

주 제 발 표

미생물연료전지의 현황과 발전전망

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환경에너지기술의 필요성

The collage consists of several elements:

- Top Left:** A graph with two y-axes. The left axis is 'Annual increments' (0 to 100) and the right axis is 'Billions' (0 to 10). The x-axis is 'Year' (1750 to 2000). A bar chart shows 'Population increment' and a line graph shows 'Annual increments'.
- Top Center:** A globe with the text 'Earth' and 'Environmental Energy Technology' overlaid.
- Top Right:** A group of people with the text 'Humans' overlaid.
- Bottom Left:** A diagram titled 'Greenhouse gases (GHG) and their sources' showing various sources like fossil fuel combustion, hydrofluorocarbons, HFCs, PFCs, and SF₆.
- Bottom Center:** A group of people with the text 'Humans' overlaid.
- Bottom Right:** Two images showing waste management: a pile of trash and a truck dumping waste.

Text overlays on the collage include:

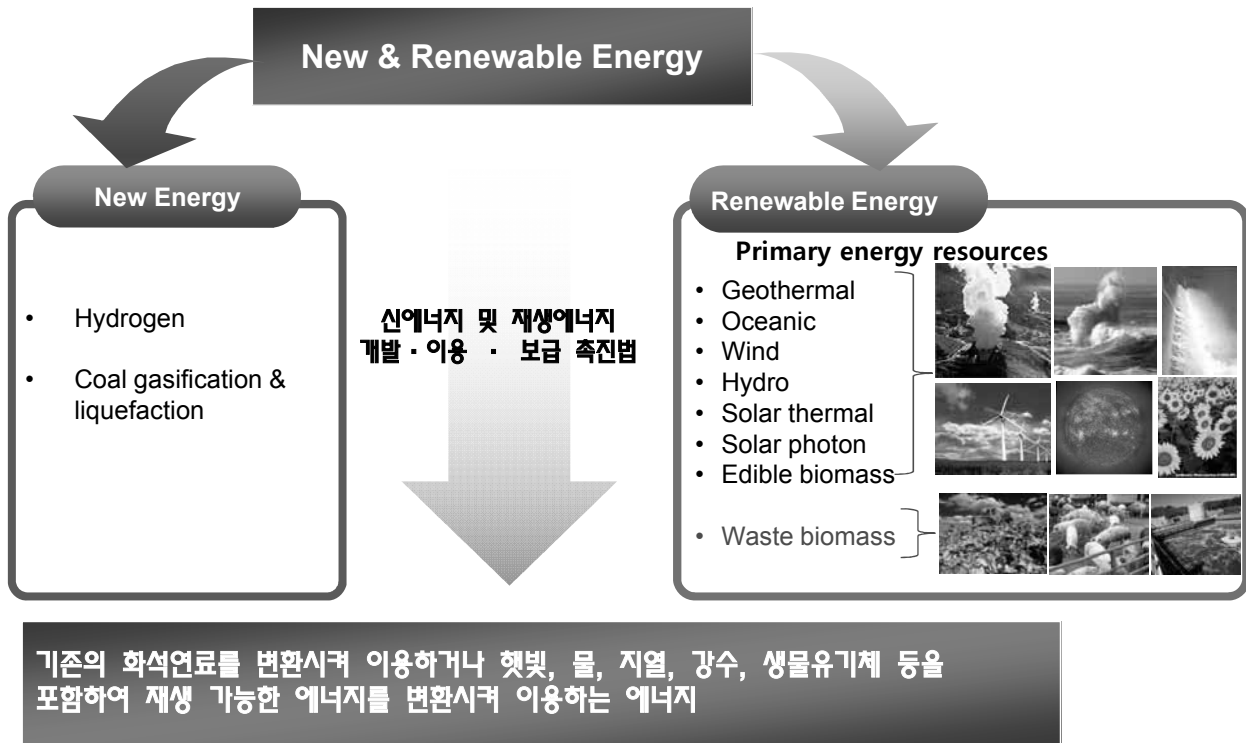
- Population increment
- Annual increments
- Earth
- Humans
- Environmental Energy Technology
- for environmental protection & energy generation
- Greenhouse gases (GHG) and their sources
- Wastes from human activities

Annual Greenhouse Gas Emissions by Sector

Wastes from human activities

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신재생에너지란?



자연계에 존재하는 다양한 1차 에너지와 그 변환 기술(1)



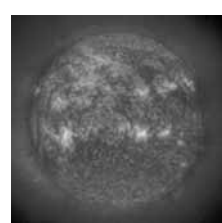
Potential energy



kinetic energy



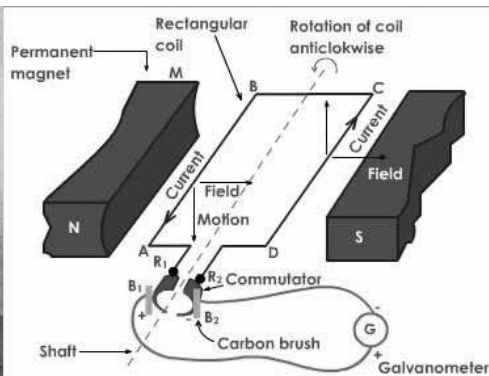
Geothermal energy



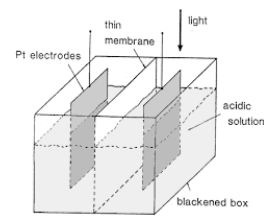
Photon



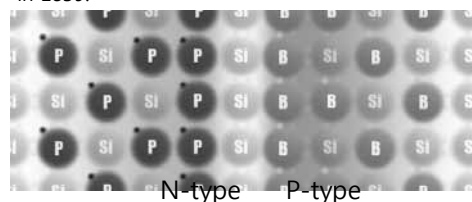
Michael Faraday (1791-1867) invented the generator in 1831.



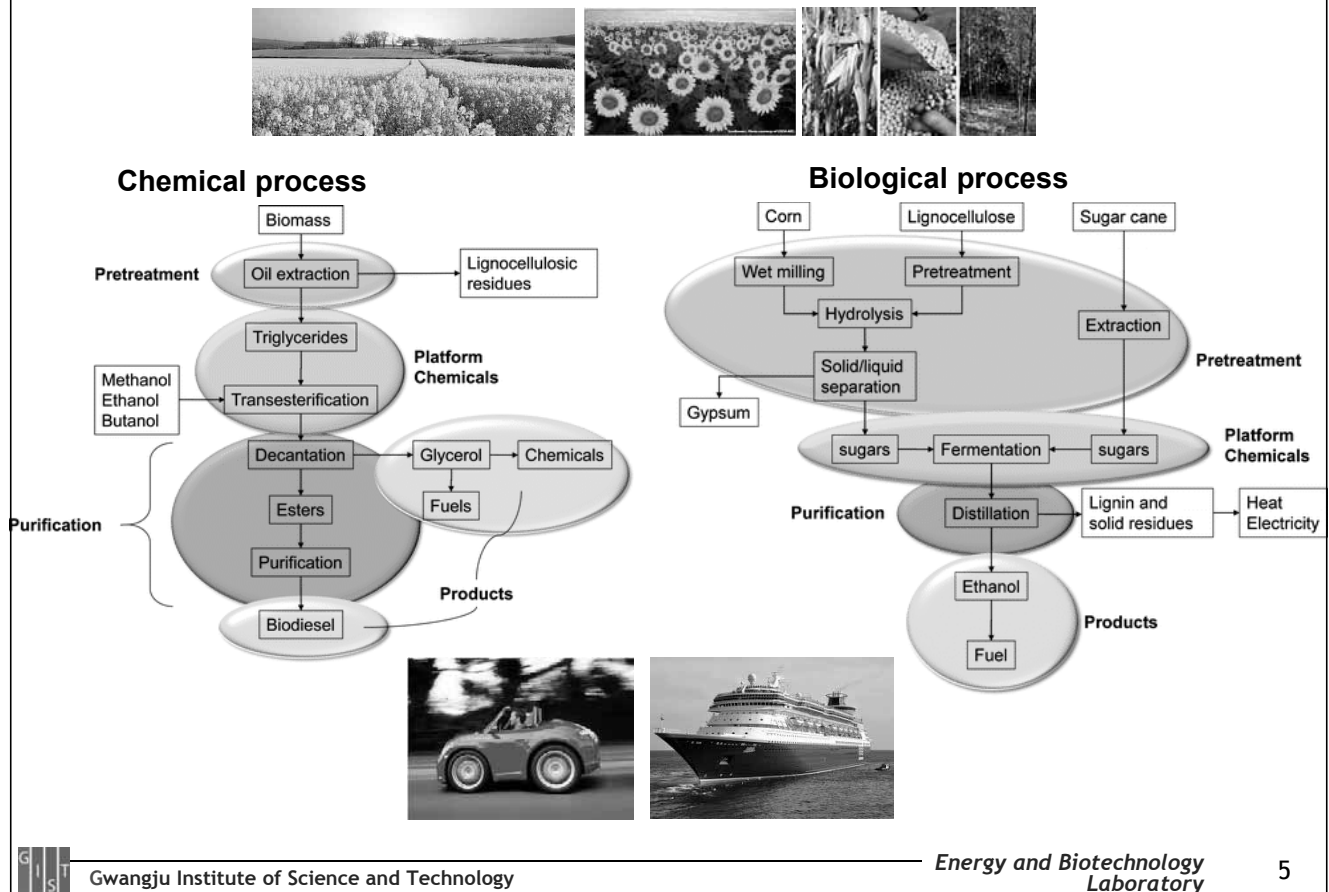
(1820-1891)



The photovoltaic effect was first observed by French physicist, Alexandre-Edmond Becquerel, in 1839.



자연계에 존재하는 다양한 1차 에너지와 그 변환 기술(2)



자연계에 존재하는 다양한 1차 에너지와 그 변환 기술(3)



Source, <https://www.google.com>; keywords: forest waste, food waste, municipal waste, industrial waste, livestock waste

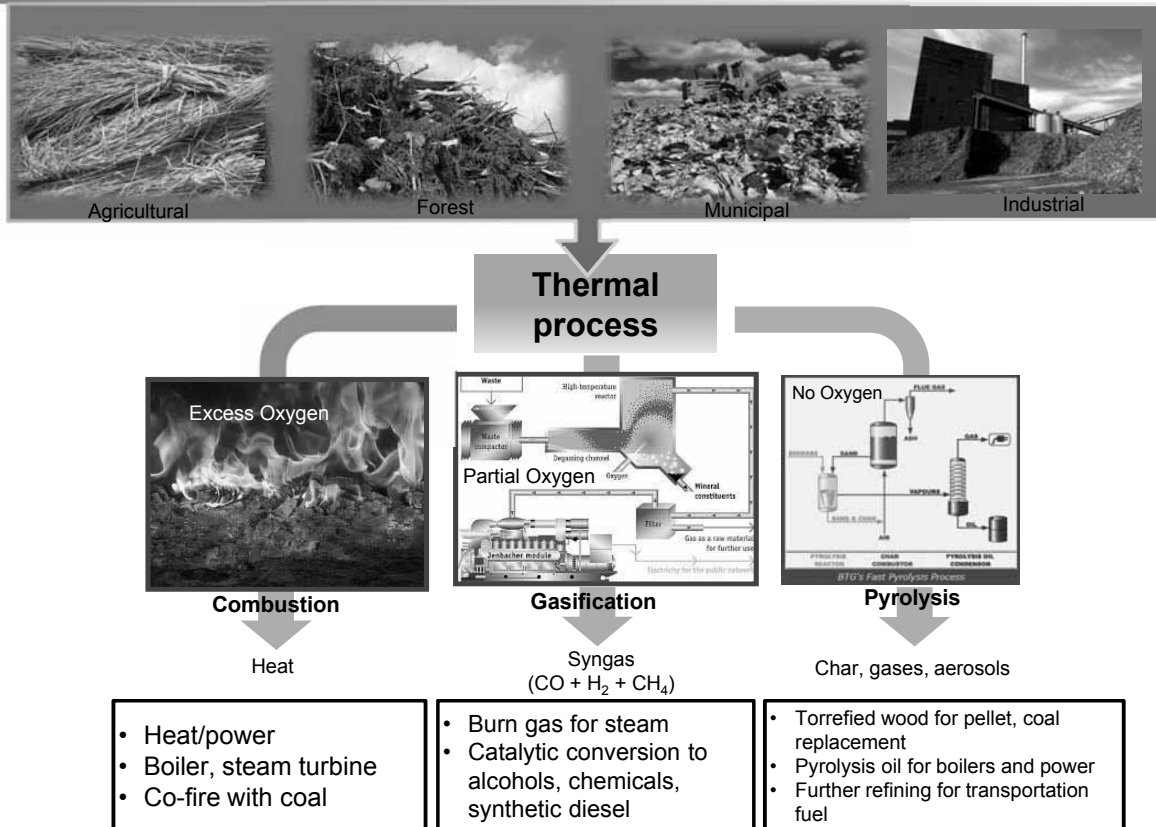
Bioresource Technology

Thermal vs Biological

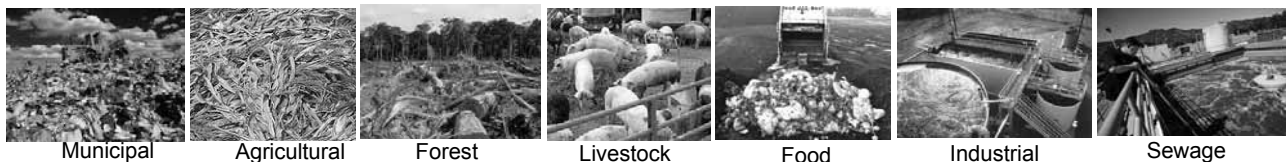


Source, <https://www.google.com>; keywords: forest waste, food waste, municipal waste, industrial waste, livestock waste

폐 바이오매스 에너지 전환 기술(1)



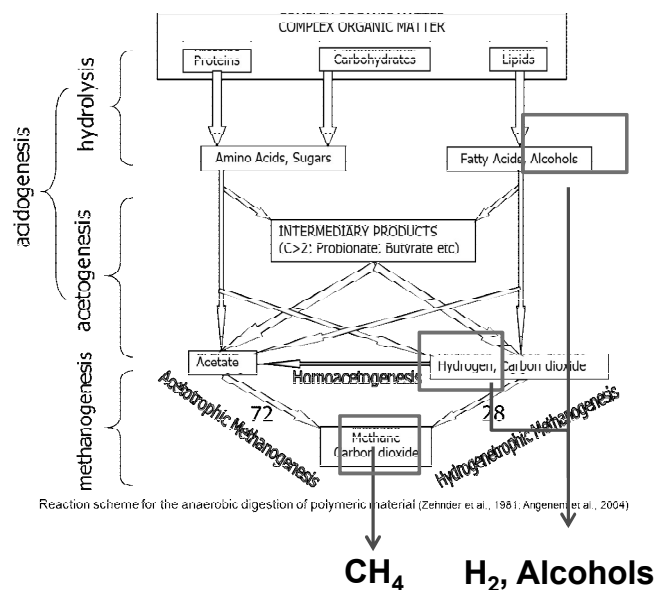
폐 바이오매스 에너지 전환 기술(2)



Landfill gas recovery

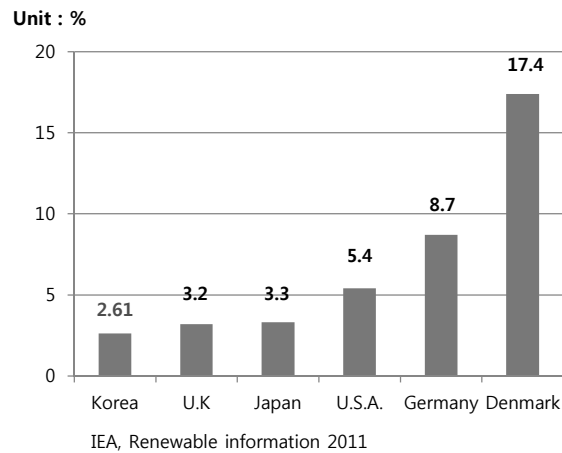


Anaerobic digester



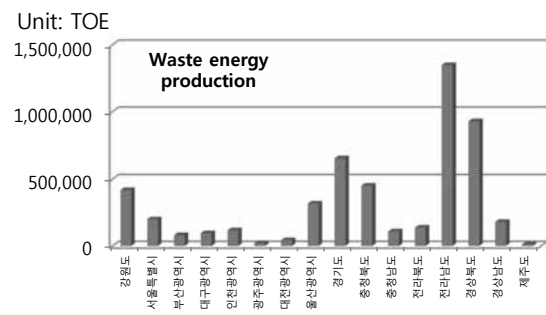
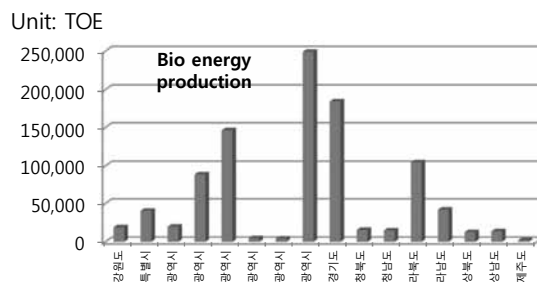
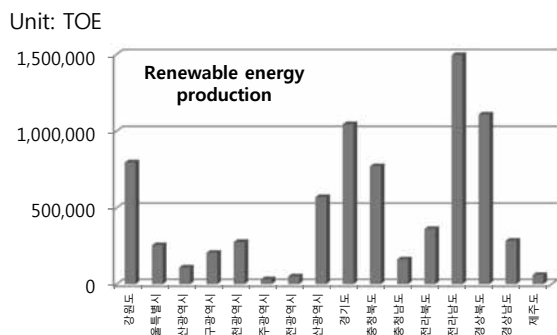
Reaction scheme for the anaerobic digestion of polymeric material (Zehnder et al., 1981; Angenent et al., 2004)

주요국 신재생에너지 공급비중(2010년)



➤ 2030년까지 신재생에너지 공급비중 11%까지 확대

국내 지역별 신재생에너지 생산량 및 비율



KOSIS (국가통계포털, 2012)

바이오에너지와 폐기물에너지의 기준 및 범위

구분	기준 및 범위		비고
바이오 에너지	기준	1. 생물유기체를 변환시켜 얻어지는 기체, 액체 또는 고체의 연료 2. 제2호의 연료를 연소 또는 변환시켜 얻어지는 에너지 ※ 제2호 또는 제3호의 에너지가 신·재생에너지가 아닌 석유제품 등과 혼합된 경우에는 생물유기체로부터 생산된 부분만을 바이오에너지로 본다.	'신에너지 및 재생에너지 개발·이용·보급 촉진법 시행령 제2조 관련 발표' 바이오에너지 등의 기준 및 범위
	범위	1. 생물유기체를 변환시킨 바이오가스, 바이오에탄올, 바이오액화유 및 합성가스 2. 쓰레기매립장의 유기성폐기물을 변환시킨 매립지가스 3. 동물·식물의 유기성(油脂)을 변환시킨 바이오디젤 4. 생물유기체를 변환시킨 펄프, 목재칩, 펠릿 및 목탄 등의 고체연료	
폐기물 에너지	기준	1. 각종 사업장 및 생활시설의 폐기물을 변환시켜 얻어지는 기체, 액체 또는 고체의 연료 2. 제2호의 연료를 연소 또는 변환시켜 얻어지는 에너지 3. 폐기물의 소각열을 변환시킨 에너지 ※ 제2호부터 제3호까지의 에너지가 신·재생에너지가 아닌 석유제품 등과 혼합되는 경우에는 각종 사업장 및 생활시설의 폐기물로부터 생산된 부분만을 폐기물에너지로 본다.	
	범위	없음	

자료: 법제처

현행의 법·제도에서 나타나는 바이오에너지와 폐기물에너지의 혼동문제를 개선하고, 바이오에너지를 활성화시키기 위하여 2013년 산업통상자원부에서는 바이오에너지 기준 및 범위설정에 관한 연구(김진오, 2013)를 통해 개선된 바이오에너지의 기준 및 범위를 제시하였으며, 이를 근거로 법 개정을 추진 중에 있다.



국내 바이오에너지 범위

구분	종류		바이오에너지의 범위
고체 바이오에너지	비성형 고체 바이오연료	목질계	장작, 목재칩, 호그 등
		임산부산물	톱밥, 잣껍질, 잔디예초물, 팜부산물 등
		농산부산물	벼짚, 보릿짚, 밀짚, 왕겨, 유채대, 콩대, 옥수수대, 땅콩껍질 등
		유기성폐기물	폐목재, 펄프 및 제지슬러지, 흑액, 하수슬러지 등
	성형 고체 바이오연료		펠릿, 브리켓, 성형탄 등
액체 바이오에너지	열분해 고체 바이오연료		목탄, 바이오차 등
	휘발유 대체 바이오연료		바이오에탄올, ETBE(47%이상), 바이오부탄올, 에스테르 바이오연료, F-T가솔린 등
	경유 대체 바이오연료		바이오디젤(FAME), 수첨 바이오디젤(HBO), 바이오 DME, 바이오 F-T디젤, 목질계 디젤 등
	기타 바이오연료		식물성 기름(PVO), 액화 바이오메탄, 바이오항공유 등
기체 바이오에너지	혐기소화가스	매립지가스	쓰레기매립장의 유기성 폐기물을 변환시킨 매립지 가스
		하수슬러지가스	하수슬러지를 혐기소화시켜 얻어지는 하수슬러지 가스
		기타혐기소화가스	기타 생물유기체(가축분뇨, 음식물쓰레기 등)를 혐기소화시켜 얻어지는 혐기소화 가스
	합성가스		생물유기체를 열화학적으로 변환시켜 얻어지는 합성가스

자료: 김진오 등, 2013

유기성 폐바이오매스로부터 전기를 생산하는 미생물연료전지

"Waste Biomass to Energy" Technologies



Livestock waste



Food waste

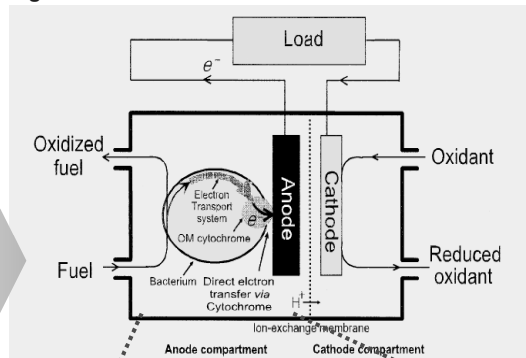


Industrial waste

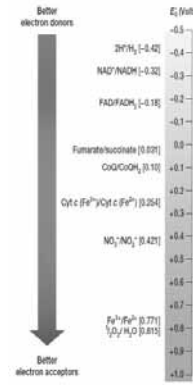


Municipal waste

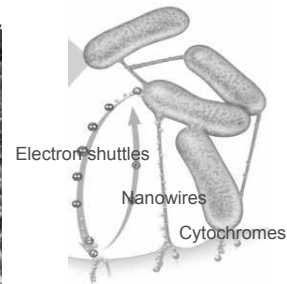
FUEL



Working principle for microbial fuel cell (left); redox tower for estimation of available voltage in MFCs (right).



Electrochemically active bacteria (EAB) producing electrons and protons on the bioanode (left); electron transfer mechanisms of EAB (right)

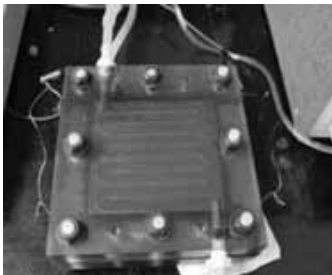


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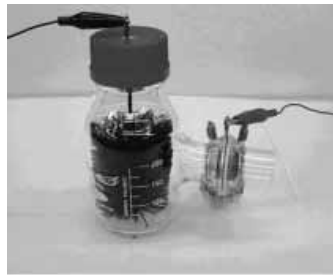
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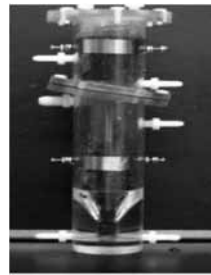
하 · 폐수 처리용 Lab-Scale 미생물연료전지와 성능



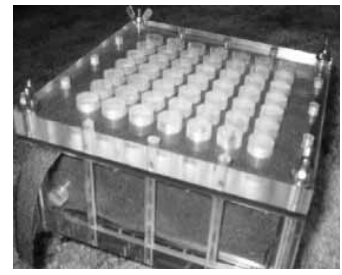
COD 제거효율 : 79%
전력생산 : $72 \pm 1 \text{ mW/m}^2$
(Min et al. 2004)



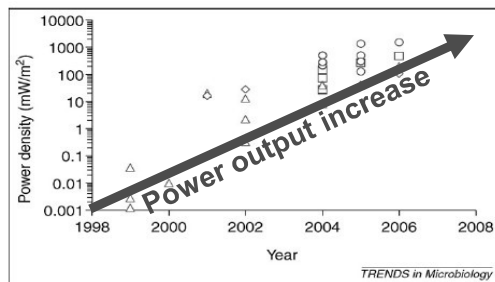
전력생산 : 2400 mW/m^2
(Logan et al. 2004)



COD 제거효율 : 90%
전력생산 : 170 mW/m^2
(He et al. 2005)

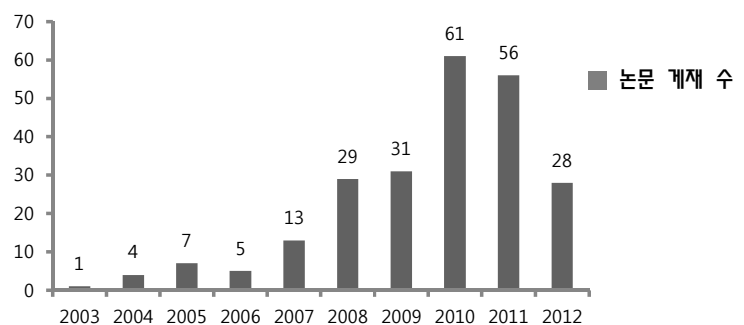


전력생산 : 2200 mW/m^3
(Liu et al. 2007)



➢ COD 처리효율: 80~90% 이상의 처리효율 유지
➢ 전력생산: $72 \sim 2400 \text{ mW/m}^2$

최근 10년간 하 · 폐수 처리용 미생물연료전지 연구 현황



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다양한 실패수를 이용한 미생물연료전지 성능 비교

Comparison in the performance of MFCs operated with different waste-water.

Types of substrates	COD (mg/L)	Types of MFCs	Max. power density (mW/m ²)	Coulombic efficiency (%)	Current density (mA/cm ²) at max. power	Reference
Swine wastewater	8,320	One-chamber MFC	261	8	0.015	Min et al. (2005)
Starch	10	Two-chambered MFC with ferricyanide catholyte	n.a.	n.a.	1.3	Niessen et al. (2004)
Landfill leachate	6000	Two-chambered MFC	n.a.	n.a.	0.0004	Greenman et al. (2009)
Livestock manure	n.a.	One reactor vessel of manure	n.a.	n.a.	0.004	Scott & Murano (2007)
Domestic W.W	600	One-chamber air-cathode MFC	146	n.a.	0.06	Wang et al. (2009a)
Brewery W.W	2240	One-chamber air-cathode MFC	205	10	0.2	Feng et al. (2008)
Beer brewery W.W	600	One-chamber air-cathode MFC	669	10	0.18	Wen et al. (2009)
Chocolate industry W.W	1459	Two-chambered MFC with ferricyanide as catholyte	1500	NP	0.302	Patil et al. (2009)
Food processing W.W	1672	Two-chambered MFC	n.a.	n.a.	0.05	Oh and Logan (2005)
Protein-rich W.W	1750	Two-chambered MFC	n.a.	n.a.	0.008	Liu et al. (2009)
Real urban W.W	330	Separate anolyte (1000 cm ³) & catholyte chambers (100 cm ³) connected with a salt bridge	n.a.	n.a.	0.018	Rodrigo et al. (2007)
Starch processing W.W	4852	One-chamber air-cathode MFC	239	8	0.09	Lu et al. (2009)



미생물연료전지 Pilot-Plant



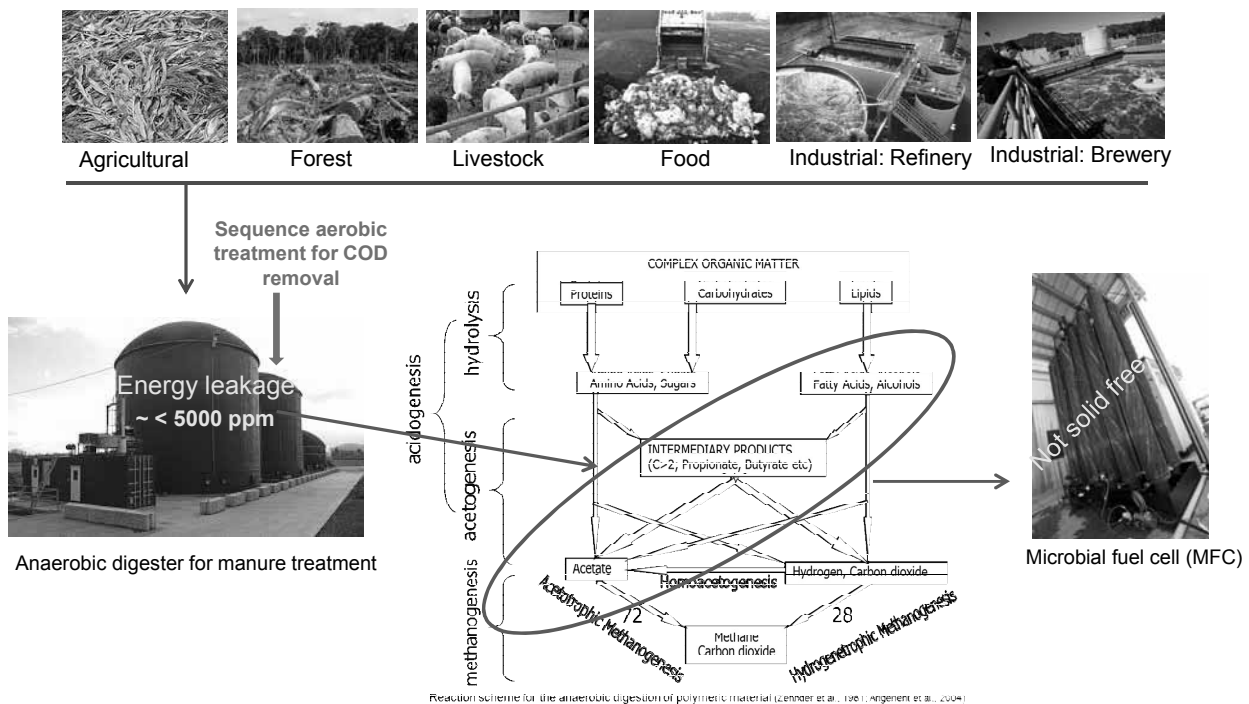
-호주의 Keller and Rabaey (2008) 등에 의해 운전된 맥주공장 발생 폐수 처리용 미생물연료전지 pilot-plant; COD 제거효율이 98%로 높은 반면 전력 생산 능력은 500 mW/m²로 아세테이트 기반 lab-scale 미생물연료전지 성능의 1/5 수준임.

Scale-up이 실패한 이유

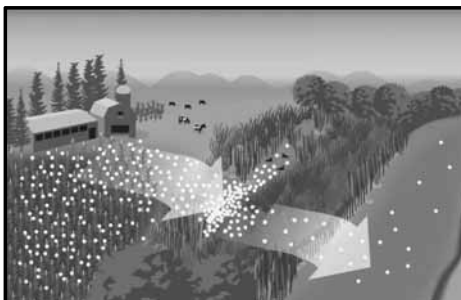
- 낮은 conductivity에 의한 음전극과 양전극 사이의 내부저항 증가
- 불안정한 전극반응
- 낮은 수소이온 농도구배
- 연료로 사용되는 폐수의 유기물 농도 및 유기물 입자크기



미생물연료전지 성능향상을 위한 혐기성공정 병합 전략



부영양화 유발 물질 회수를 위한 미생물연료전지



<http://blogs.edf.org/growingreturns/2014/08/06/lake-eris-fertilizer-problem-isnt-over-but-were-working-on-it/>

- Utilization as a fertilizer for growth of agricultural crops
- Environmental problems such as eutrophication and acidification (Arredondo et al., 2015)

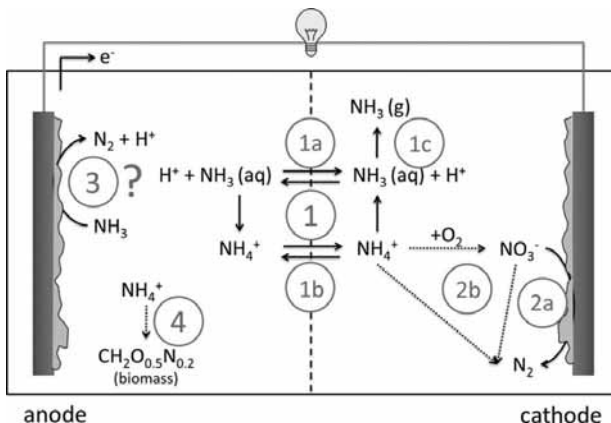
→ Need to be removed or recovered



<http://www.thewaterstour.com/prevention-learning-from-a-canadian-case-study-in-eutrophication/>

<http://www.greenpackonline.org/english/environmental-components.php?id=03-03-02>

미생물연료전지를 이용한 축산폐수 암모니아 회수 원리



anode

cathode

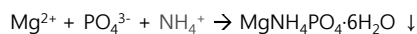
Fig. 3. Overview of the ammonia removal mechanisms in an MFC. (Kuntke et al., 2012)

- Transported through the membrane
 - Passively via diffusion of ammonia
 - or actively via migration in the form of ammonium
 - ammonia loss by evaporating into its gaseous form as a result of the elevated pH in the cathode
- Biological treatment at cathode
 - At the cathode chamber, it can be (biologically) oxidized by oxygen and denitrified by microorganisms at the cathode (denitrification)
 - or in solution – the dashed lines show processes that are independent of the electrodes.
- At the anode, it has been suggested that ammonia can be directly nitrified/denitrified to nitrogen gas by microorganisms.
- In the anode or cathode, ammonium can be incorporated in biomass for growth.



• Struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$)

- ✓ directly usage of slow release fertilizer
- ✓ recovery of P source



• Ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$)

- ✓ fertilizer for alkaline soils
- ✓ many applications in the chemical, wood pulp, textile, and pharmaceutical industries.

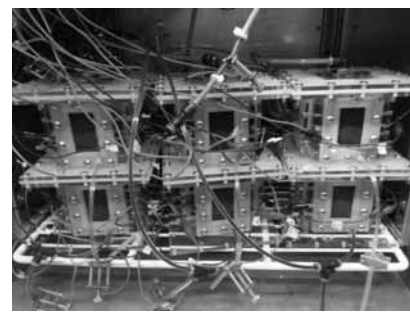


축산폐수 암모니아 회수를 위한 미생물연료전지 시스템



MFC-feeding ADs

Fuel supply



MFCs for ammonia recovery (Bioresource Technology, Kim et al., 2015)

Table 2. Ammonia recovery efficiency in CCM and OCM for 192 h.

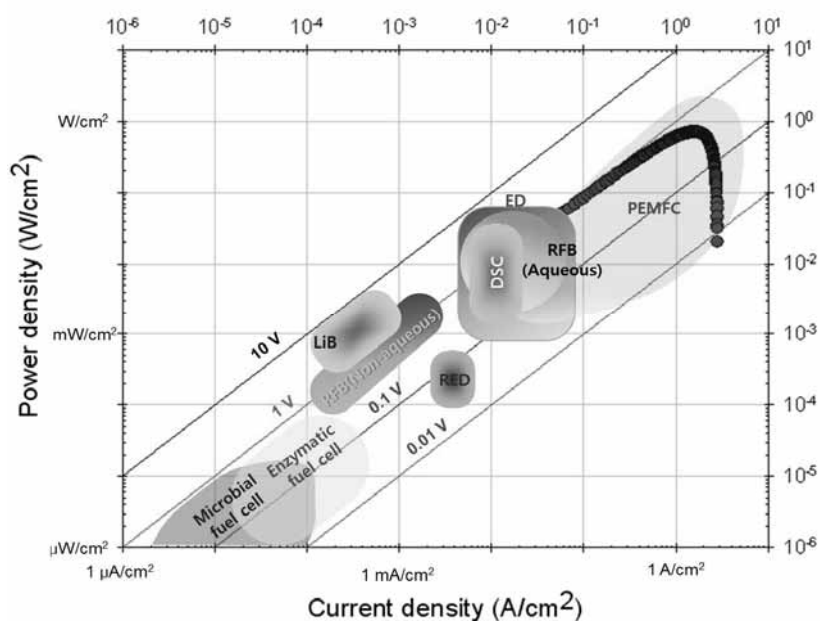
	Ammonia recovery efficiency in CCM (%)	Ammonia recovery efficiency in OCM (%)
pH 7	59.4	37.3
pH 8	59.1	53.2
pH 8.6	66.8	73.1

Table 3. Ammonia recovery efficiency by NH_4^+ migration and energy efficiency in the MFCs for 192 h.

	Ammonia recovery efficiency by NH_4^+ migration (%)	Energy efficiency by NH_4^+ migration (%)	Ammonia removal by biological paths (%)
pH 7	23.3	27.4	36.1
pH 8	5.0	7.0	54.1
pH 8.6	< 5.0	< 7.0	> 61.8

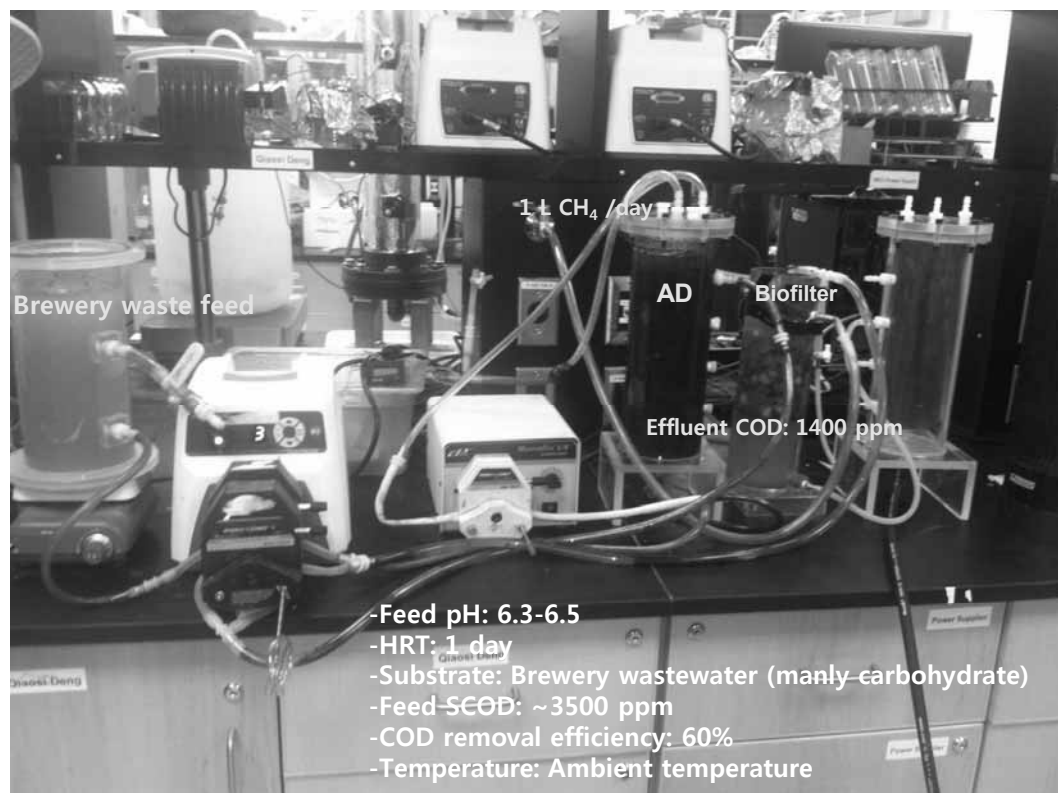
타 연료전지와의 전력밀도 비교 (2012년)

Courtesy of Prof. SH Moon (at GIST)

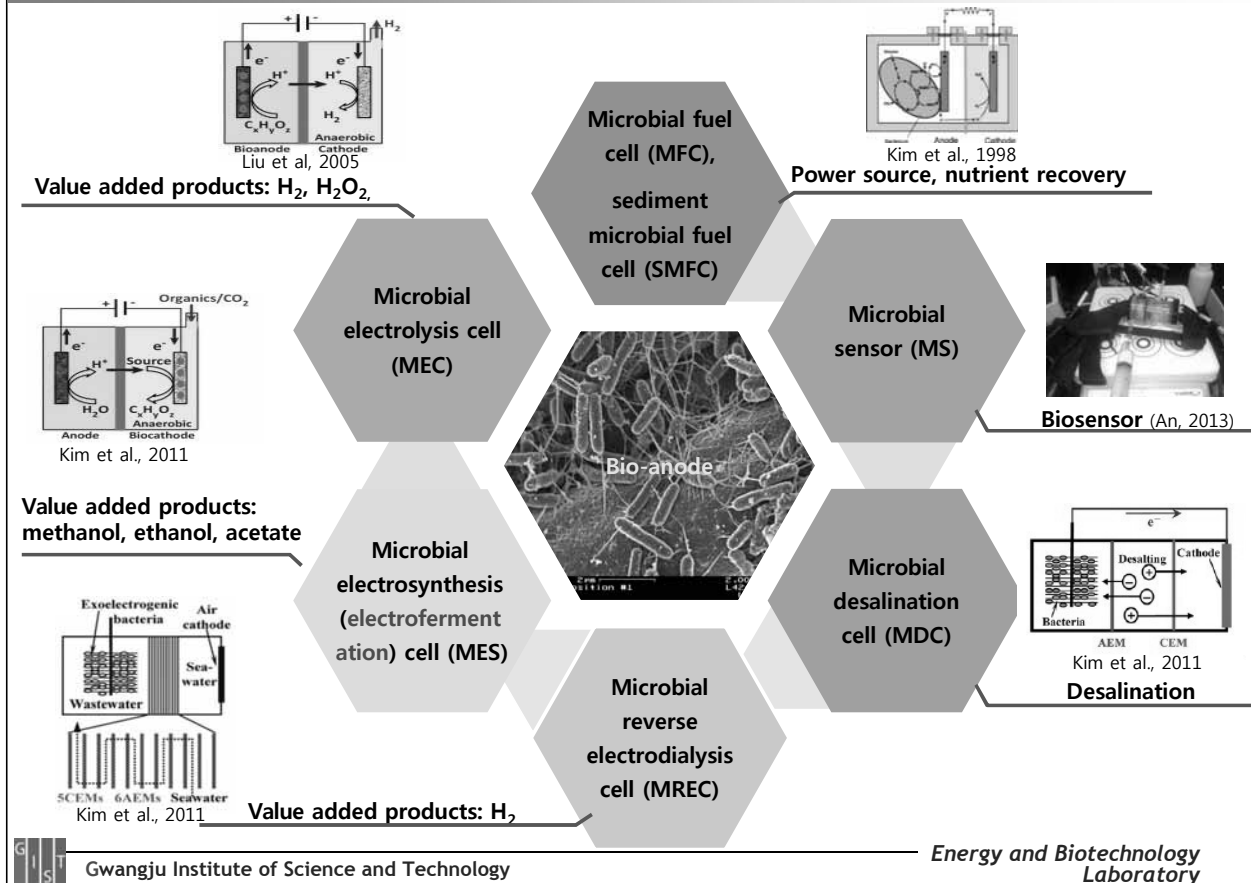


Comparison of power densities for MFCs and other chemical fuel cells

바이오전기화학전지 시스템과 병합을 위한 Packed-Bed Reactor



바이오에노드 기반 바이오전기화학전지 시스템



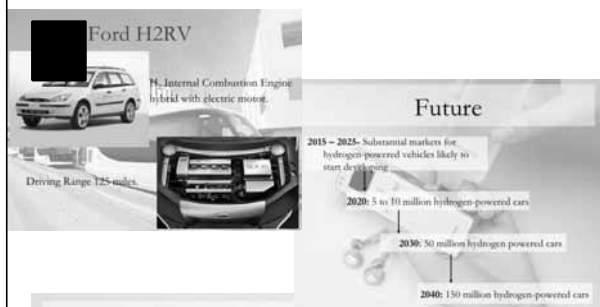
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수소와 과산화수소 생산



Hydrogen

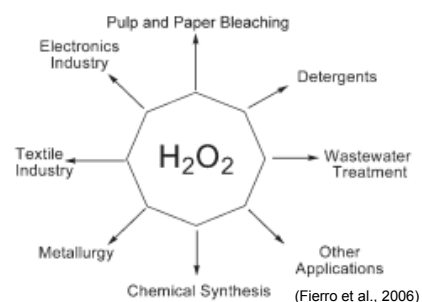


Some Limitations

- Hydrogen:
 - Not readily available, must use other energy sources to convert
 - Infrastructure not in place
 - Difficult to store/distribute
- High Capital Cost
- Non-technical barriers
 - Could have dramatic impact

(Courtesy of Saxena)

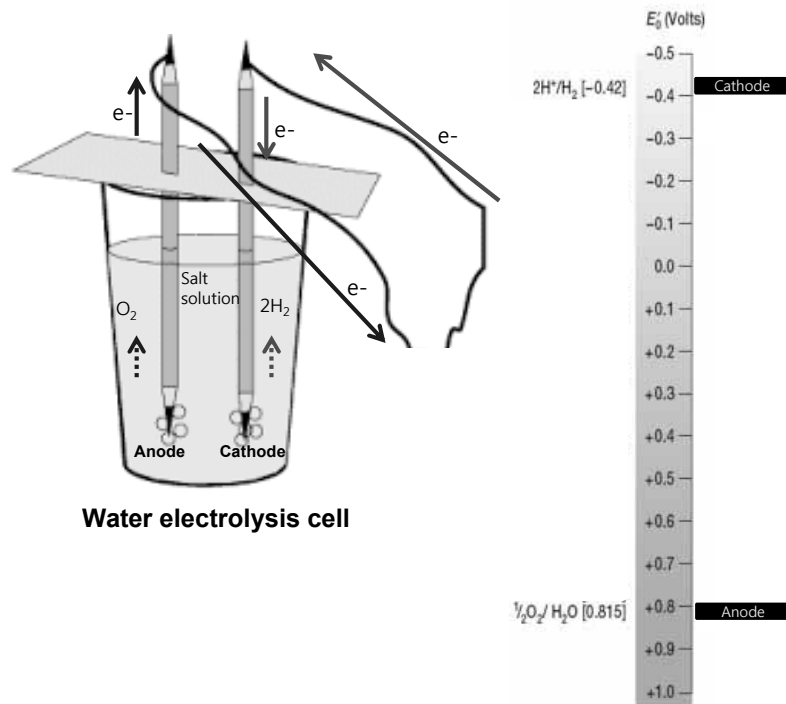
Hydrogen Peroxide



Source: <http://www.slideshare.net/>

Electrolysis Cells

* Assumption: No energy loss in the cell



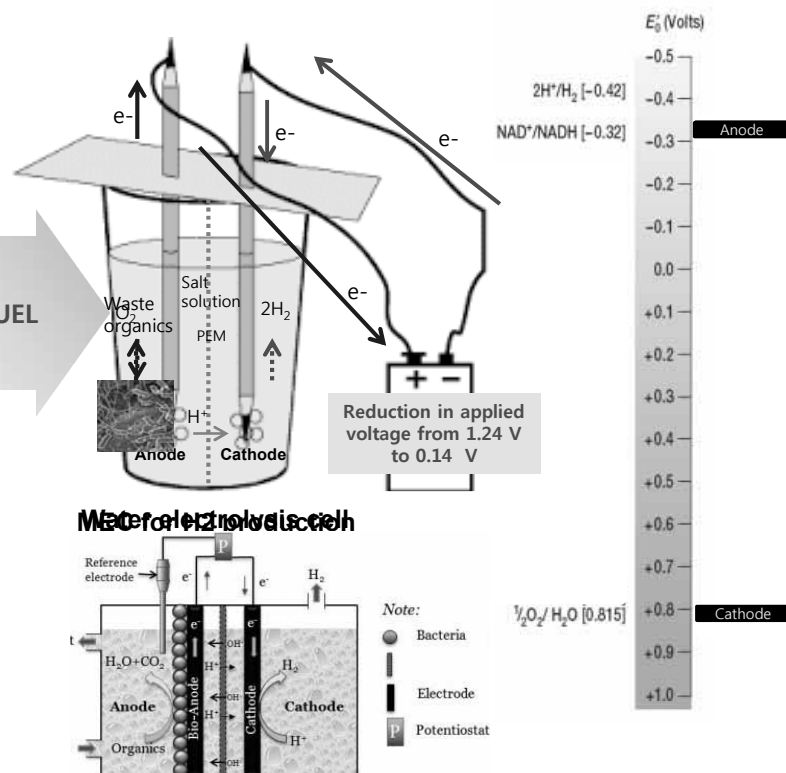
Water electrolysis cell

Water Electrolysis Cell to MEC

* Assumption: No energy loss in the cell



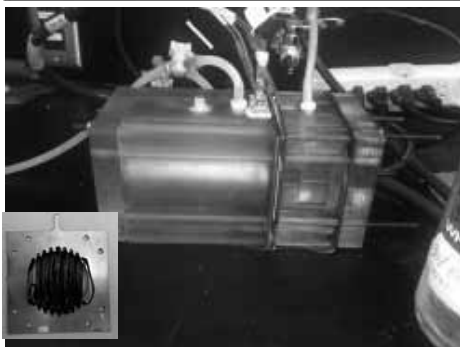
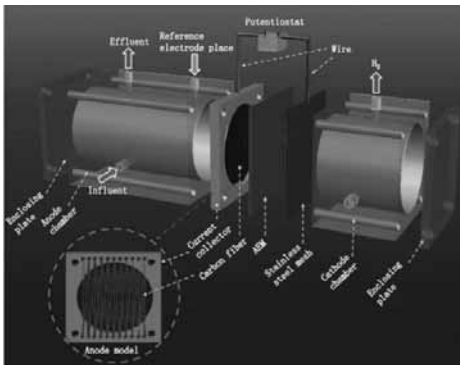
FUEL



Microbial Electrochemical Cell

Note:
 Bacteria
 Electrode
 Potentiostat

수소 생산을 위한 MEC



MEC for H₂ production (RSC Advances, An et al., 2013)

Anode Chamber (289 mL):

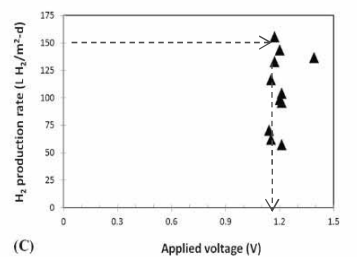
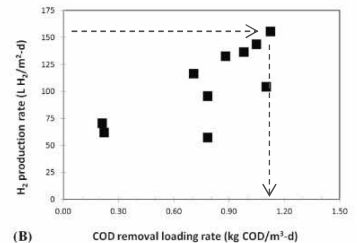
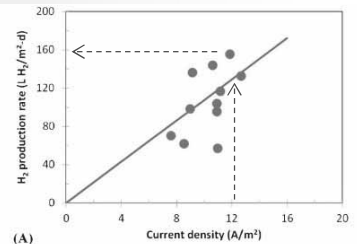
- Used anode: carbon fiber
(per projected area of a membrane: 31.7 cm²; measured surface area: 1060 cm²)
- Fed 25 mM acetate medium
- Fixed the anode potential at -0.03 V

Cathode Chamber (120 mL):

- Used cathode: stainless steel mesh
(per projected area of the membrane : 31.7 cm²)
- Filled with deionized water (18 mΩ-cm)
- Operated in a continuous mode with a loading rate of 6.3 kg COD/m³ d

Membrane:

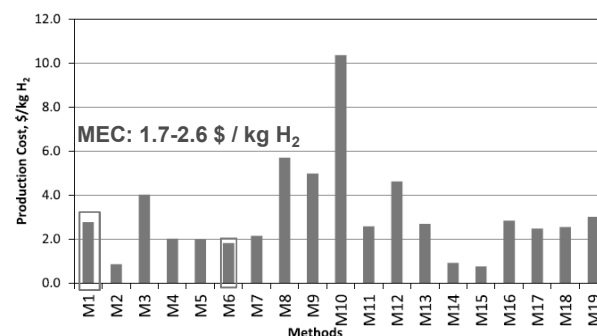
- Anion exchange
- Surface area: 33 cm²



타 기술과의 수소생산 단가 비교



Overall comparisons of selected hydrogen production methods (Normalized).				
Method		Energy efficiency	Exergy efficiency	Cost
M1	Electrolysis	5.30	2.50	7.34
M2	Plasma arc decomposition	7.00	3.20	9.18
M3	Thermolysis	5.00	4.00	6.12
M4	Thermochemical water splitting	4.20	3.00	8.06
M5	Biomass conversion	5.60	4.50	8.10
M6	Biomass gasification	6.50	6.00	8.25
M7	Biomass reforming	3.90	2.80	7.93
M8	PV electrolysis	1.24	0.70	4.50
M9	Photocatalysis	0.20	0.10	5.19
M10	Photoelectrochemical method	0.70	0.15	0.00
M11	Dark fermentation	1.30	1.10	7.52
M12	High temperature electrolysis	2.90	2.60	5.54
M13	Hybrid thermochemical cycles	5.30	4.80	7.41
M14	Coal gasification	6.30	4.60	9.11
M15	Fossil fuel reforming	8.30	4.60	9.28
M16	Biophotolysis	1.40	1.30	7.27
M17	Photofermmentation	1.50	1.40	7.61
M18	Artificial photosynthesis	0.90	0.80	7.54
M19	Photoelectrolysis	0.78	0.34	7.09
Ideal	(zero-emissions and cost, 100% efficiency)	10.00	10.00	10.00

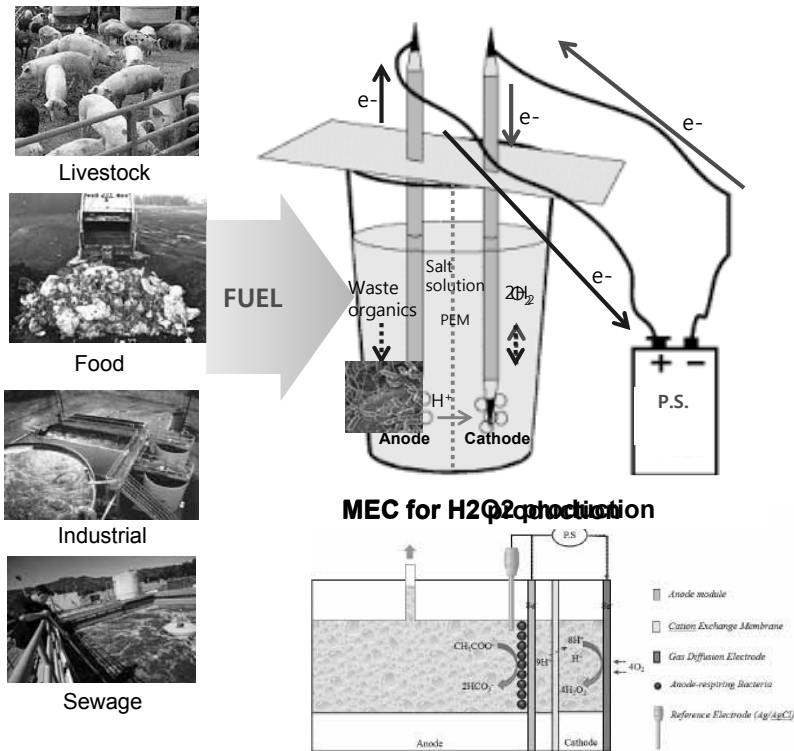


Production cost of selected hydrogen production methods (per kg of hydrogen).

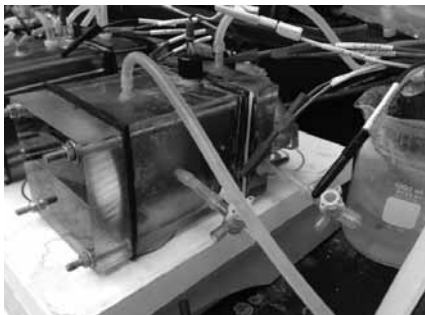


Conversion of H_2 MEC to H_2O_2 MEC

* Assumption: No energy loss in the cell



과산화수소 생산을 위한 MEC



Lab-scale MEC for H_2O_2 production (Sim et al., 2015)

Anode Chamber (289 mL):

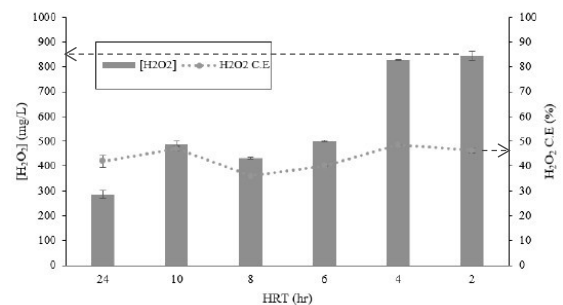
- Used carbon fibre as anode
- Fed 5 mM acetate medium at HRT 2 h, 6 h, and 10 h
- Fixed the anode potential at -0.4 V

Cathode Chamber (70 mL):

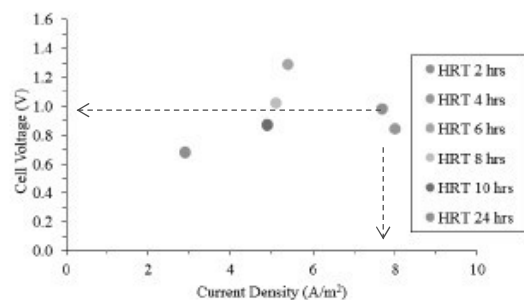
- Used gas diffusion cathode (surface area: 33 cm²)
- Filled with deionized water (18 mΩ-cm)
- Operated in a batch mode for 24h

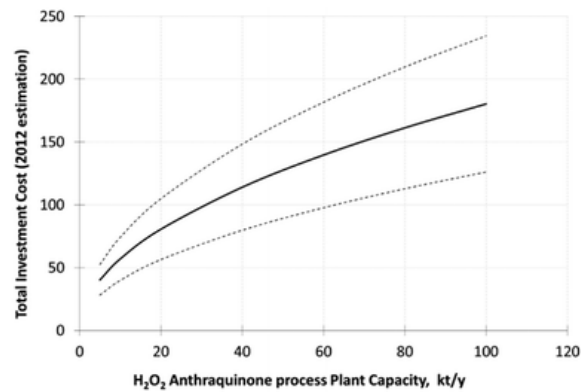
Cation exchange membrane

- Surface area: 33 cm²



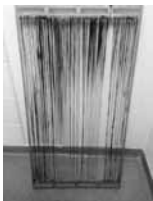
Cumulative H_2O_2 concentration and H_2O_2 conversion efficiency at 6 hr of cathode operation in the acetate-fed MEC at different HRTs (bars represent standard deviation).





- Price estimation of a H_2O_2 plant via traditional auto-oxidation process (2012 price basis).
 - 141 \$ / ton (large scale) ~ 376 \$ / ton (small scale)
- MEC: 315 \$ / ton

수소 및 과산화수소 생산을 위한 Pilot-Scale MEC



Anode module
with carbon fiber



Five anodes in
the anode chamber



Membrane
installation



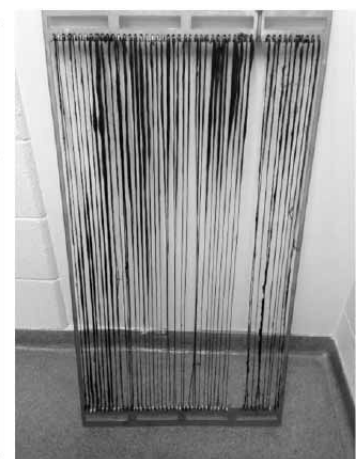
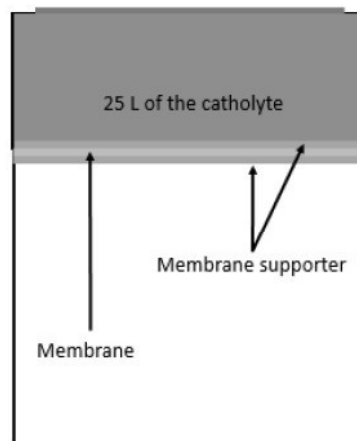
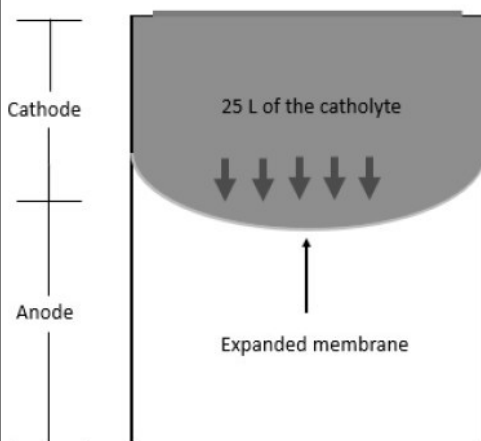
Air-cathode
installation



Leakage
checking



Colleagues

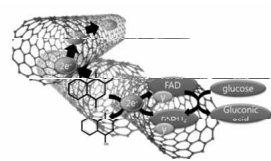


Nano/Micro/Macro Bioelectronics Platform

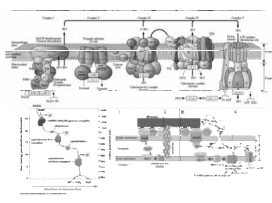
Nano-scale Bioelectronics Platform

Determination of the electron transfer system in microorganism & Finding the main mechanism of potential drop

Determination of the electron transfer system in the electrode & Search the main mechanism of potential drop



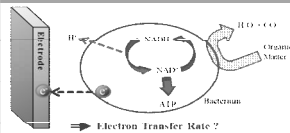
< Electron Transport System in Electrode >



Micro-scale Bioelectronics Platform

Confirmation of the electron transfer system and the theoretical maximum current density

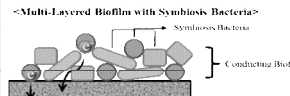
Confirmation of the electron transfer system in the biofilm (singly, multi, symbiosis)



<Single Layered Biofilm>

<Multi-Layered Biofilm>

<Multi-Layered Biofilm with Symbiosis Bacteria>



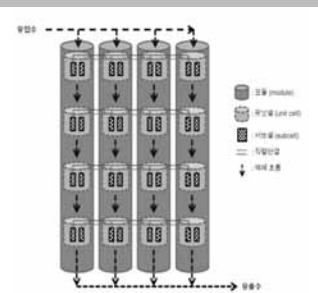
Macro-scale Bioelectronics Platform

Operation of scaling-up system as pilot plant

Specialized electrode material of bio-electronics

Specialized current collector of bio-electronics

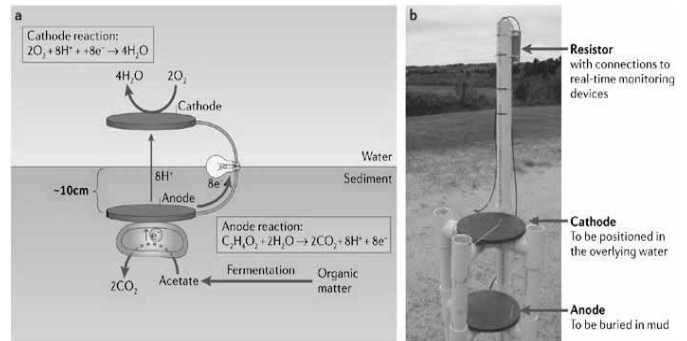
Specialized separator of bio-electronics



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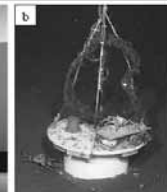
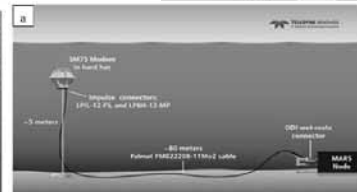
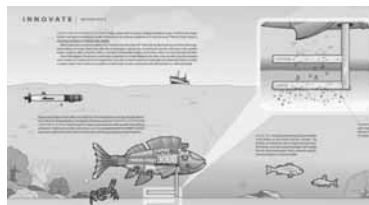
퇴적토로부터 전기를 생산하는 미생물연료전지



Center for Biological and Molecular Science and Engineering
Naval Research Laboratory, USA



Ocean Ecology and Biogeochemistry, USA



Aquatic sensors being driven with SMFCs (for the detection of a torpedo (upper); for temperature monitoring (lower))

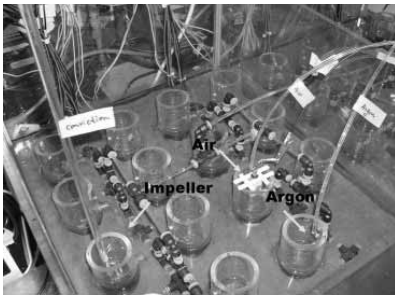


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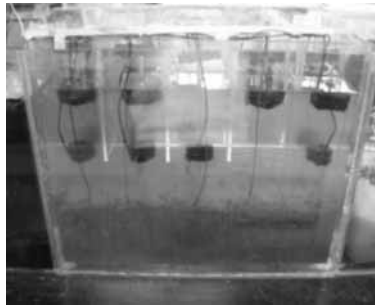
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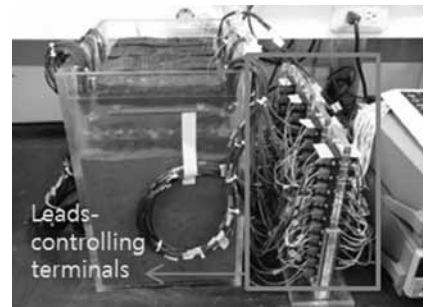
국내외 퇴적토 미생물연료전지 성능 비교



Marine mud batteries (JEM, 2010)
Marin mud battery: 28-20 mA/m², 0.4-0.5 V



Multi-phase MFC (ES&T, 2010)
Multi-phase MFC system: 60-30 mA/m², 0.3-0.4V



Sediment MFCs (Bioresource Technology, 2014)
Sediment MFC: 40-30 mA/m², 0.4-0.5 V

Comparison in the performance of other SMFCs that were applied to natural water systems as a power source for various sensors (An, 2012)

Year	Operation Site	Voltage and current Produced from SMFC (V, mA)	Sensor Type	Voltage and current Requirement (V, mA)
2011 (Zhang et al.)	Lake Michigan	0.4 V, 5.4 mA	Wireless temperature sensor	3.3 V, 15 mA
2011 (Donovan et al.)	Palouse River	0.35 V, 9 mA	Remote temperature sensors	5 V, 500 mA
2011 (Gong et al.)	Yaquina Bay	0.35 V, 11 mA	Oxygen & temperature sensors	5 V, 50 mA
2008 (Donovan et al.)	Palouse River	0.48 V, 5 mA	Wireless temperature sensor	3.3 V, 15 mA
2005 (Shantaram et al.)	Roskie Creek	0.4 V, 14 mA	Wireless temperature sensor	3.3 V, 15 mA



감사합니다.

