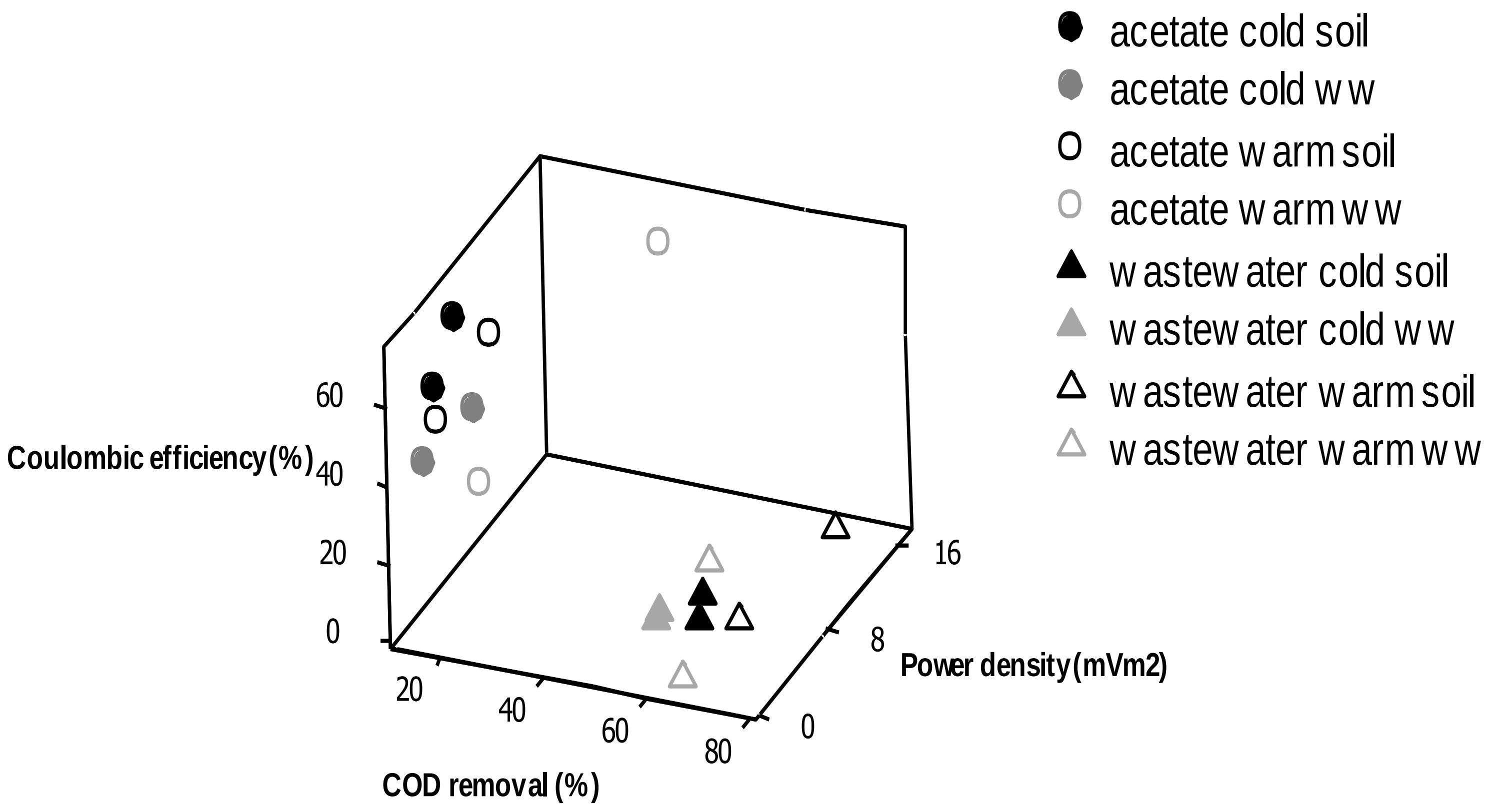
Two: Seeds, temperatures + feeds

Arctic soils

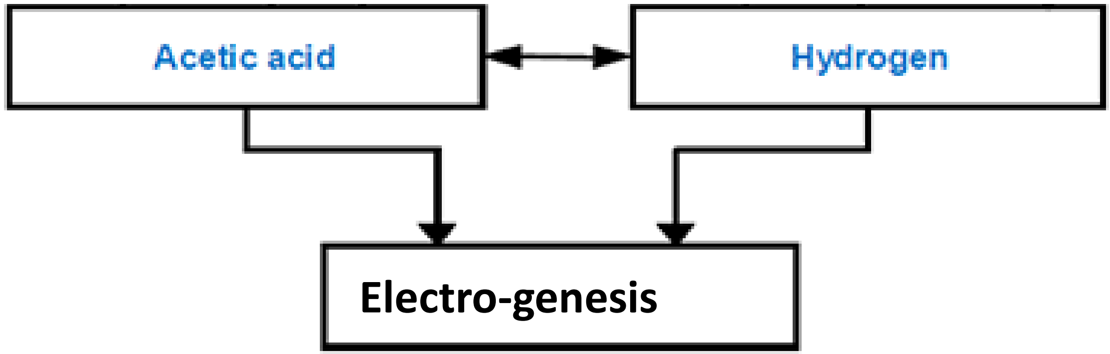
Lise Øvreås

UK wastewater

Temp and seed: little effect
Feed: big effect



Electro-genesis



Acetate diversity: not a subset of wastewater diversity

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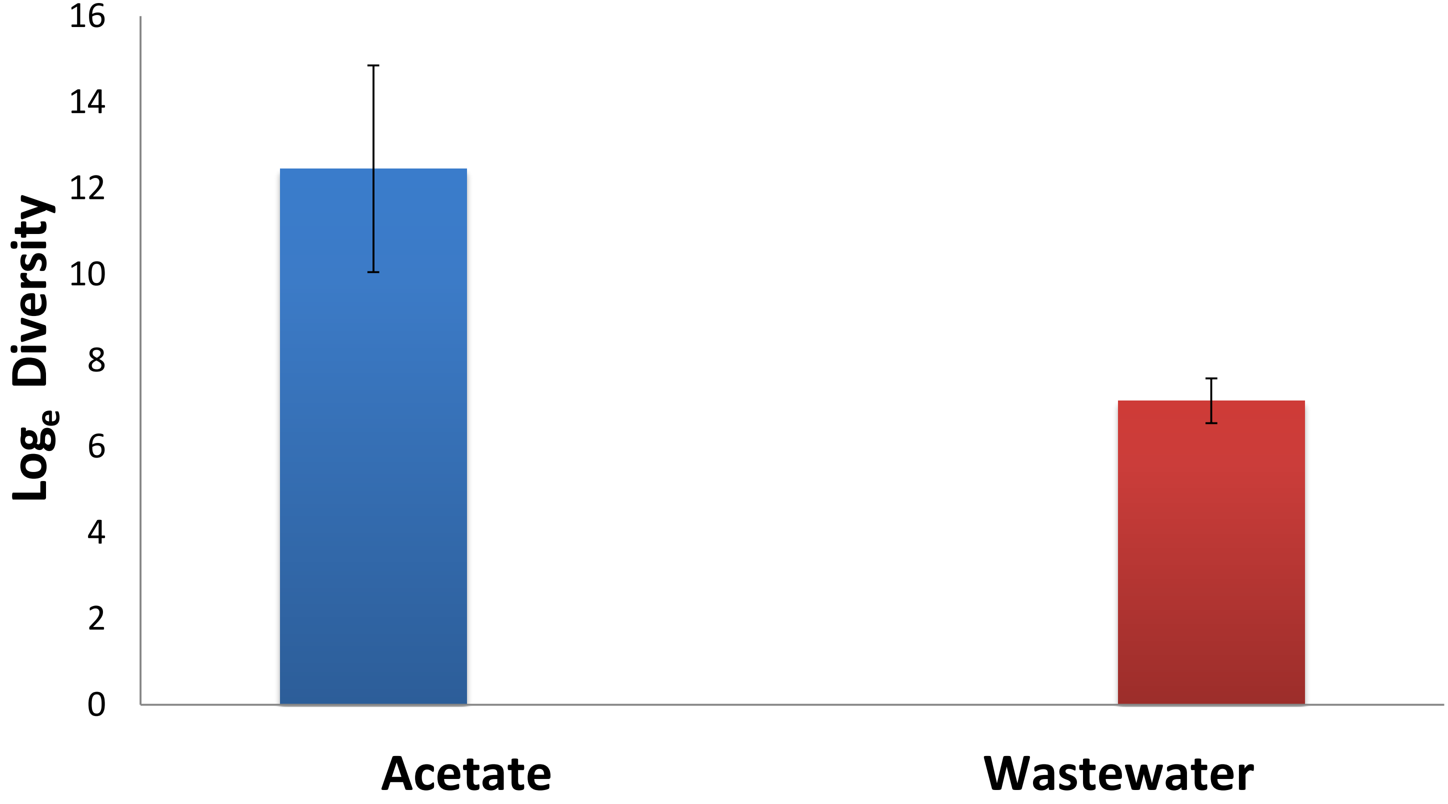
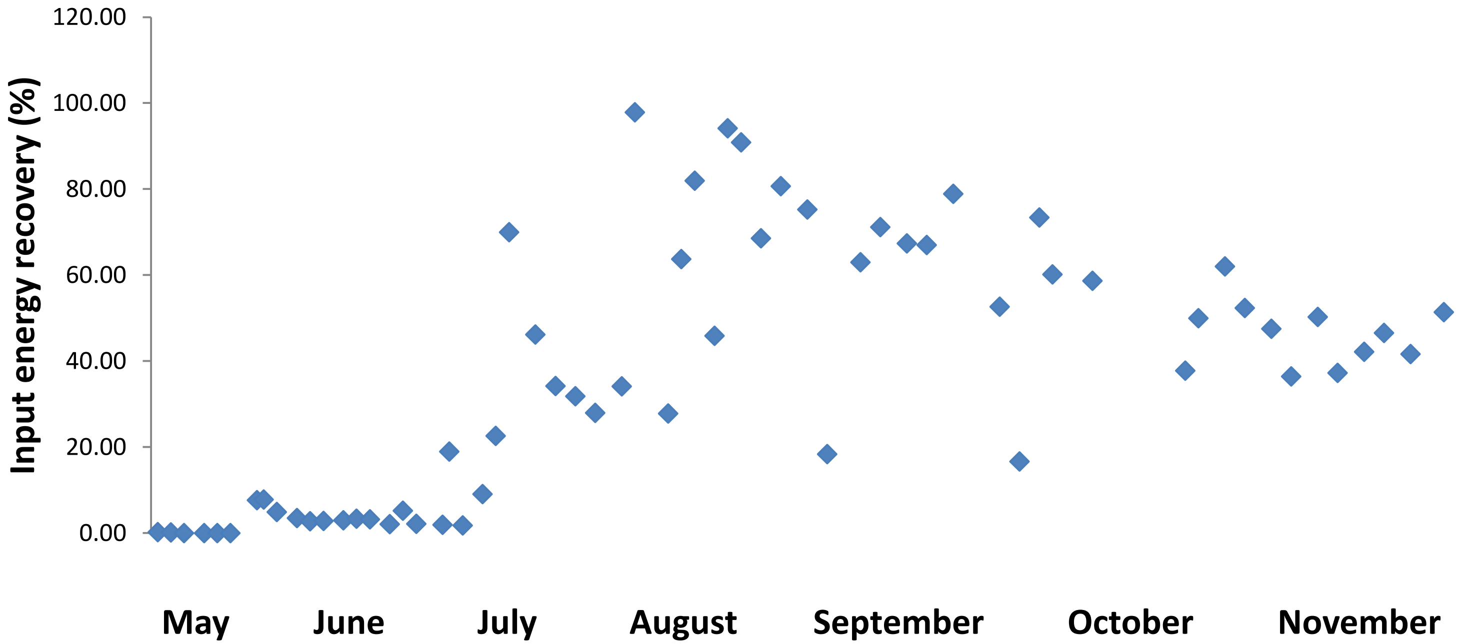


Bigger Trials

Worst conditions

- Heath Robinson design
- Low load
- Low temperatures
- Cheap materials

Energy recovery – Encouraging



Heidrich et al., 2012

It's the first time I have analysed the up-to date data - it does seem to be reducing in performance as we move from the summer (water temperature of 15- 20°C) to the winter (6-10°C). But even if it levels at 50% over the winter – with better design I'm sure it could be brought up – the main thing is its still working. The decline could also be due to time in operation – membranes clogging etc.

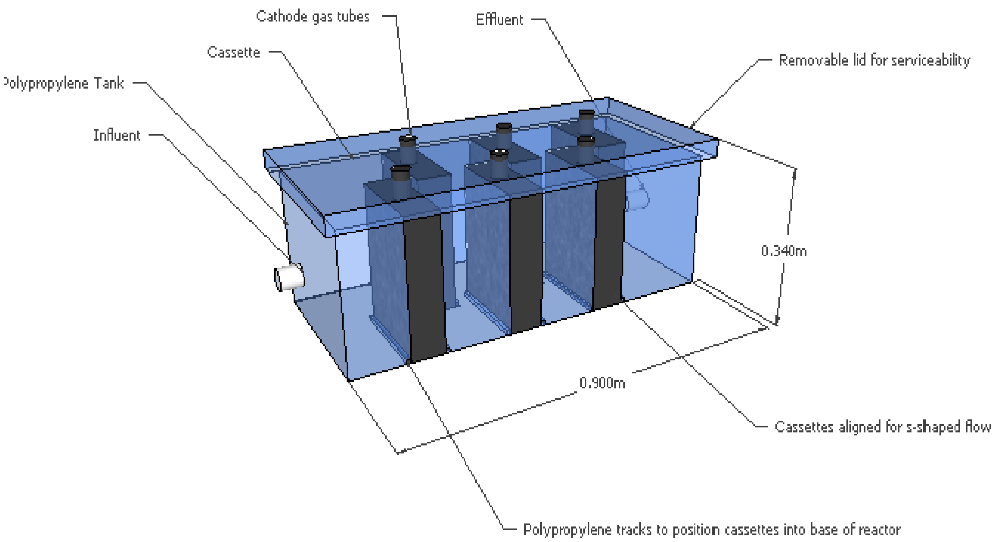
First Successful “Large” Trial

- Previous known failures
  - Warm climates
  - Low conductivity

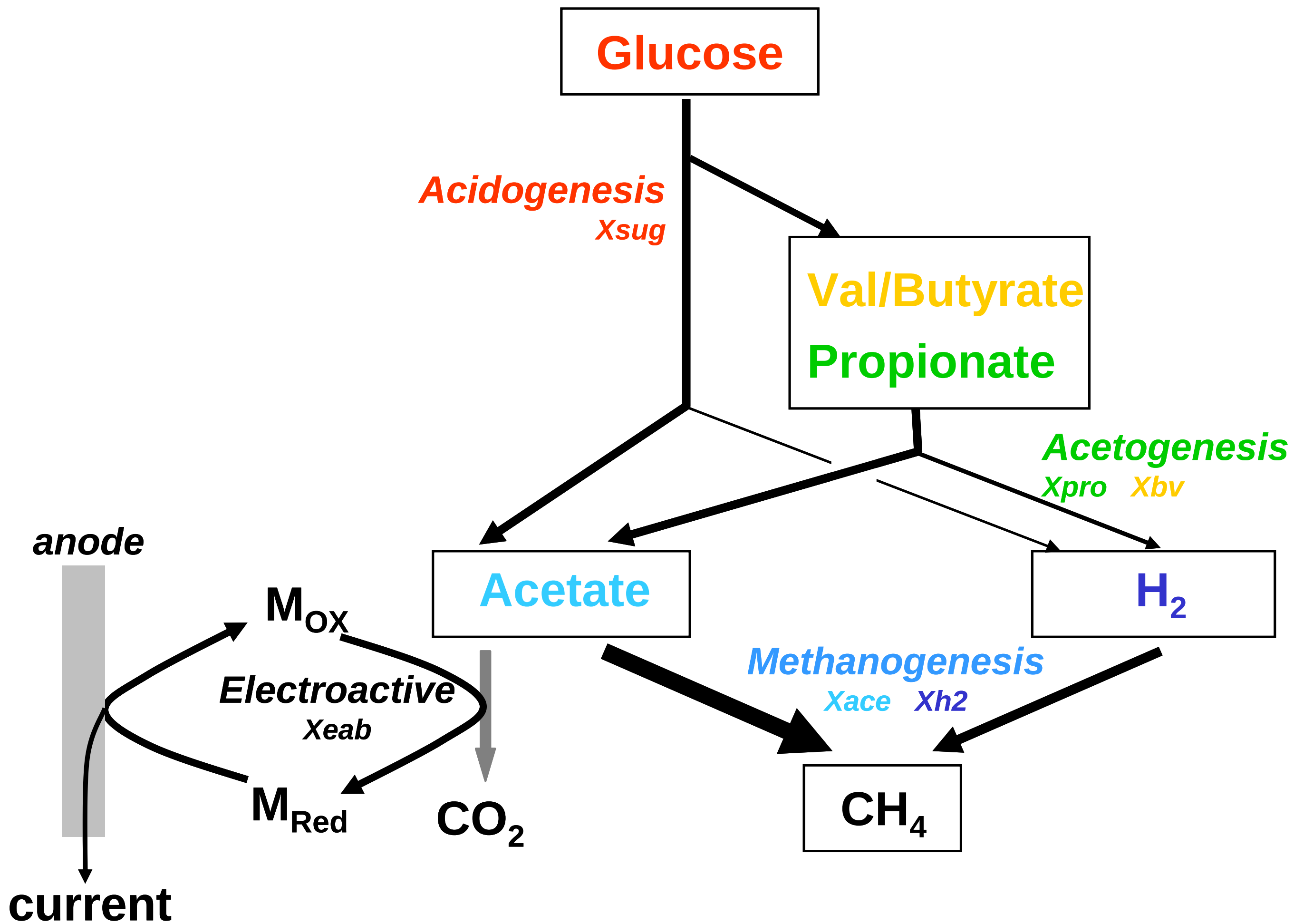
- Californian Vineyard
  - The temperature was 30°C, there was no membrane and competitors to methanogens used the hydrogen
- Australian Brewery
  - It used reverse osmosis water and therefore the wastewater had excesively low conductivity

Future Research: short term

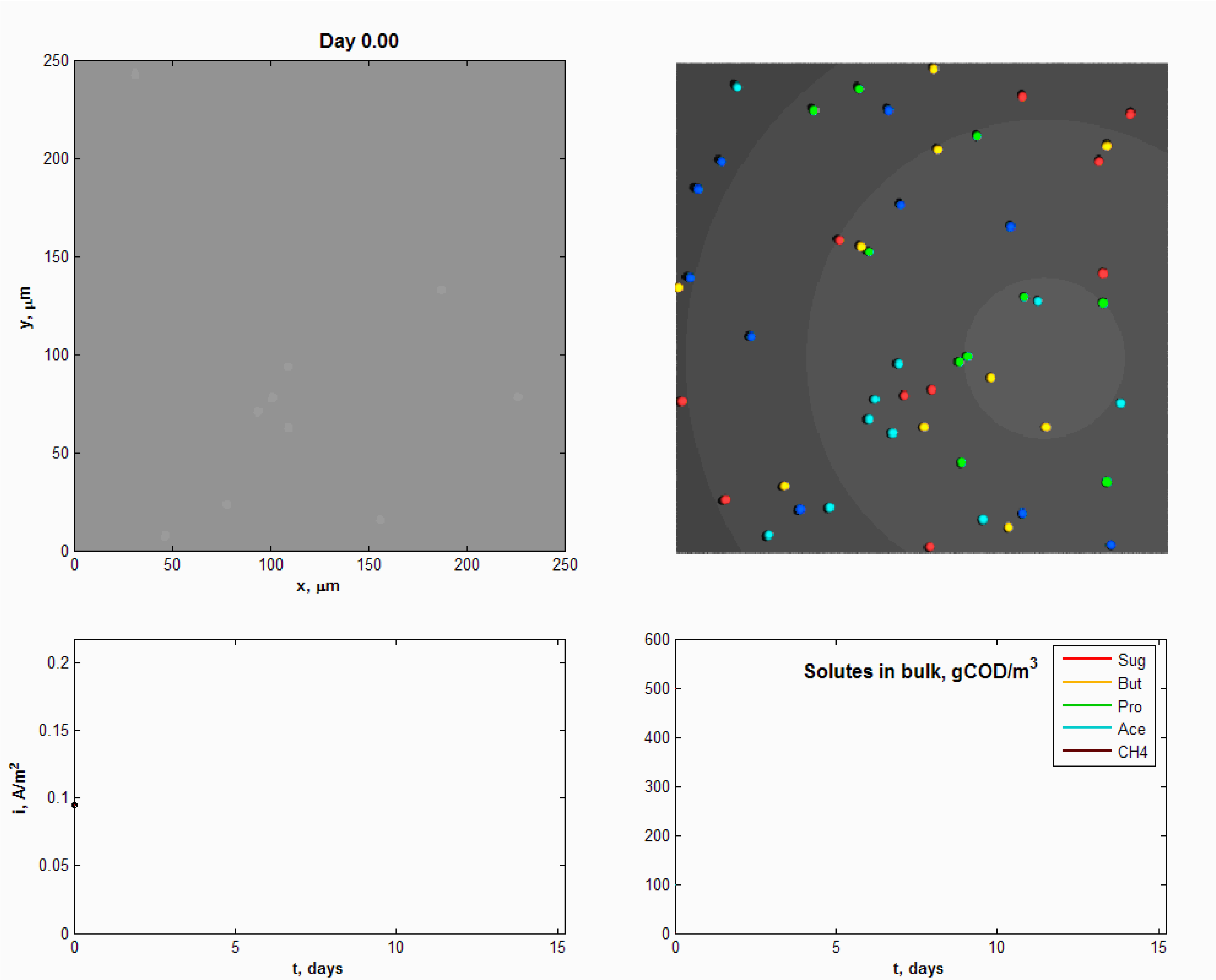
- Suck it and see!
- Building 4 replicate pilot plants
- Improved hydrogen retention
- Improved cathodes



Long term: modelling



EPSRC Frontier! Long term multi-scale modelling with individual based foundation



Picioreanu, C., Head, I.M., Katuri, K.P., van Loosdrecht, M.C.M., Scott, K. (2007). A computational model for biofilm-based microbial fuels cells. Water Research 41, 2921-2940

Examples of Important work by other groups

- Animal wastes
  - Lars Angenent
- Nutrient Removal
  - Wetsus
- Novel applications
  - Bruce Logan
- Novel cathode processes
  - Korneel Rabaey

Summary

- Wastewater contains 4 x more energy than required to treat it.

- MEC one possible solution
  - Process fundamentals are obscure
  - Most “practical research” is unrealistic

- Progress needs:
  - Cheap materials
  - Realistic Trials
  - Fundamental investigation leading to
  - New generation of models