Biogas Upgrading / CO_2 Reduction Using Renewable Hydrogen and Biocatalysts

U.S. Department of Agriculture and Department of Energy
Circular Carbon Economy Summit
Denver, CO
July 24-25, 2018

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SoCalGas

- Largest U.S. natural gas distribution utility
- 140 years young
- Population 21 million
- 8,000 employees
- 1 Tcf/year

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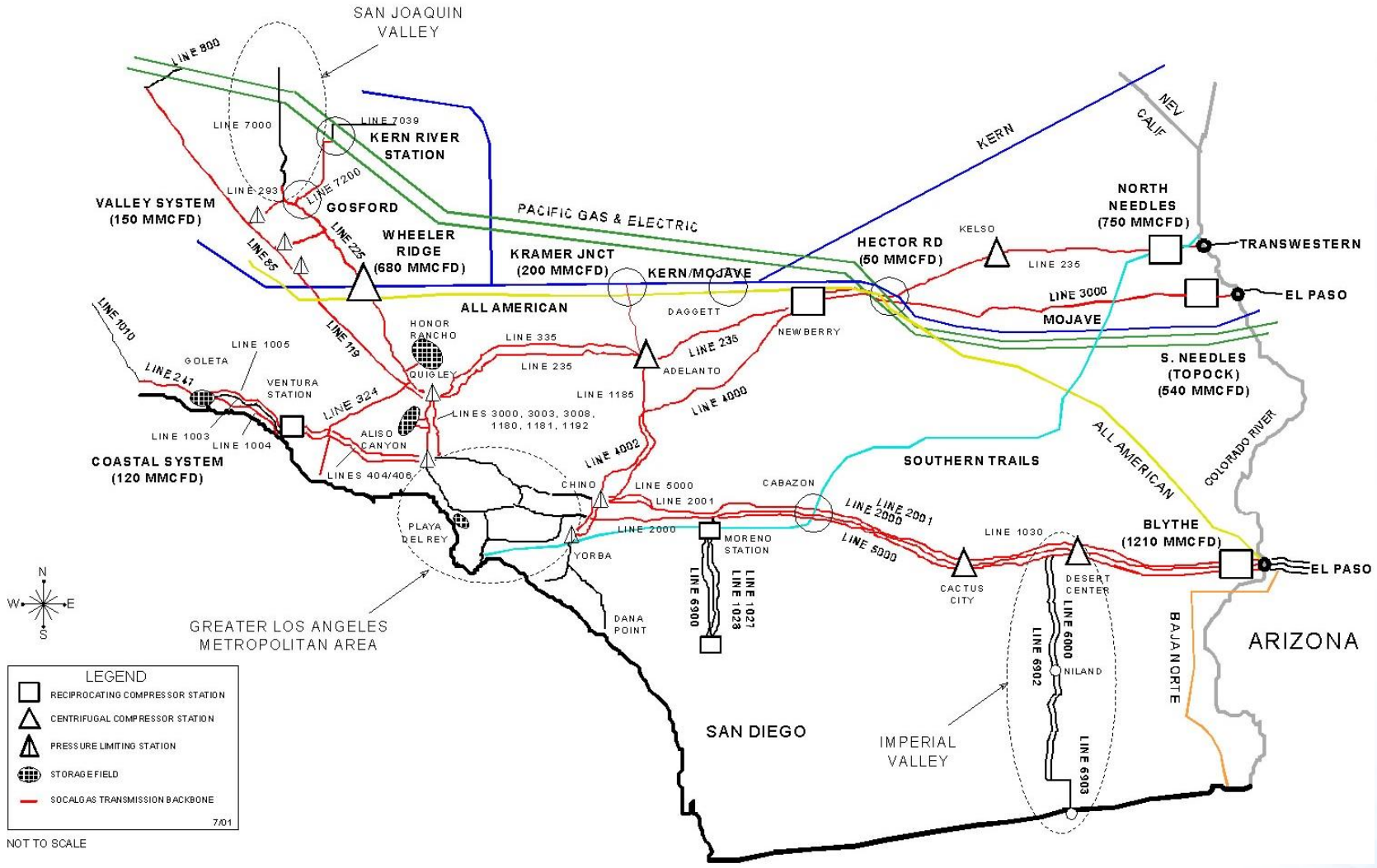
SoCalGas Transmission System



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Our Focus: Customer Needs and Emerging Trends

Industry Themes	Implications	Solutions
Affordability	• Rising utility bills • Large percentage of customers on assistance • Need to continue to provide affordable energy	• Appliance energy efficiency • Develop technologies to meet air quality standards • Utilize existing infrastructure and domestic supplies of natural gas
Air Quality / NOx	• Acute public heath problem • Transportation is 80% of NOx • Potential to replace diesel with clean fuels	• Appliance emission standards • Renewable natural gas for transportation • Low Nox engines • Fuel cells
Greenhouse Gas Emissions	• Demand for renewable gas • Wind and solar overgeneration (duck curve) • Depressed power prices • Growing need for energy storage solutions	• Renewable gas from biomass and excess wind & solar power (power-to-gas) • Hydrogen for fuel and pipeline blending • Electric and gas grid integration • Carbon up-cycling
Reliability and Safety	• Pipeline Monitoring • Leak detection • Distributed energy applications	• Enhance pipeline safety • Monitor and reduce methane emissions • Robust power reliability

RD&D

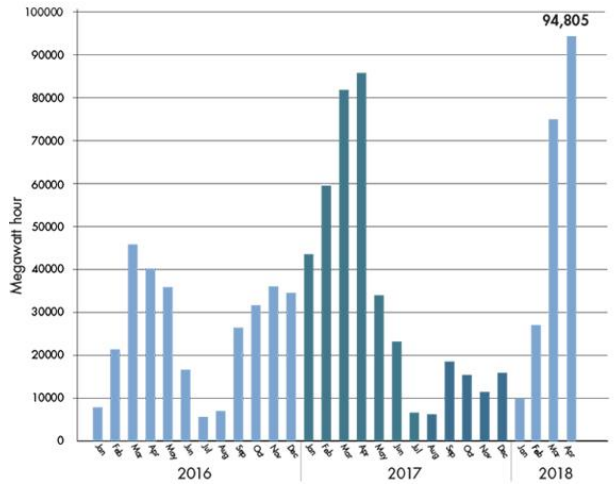
- **Objectives (PUC Code 740.1)**
  1. Environmental improvement
  2. Public and employee safety
  3. Conservation by efficient resource use or by reducing or shifting system load
  4. Development of new resources and processes, particularly renewable resources and processes which further supply technologies
  5. Improve operating efficiency and reliability or otherwise reduce operating costs

Research, Development and Demonstration (RD&D)

- End-Use Appliances
- Clean Transportation
- Emerging Technologies
- Low-carbon Resources
  - Power-to-Gas

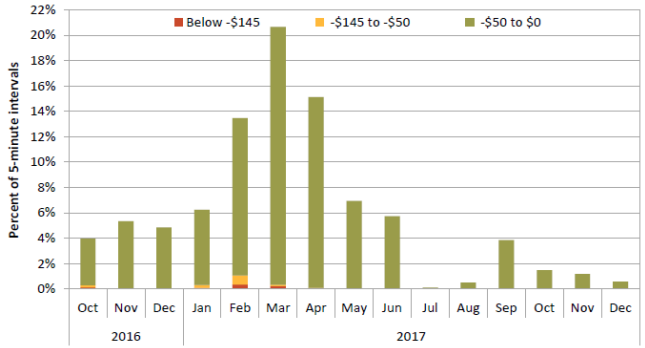
Increasing Share of Renewables Drives the Need for Long-Term Energy Storage

Monthly Power Curtailments



% of renewable generation	35%	38%	42%	50% in 2020

Frequency of Negative Power Prices



The gap between electricity supply and demand

- Overgeneration from wind and solar is creating grid congestion
- Solar and wind production vary significantly between seasons
- Europe, the US, and Australia already experience days during which electricity prices reach negative levels due to surplus wind or solar supply
- California curtailed 80 GWh of renewable energy in March 2017
- Overgeneration in peak hours exceeds evening peak demand
- With California's increased interest in moving to higher Renewable Portfolio Standards, long-term energy storage will become a large-scale need with few available solutions
- In 2017 California curtailed about 420 GWh of wind and solar production curtailments.
- Curtailments are on track to exceed 700 GWh in 2018 even while power outages are threating.

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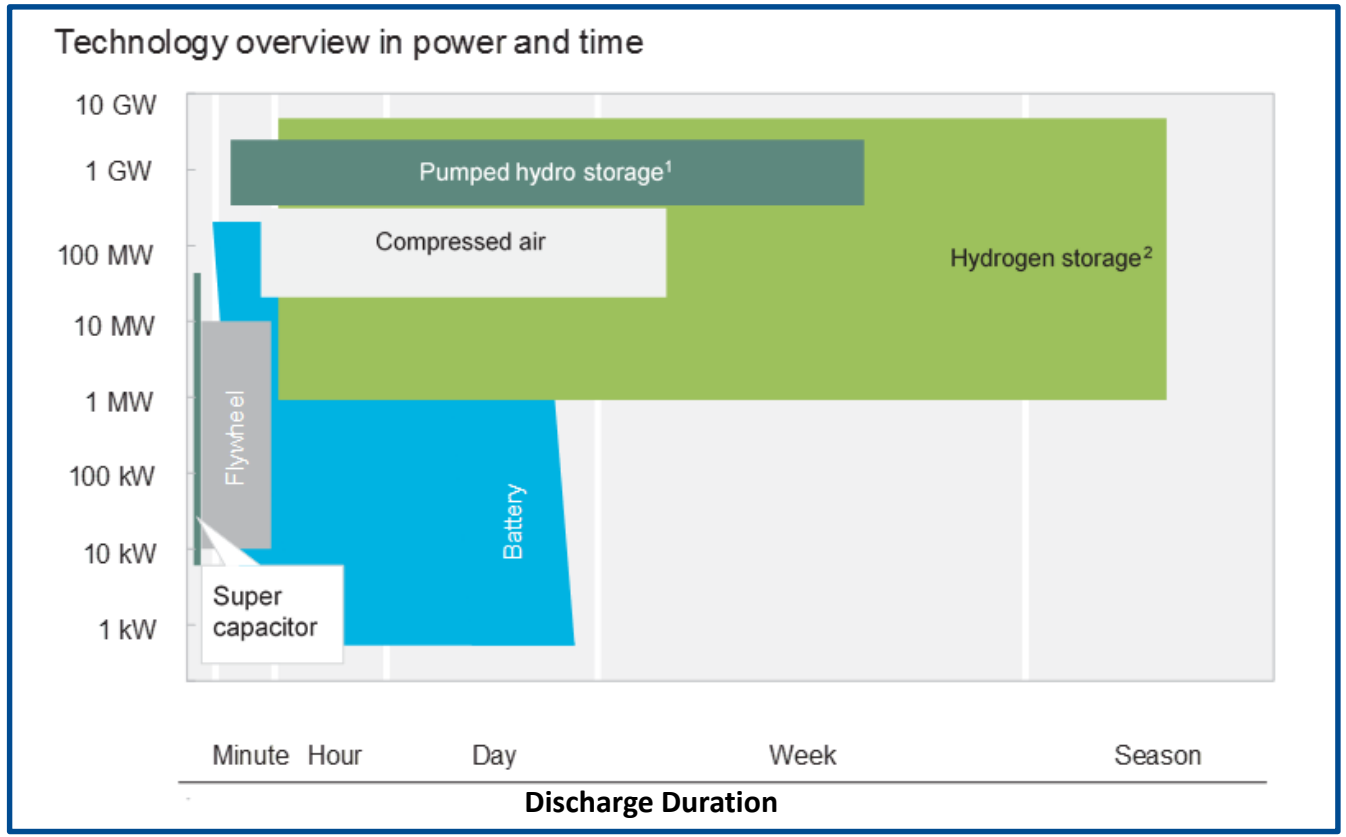
Hydrogen: Energy Storage Capabilities and Complementarity with Batteries



[1] Limited capacity (<1% of energy demand)
[2] As hydrogen or syngas
Source: IEA Energy Technology Roadmap Hydrogen and Fuel Cells

Solution: Energy Storage systems

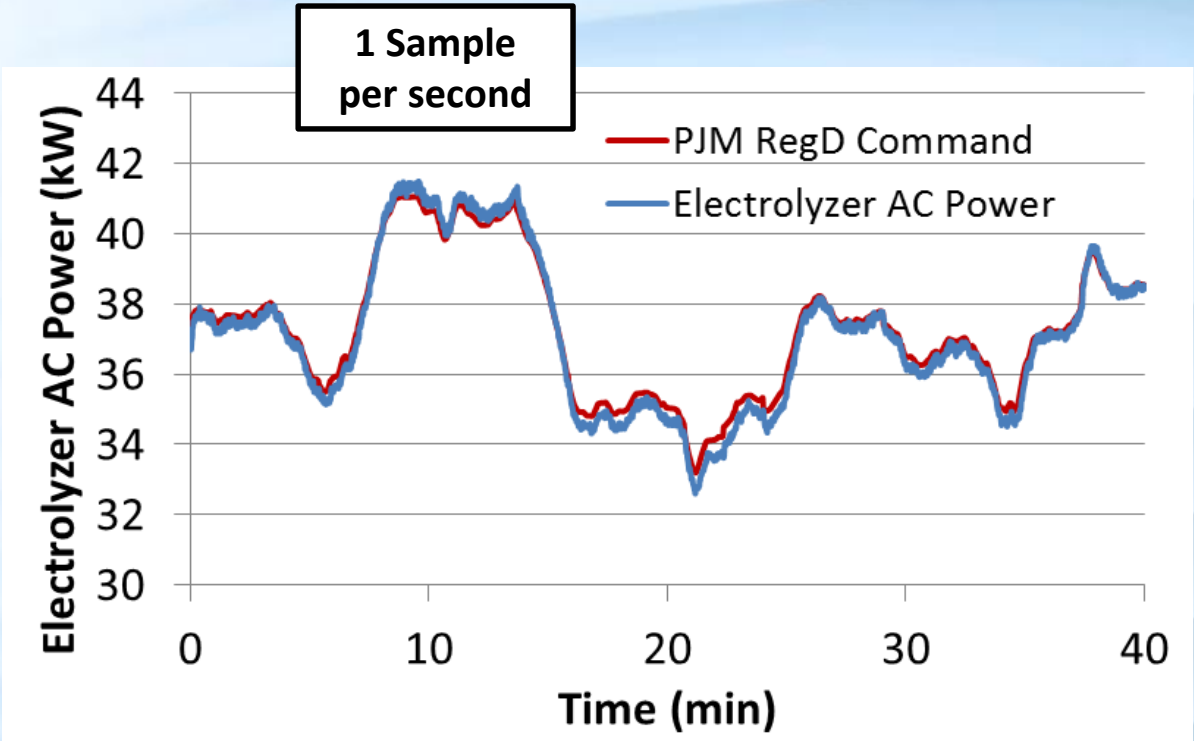
- Short-term balancing is likely to employ technologies such as demand-side management and batteries
- Long-term storage options will be required to meet CA's ambitious goals in greater capacity of solar and wind generation
- Long-term storage will:
  - Provide clean dispatchable power
  - Act as a strategic reserve and buffer to absorb supply chain constraints

Grid Support – Systems Integration

Electrolyzer energy conversion systems are flexible electrical loads that can help stabilize the electricity grid and enable higher penetrations of renewable electricity.

Supporting grid stability

- Typical utility profile to validate performance
- System response, not just stack
- 120 kW PEM stack operating on NREL's electrolyzer stack test bed
- Flexible demand side management tool could be used to provide frequency response service



Source: Harrison K., Mann M., Terlip D., and Peters M., NREL/FS-5600-54658

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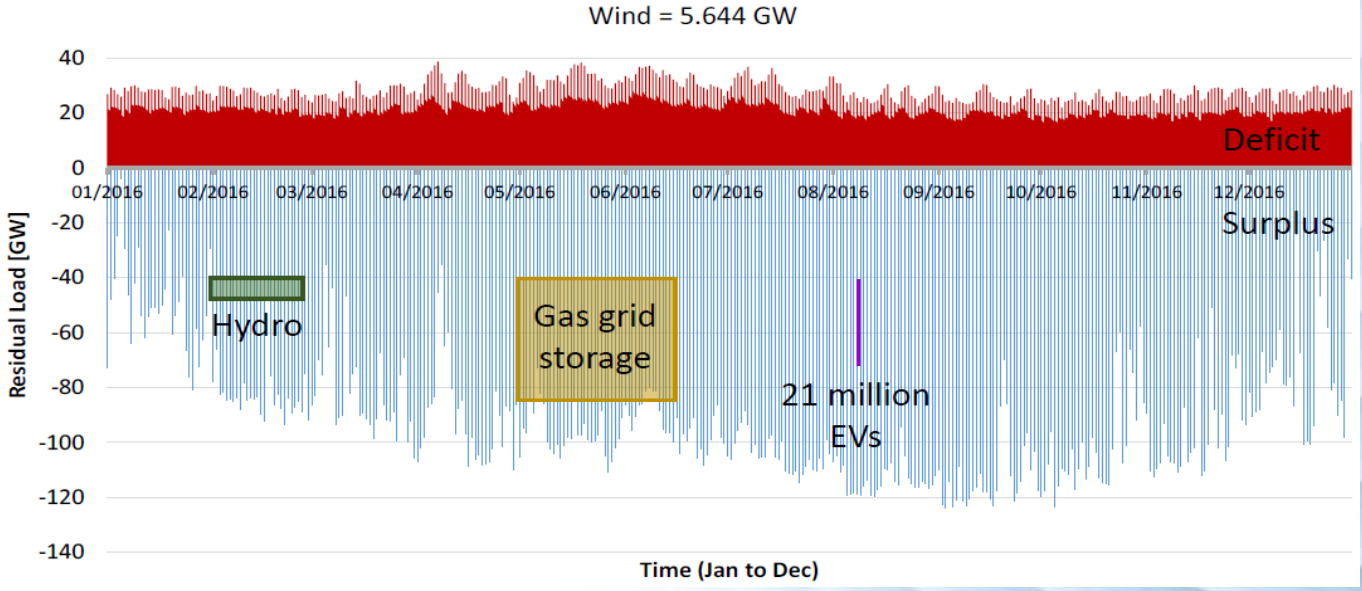
Storing Energy in the Form of Chemical Bonds

- Energy storage enables higher penetrations of renewable electricity to be added to the electricity grid
- Storing energy as chemical bonds has much greater potential than batteries

- In the graph, 107 TWh of storage is needed from the excess (**Blue**) to fill in the deficit (**Red**)
- Width of boxes (time)
- Height (power)
- 21 million battery electric vehicles won't make it

100% Renewable California Power System

- **Wind capacity = 5.644 GW (equal to 2016 installation)**
- **PV capacity = 162.286 GW**
- **Total excess = 260 TWh (peak = 123.8 GW)**
- **Total deficit = 107 TWh (peak = 36.6 GW)**



Rethink Methane 2018, Sacramento, CA, "Challenges to Renewable Hydrogen", Jack Brouwer, 2/6/2018

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Power-to-Gas, Step 1: Water Electrolysis

Use renewable electricity to split water into hydrogen and oxygen in an electrolyzer

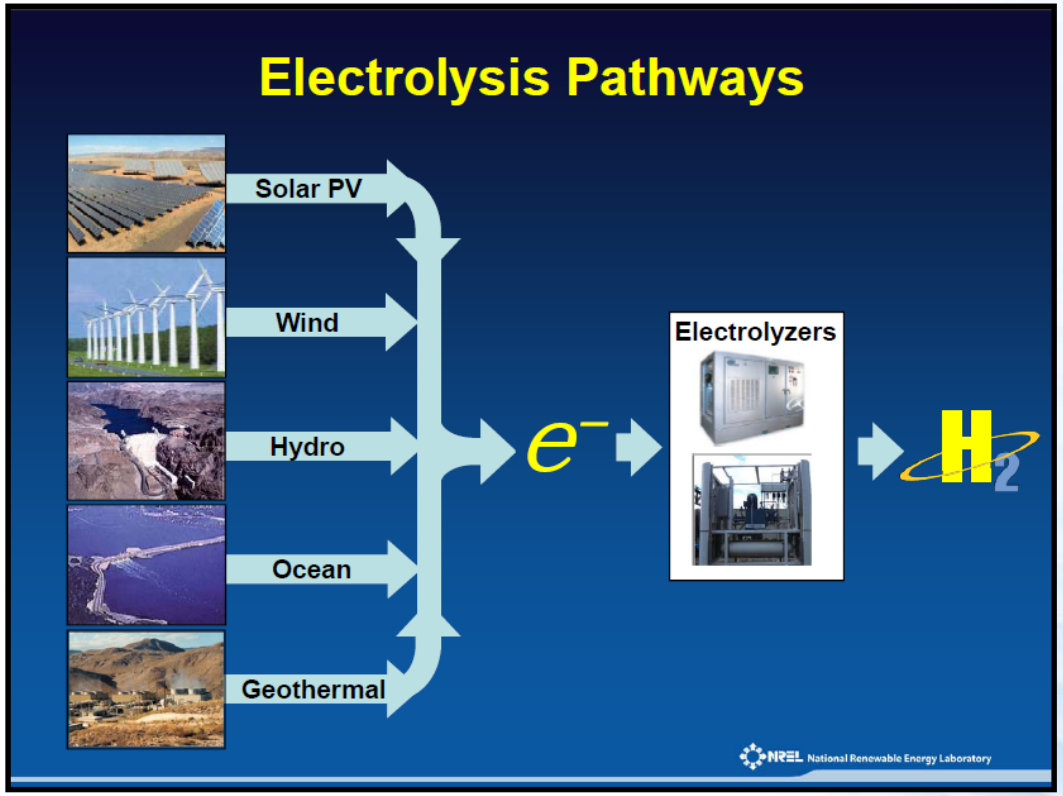
Benefits of electrolysis gas storage

- Enables higher penetration of renewable electricity
- Electrolyzer can provide grid services
- H_2 used in many processes
- O_2 is a byproduct, too
- Growing transportation sector
- Reduces fossil fuel consumption
- Scale-able, non-toxic, low temperature process

Rules of thumb:

- 50 – 55 kWh to make 1 kg of H_2
- $1MW_e$ electrolyzer, 430 kg /day

$$2H_2O + e^- \longrightarrow 2H_2 + O_2 + Heat$$



1 kg of H_2 ~ gallon of gasoline (energy)

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Power-to-Gas, Step 2: Methanation

Using the renewable H_2 (from Step 1) and CO2 in a downstream methanation process to produce renewable methane and water

$$4H_2 + CO_2 \xrightarrow{\text{Biocatalyst}} CH_4 + 2H_2O + \text{Heat}$$

Benefits of Renewable CH_4 via P2G

- Enables higher penetration of renewable electricity
- Recycles CO_2
- Meets pipeline quality standards
- Provides long-duration energy storage in the NG network
- Upgrades waste streams containing CO_2
  - Ethanol, dairies, wastewater, breweries
- Scale-able, non-toxic, self-replicating biocatalyst, low temperature systems

Rule of Thumb: $10MW_e$ of electrolysis feeding a bioreactor can recycle 7500 tons of CO_2 per year

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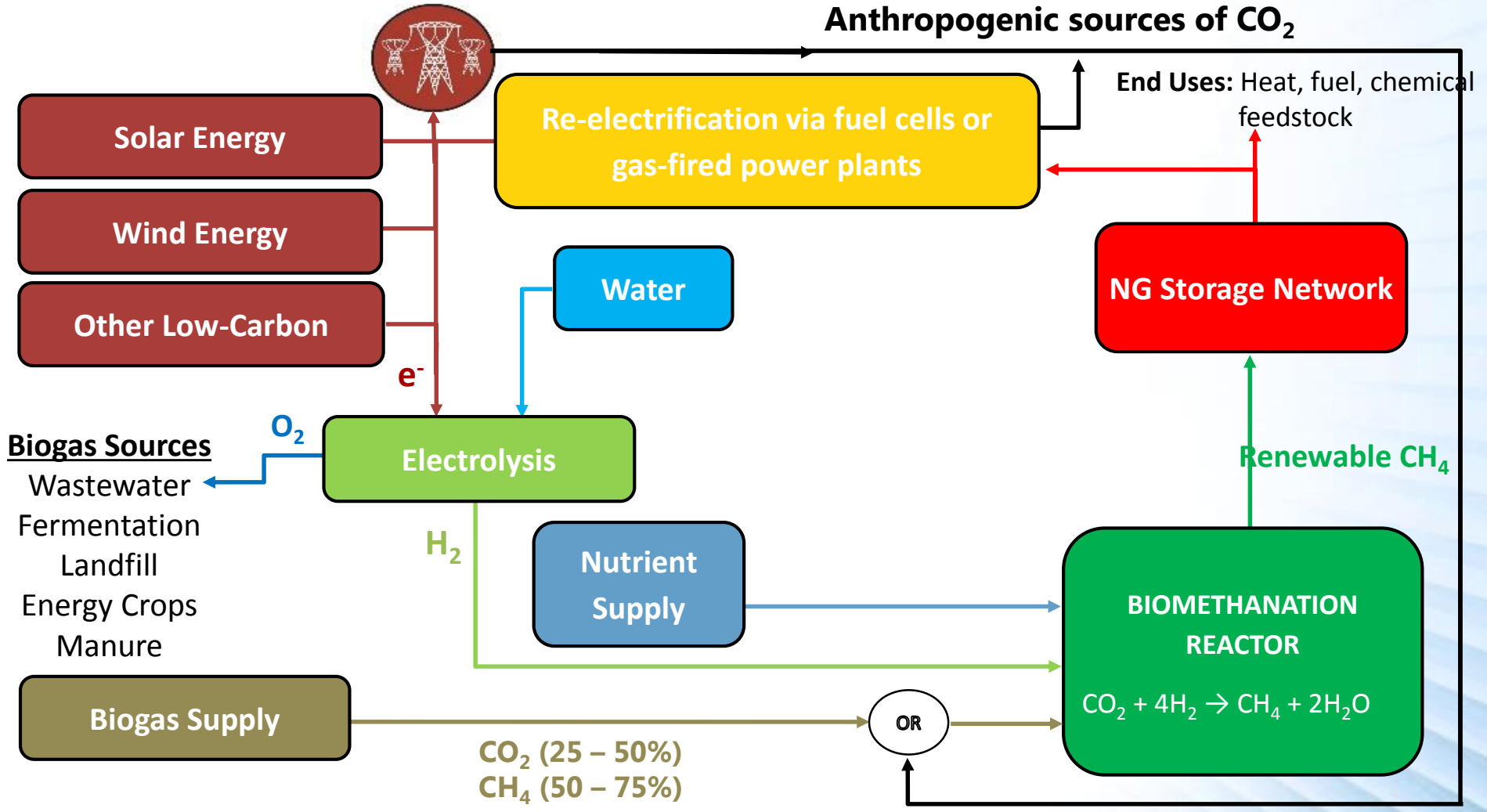
Renewable Power H_2 + Methanation of CO_2



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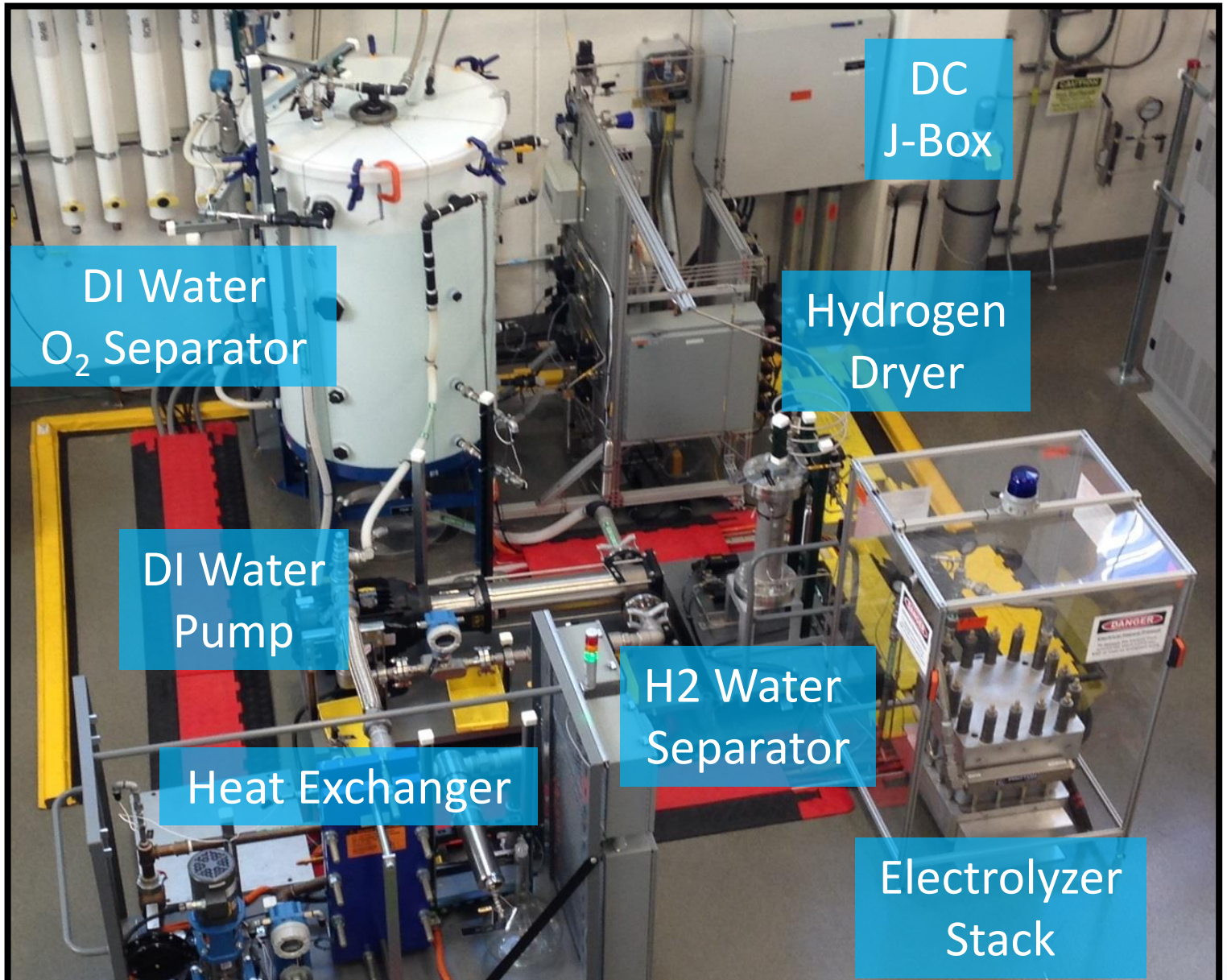
NREL's Electrolyzer Test Bed



NREL Biomethanation System

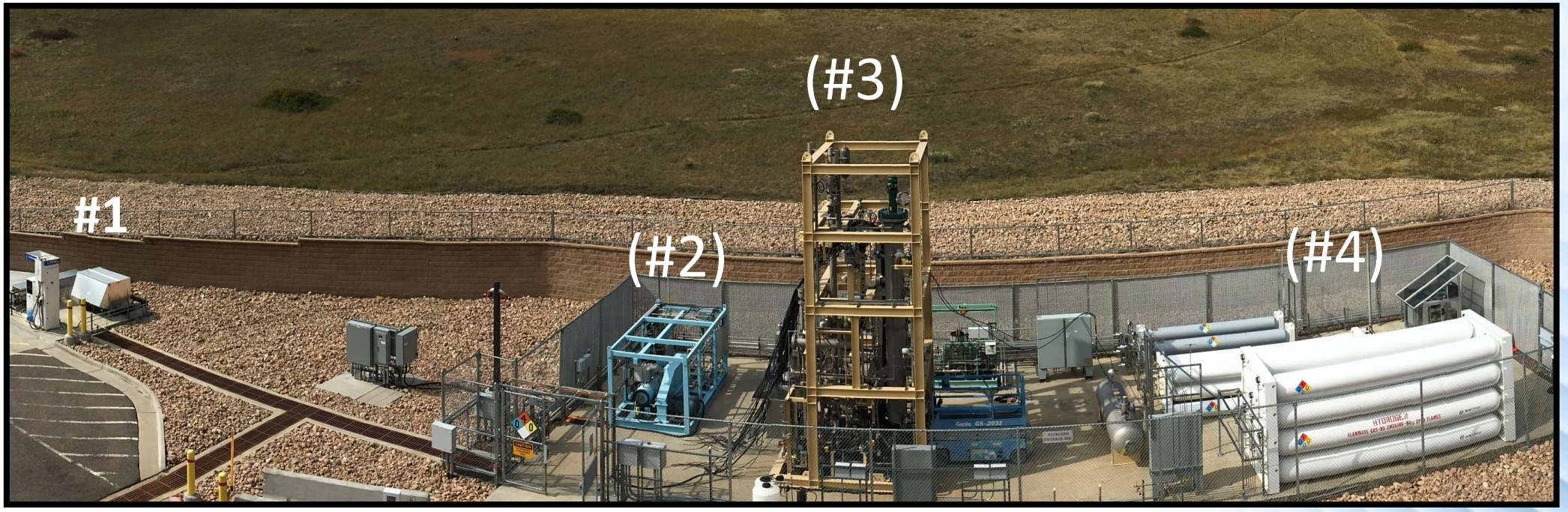
NREL's H_2 and Electrofuels R&D Site (below)

#1) 350/700 bar pre-cooled H_2 dispensing system

#2) Compression R&D

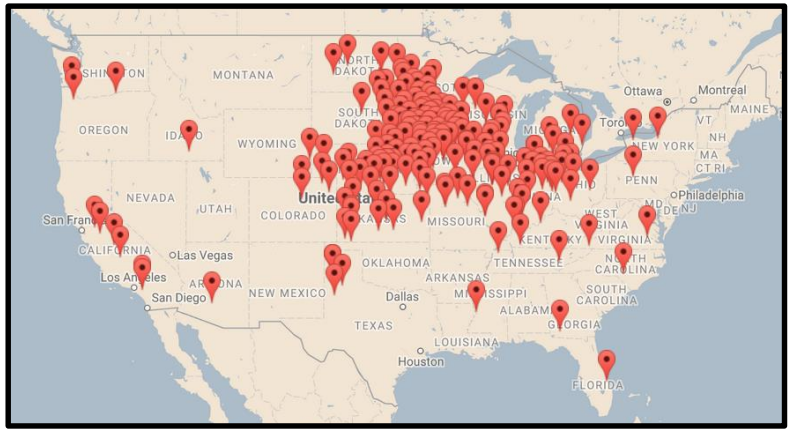
#3) 700 L bioreactor contains biocatalyst that combines H_2 and CO_2 to produce pipeline quality methane

#4) 200, 400 & 875 bar storage (350 kg Total)



Early Market CO_2 Sources – Plenty of Resource

- As of May 2018, the United States has over 200 operating refineries producing 15.8 billion gallons of ethanol per year (http://www.neo.ne.gov/statshtml/122.htm)
- Typical ethanol plant produces 50 Million gallons of ethanol per year and 150,000 metric tons of CO_2
- Each 50 MW of electrolysis (432 kg H2/day) feeding a bioreactor can recycle 37,000 metric tons of CO_2
- Therefore, It would take 200 MW of electrolysis per typical ethanol plant to recycle all of the CO_2 into CH_4



http://www.ethanolrfa.org/resources/biorefinery-locations/
Last updated: April 30, 2018

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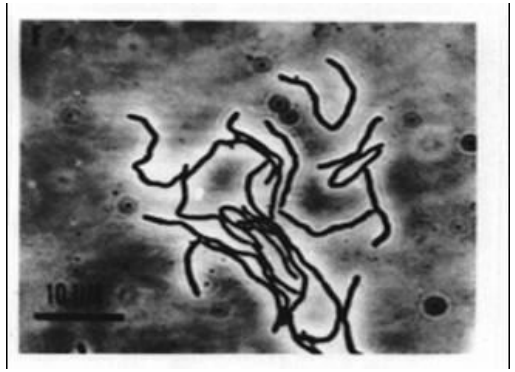
Biocatalyst – Methanogenic Archaea

About the organism

- Self-replicating
- Found in extreme environments
- Thermophile up to 80°C (176°F)
- Selectively evolved, not genetically modified
- Anaearobic, but tolerates some O_2

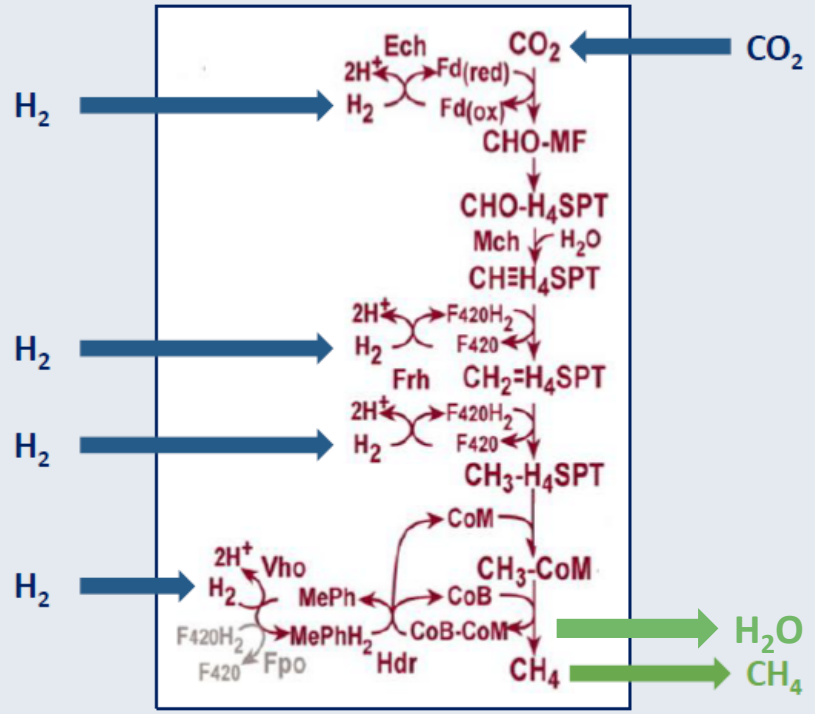


Methanothermobacter thermautotrophicus
Image source: http://web.umr.edu/~microbio/BIO221_2002/Methanobacterium_thermoautotrophicum.htm

Chemistry & Biochemistry

Chemical Reactions:

1) Electrolysis	$4H_2O \rightarrow 4H_2 + 2O_2 + Heat$	η=0.80
2) Methanation	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O + Heat$	η=0.75
Net Reaction	$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2 + Heat$	η=0.60



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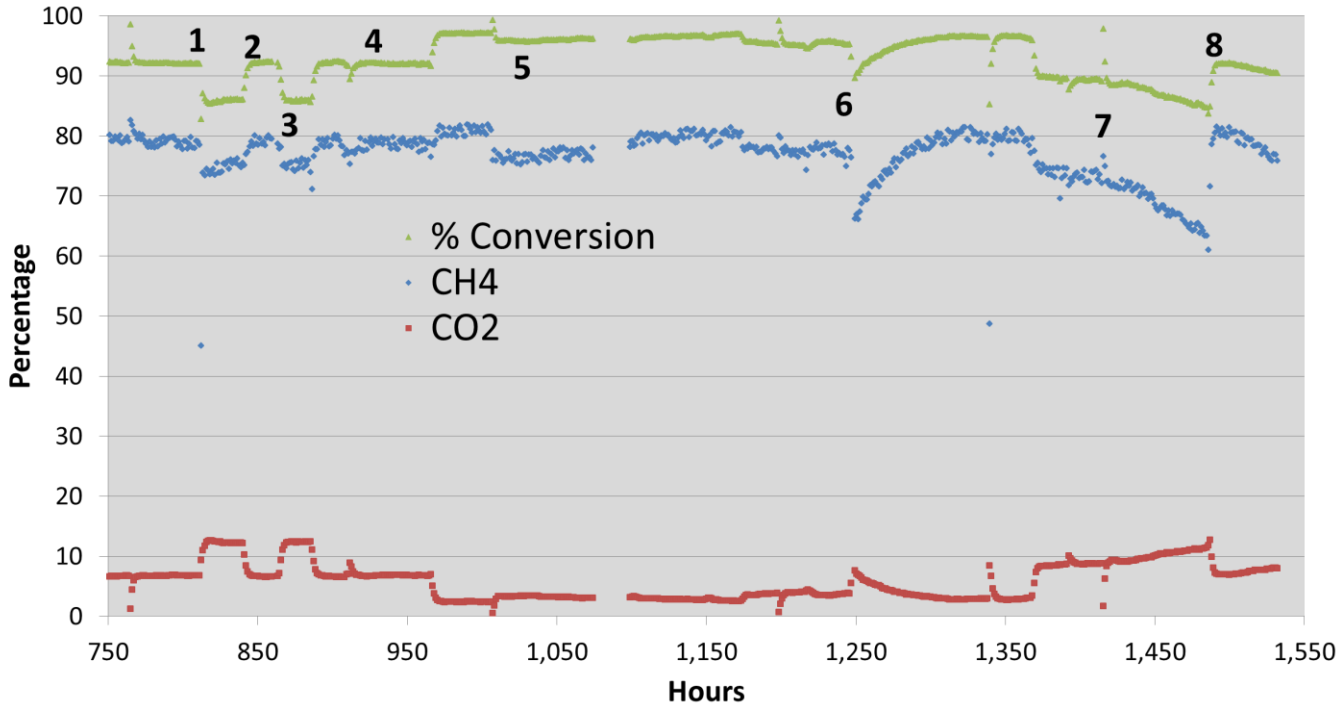
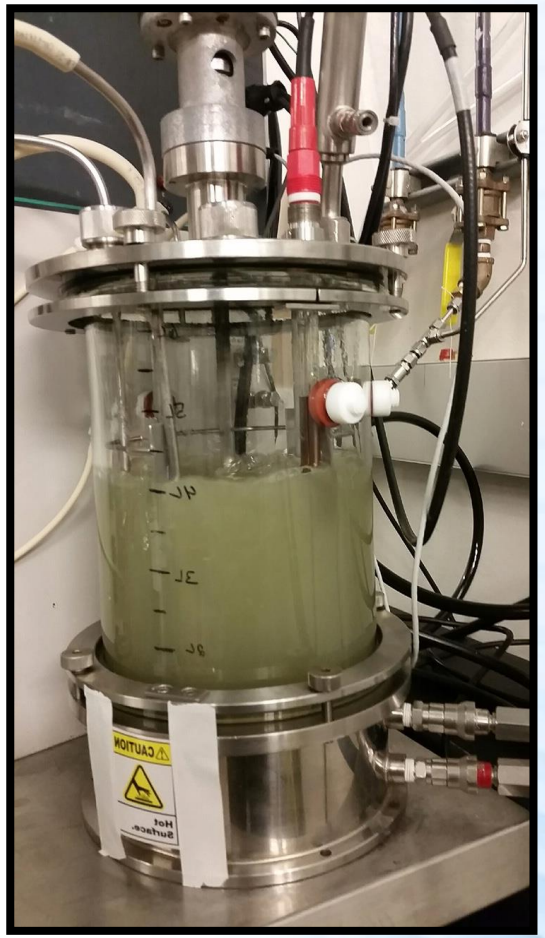
Electrochaea

Performance Results



- Over 70 days of continuous operation
- Ambient pressure and 60°C
- 85 – 95% conversion efficiency **(Green above)**



5L, 1atm reactor

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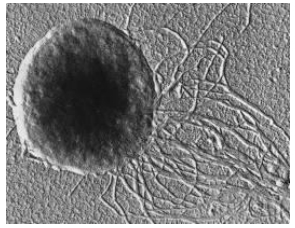
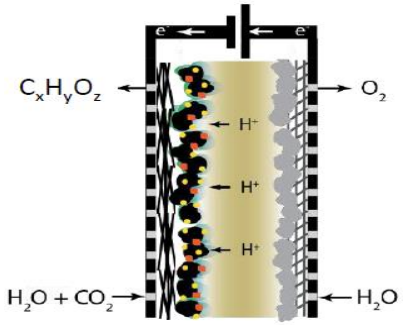
Direct Power-to-Methane

- The hydrogen production step can eliminated with direct methanation
  - PV (e-) → Methanation (CH_4)
- Opus 12, a Cyclotron Road start-up is developing a direct thermocatalytic process to convert carbon dioxide and water into methane.
- Lawrence Livermore National Laboratory and Stanford University are using *Methanococcus maripaludis* to convert carbon dioxide and water into methane.



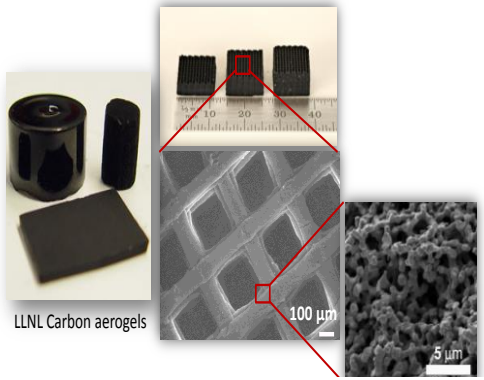
Methanococcus maripaludis

Image source: http://www.bact.wisc.edu/Bact303/Methanococcus.jpeg

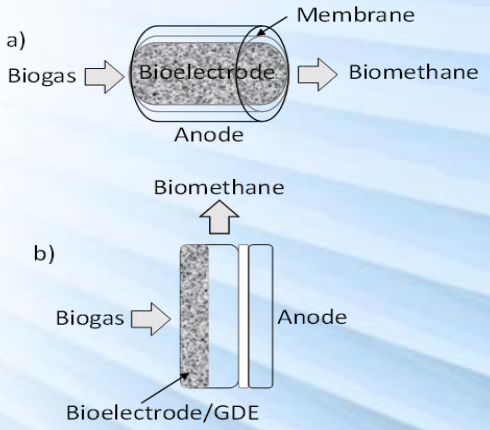


Opus 12 Electromethanogenesis –
metal nanoparticle catalyst/polymer membrane

LLNL/Stanford Microbial Electromethanogenesis



Carbon aerogels and printed aerogels with hierarchical pore structures.



(a) flow through aerogel tube-based reactor design; (b) GDE stack-based reactor design.

Additional Information

- “Inventors search for 'missing link' in renewable energy,” John Fialka, E&E News reporter, Climatewire, Wednesday, January 17, 2018
- “Novel Power-to-Gas Tech Begins Testing in the US”, Katie Fehrenbacher, Green Tech Media, October 16, 2017
- “First US Biomethanation Reactor System for Power-to-Gas Testing Installed in Colorado”, Dan McCue, Renewable Energy Magazine, October 13, 2017
- “SoCal Gas, NREL install bioreactor for pilot power-to-gas project”, Renewables Now, October 12, 2017
- “Undersea Microbes Provide Path to Energy Storage”, Wayne Hicks, NREL Feature Article, October 11, 2017
- “NREL + Southern California Gas, Power-to-Gas Pilot Converts Electricity to Hydrogen, Stores it as Methane”, NREL Fact Sheet, September 2017
- “NREL and Southern California Gas Launch First U.S. Power-to-Gas Project”, NREL Press Release, August 2017
- “Batteries can’t solve the world’s biggest energy-storage problem. One startup has a solution.” Akshat Rathi, Quartz, December 11, 2017
- “SoCalGas Power-to-Gas Project Selected by U.S. Department of Energy’s National Renewable Energy Laboratory to Receive Funding”, Sempra Energy, April 24, 2017