NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Energy Systems Integration

Renewable Power-to-X: Biological Methane Production

Utilizing biological gas fermentation, carbon dioxide and renewable electricity to produce renewable hydrogen, methane, chemicals and other high-value products

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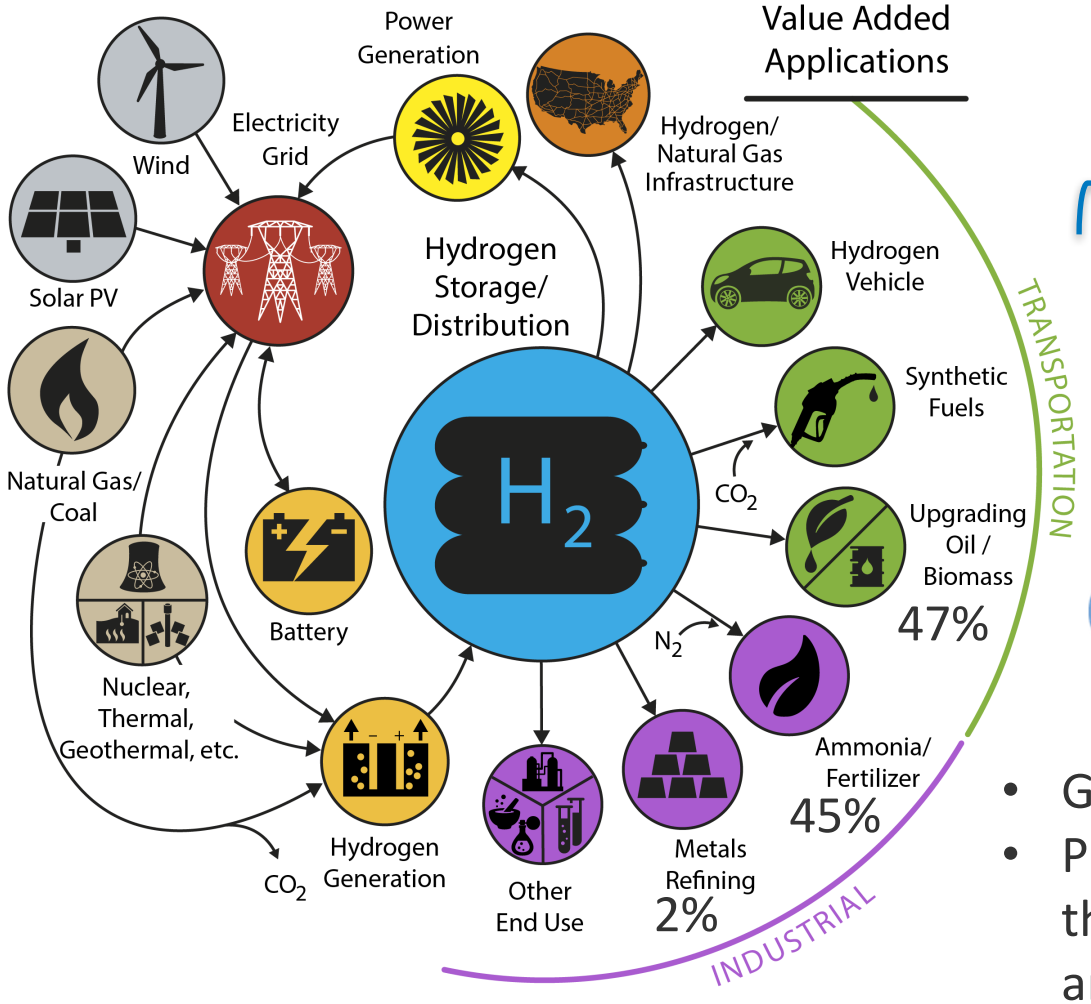
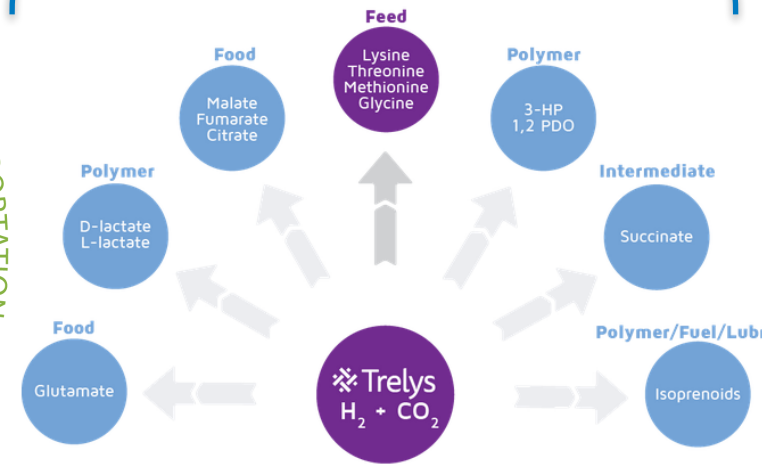
H2@Scale Vision



Other End Use



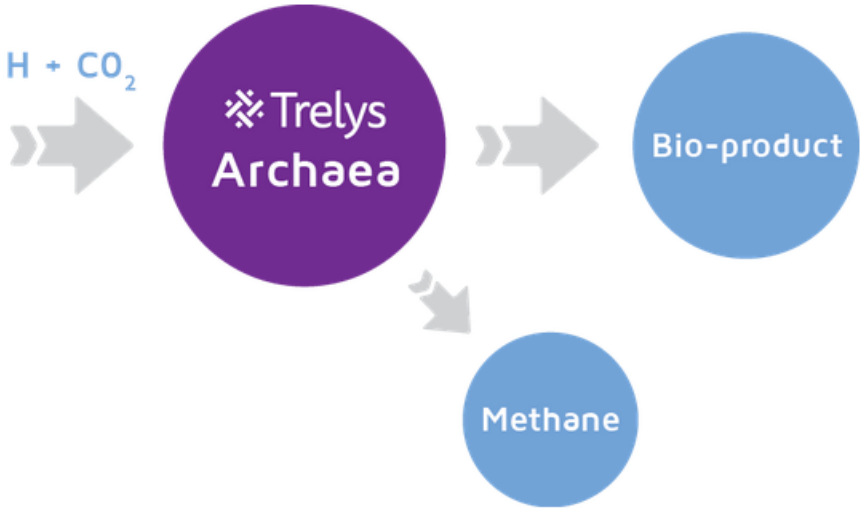
http://www.trelystech.com/

- Growing demand for amino acids
- Plant protein contains less lysine, threonine and methionine than animal protein

In the iron and steel industry, H_2 is used to reduce iron ore to iron

Biocatalyst – Archaea Methanogens

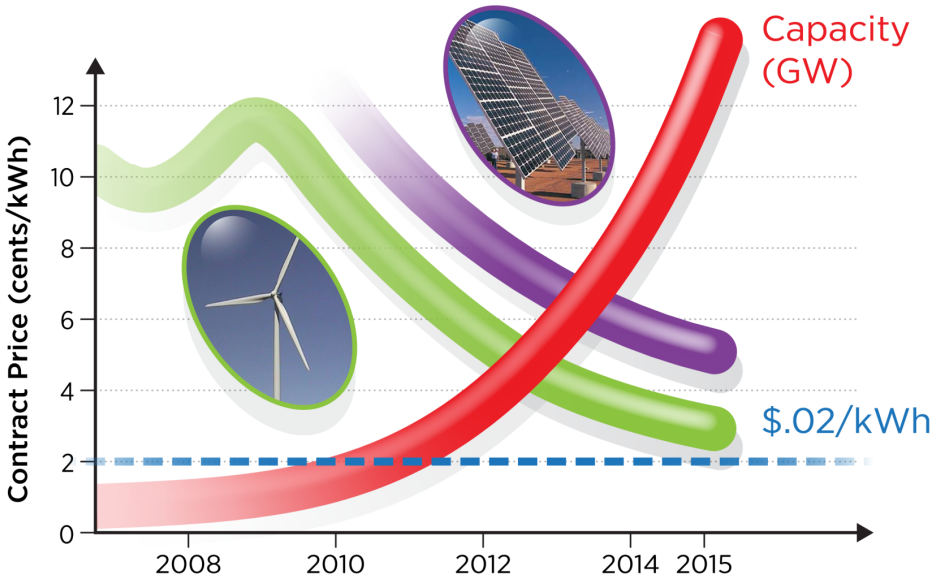
- Consume CO_2 and H_2 to produce CH_4
- Under the right conditions these microorganisms can produce a host of byproducts
- One byproduct just happens to be the alpha amino acids—such as lysine, methionine and threonine.
  - Which just happen to be essential to healthy people, and also healthy cows and chickens. And just happen to be something that animal protein is relatively replete with, but vegetable protein is not.



Drivers: Carbon-free electricity prices

In October, a tender for 300 megawatts of solar power in Saudi Arabia saw Abu Dhabi developer Masdar offering a price of $17.86 per megawatt-hour.

Wind power also hit an eye-poppingly low price point in Mexico, coming in at $22 per megawatt-hour for a 118-megawatt project proposed by Engie Wind.



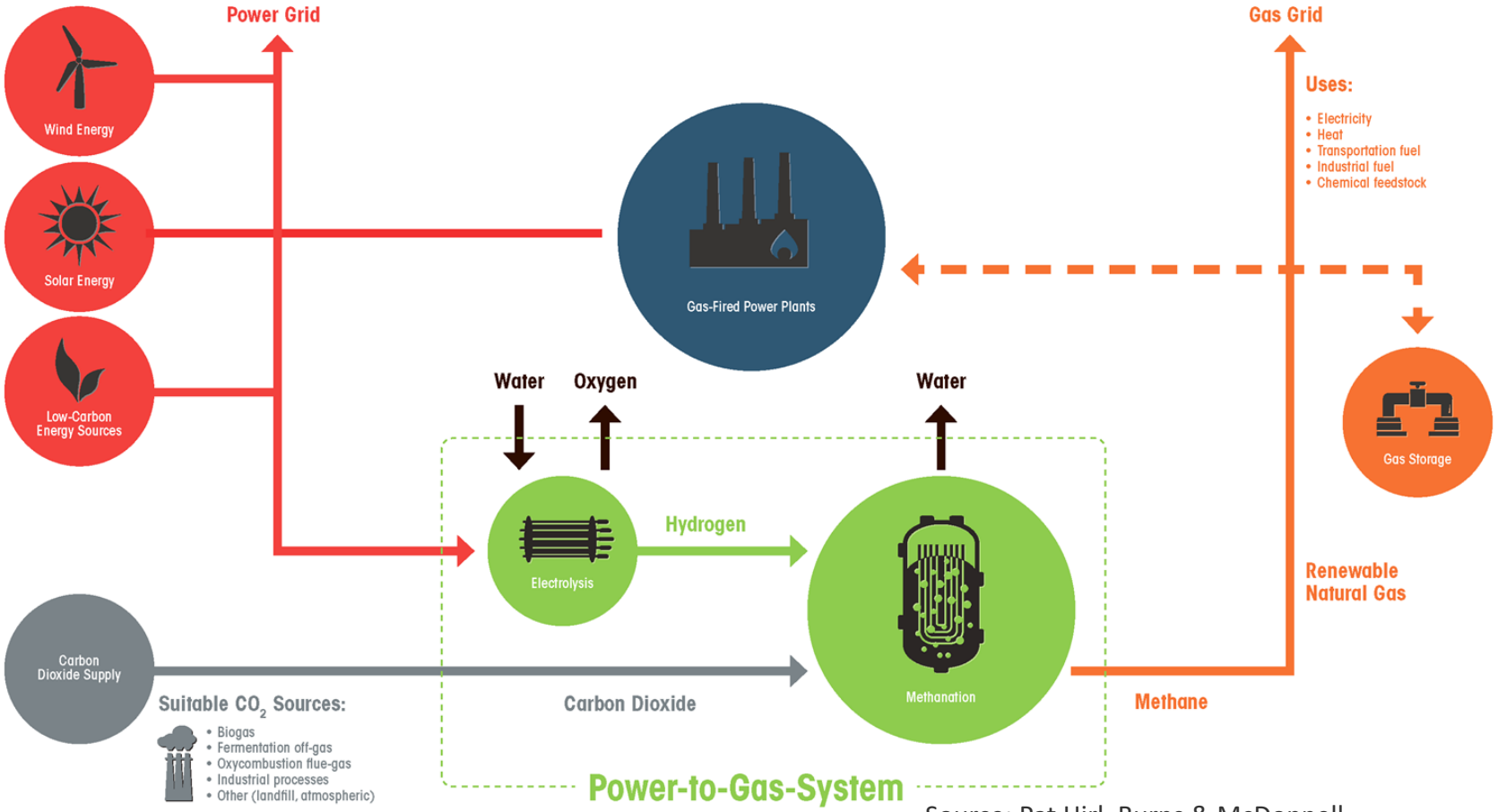
Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1'15 Report, 2. DOE EERE Wind Report, 2015

The Mexican government this month (November 2017) announced the average price achieved in its third long-term auction of 2017 was $20.57 per megawatt-hour, which it said is "one of the lowest prices achieved internationally."

https://www.greentechmedia.com/articles/read/mexico-auction-bids-lowest-solar-wind-price-on-the-planet#gs.cOGES7Y

Renewable Power-to-H_2 → Methanation of CO_2

- Fixed rate of storage based on electrolyzer capacity
- Natural gas pipeline provides extensive storage
  - Southern California Gas estimates 1 TWhr storage in storage fields and pipeline
- Natural gas pipeline provides transportation
- Recovery of electricity using existing generation equipment



Source: Pat Hirl, Burns & McDonnell

Renewable Power-to-X → Methanation of CO_2

The methanation of CO_2 in to RNG and a host of other end products including essential amino acids for food

- Renewable Hydrogen is an intermediate product in the two step bio-methanation process to produce renewable natural gas and other products
  - For example, renewable hydrogen can be stored and sold as fuel in FCEVs
- This approach crosses many sectors;
  - Connects the electrical power back to the natural gas network results in a flexible (Daily – Seasonal) energy storage system from multiple sources
  - For example, essential amino acids production from different archaea

The U.S. emits 5-6 billion tons of CO_2 into the atmosphere each year

Total U.S. energy-related carbon dioxide (CO_2) emissions were 5,171 million metric tons in 2016. https://www.eia.gov/tools/faqs/faq.php?id=75&t=11

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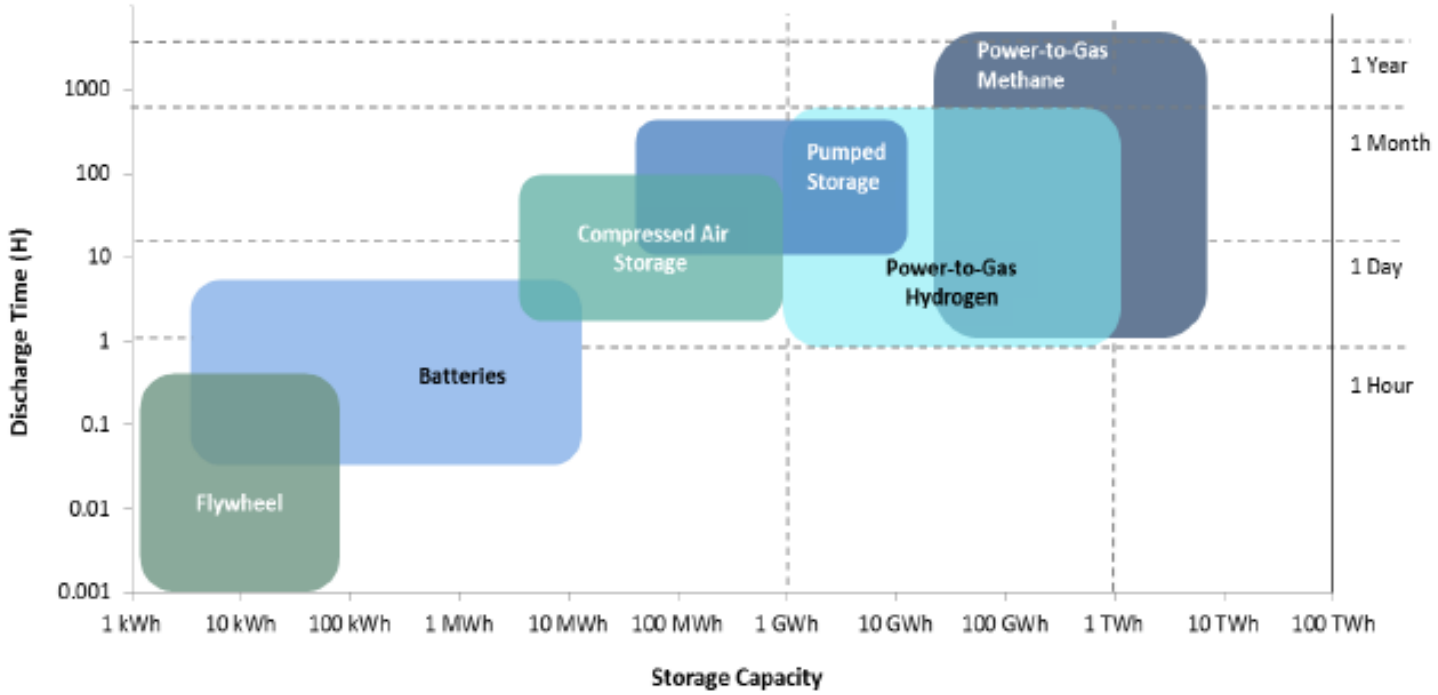
Storing Renewable Energy as Natural Gas

- Over 130 billion cubic feet of natural gas storage capacity exists in Southern California.
  - To put this in perspective, this is enough to supply all of the gas-fired generation in the region for more than two months.



The biological conversion of H_2 and CO_2 into CH_4, using methanogenic archaea is an interesting technology for CO_2 conversion, energy storage and biogas upgrading.

SoCal Gas & NREL – Power-to-Gas

Objective

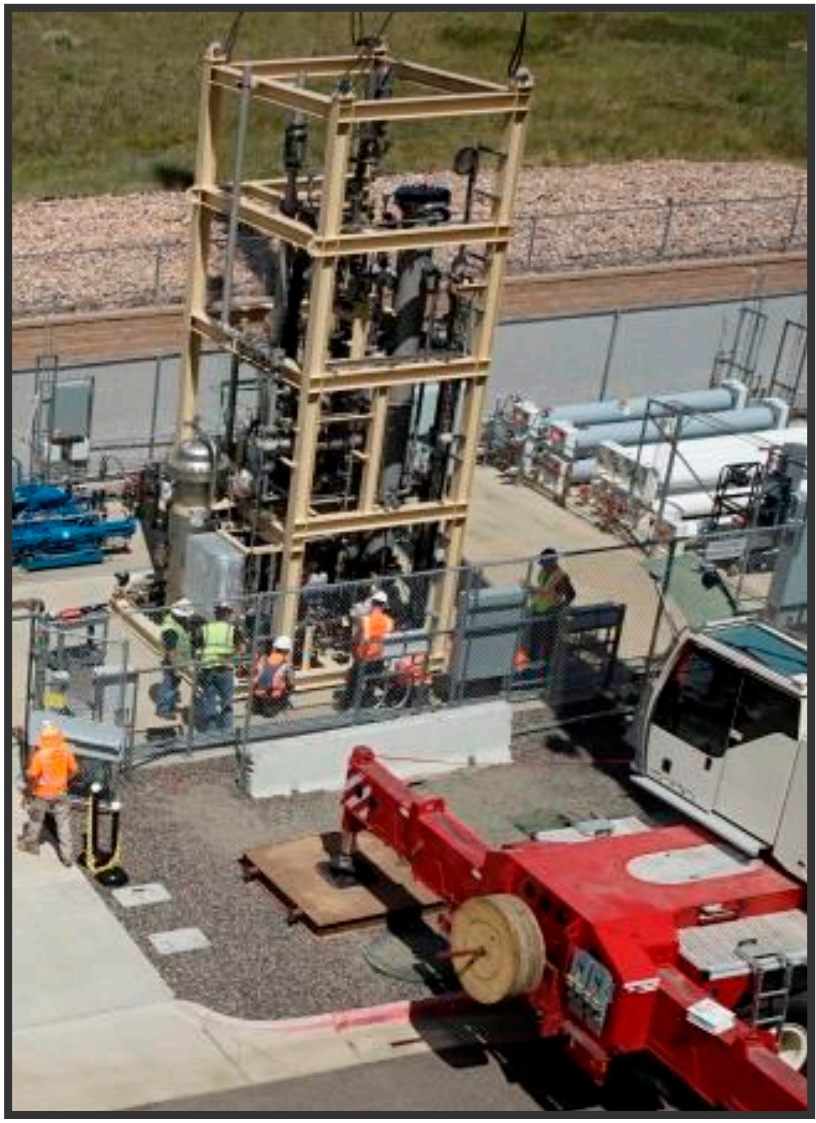
- Production of pipeline quality methane under variable power to electrolyzer

Biomethanation

- Inputs: H_2, CO_2 and Nutrients (i.e., salts)
- Outputs: CH_4, H_2O, Heat
- Partner: Southern California Gas Company and Electrochaea
- *Biocatalyst: Methanothermobacter thermautotrophicus*

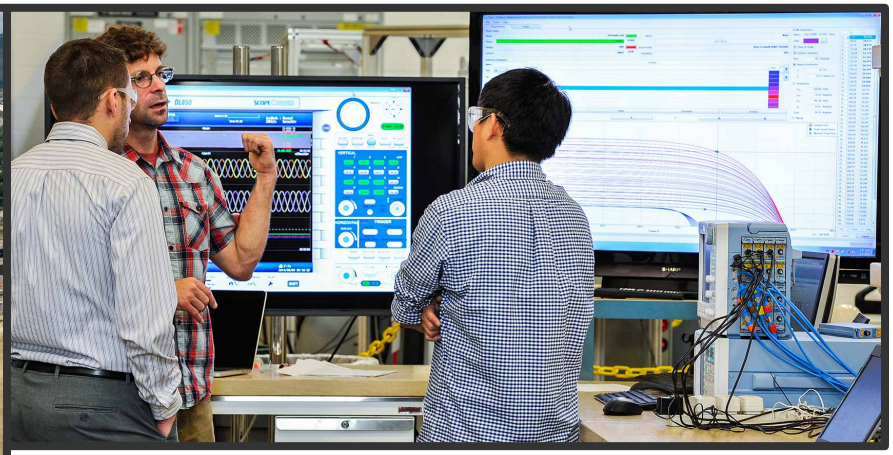
Challenges

- Hydrogen solubility in water
  - Gas mass transfer
- Maintaining product gas quality
- Investigate and characterize impact of daily cycling, agitation, circulation, pressure, gas ratio and temperature on methane production rate



Energy Systems Integration Facility

- Labs focus on R&D of integrated energy systems Electricity, Fuels, Transportation and Buildings
- Research Electrical Distribution Bus at 250A and 1600 A
  - AC: 600V, 4 wire, 16.67 to 400 Hz
  - DC: ±500V pole to common or 1000V to negative, 3 wire
  - 1MVA grid simulators, 1.5 MW PV simulator and RLC load banks
- 250 kW electrolyzer (5 kg/hr) meeting J2719 FC quality standard
- Also, systems for thermal, RTDS, Water, Computing and Cyber Security



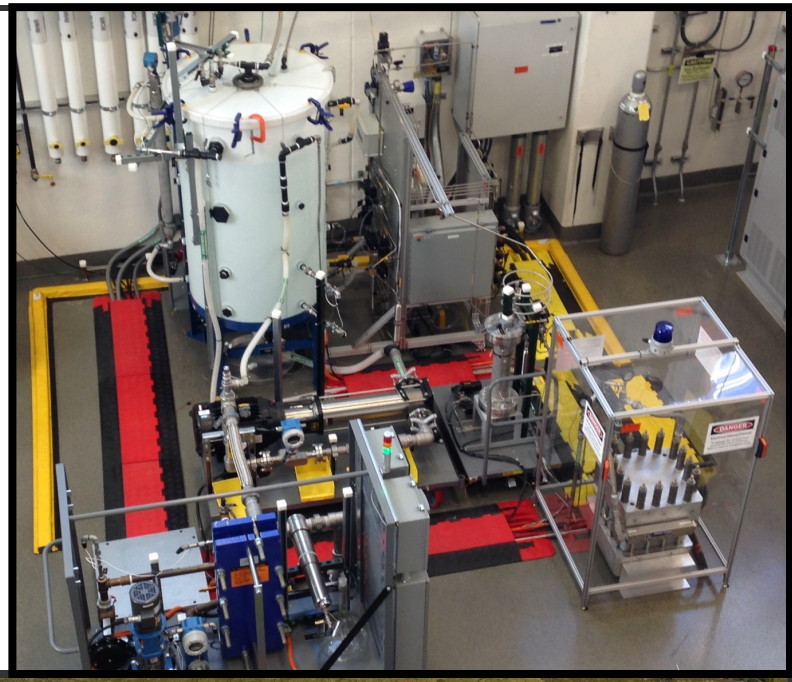
National User Facility

http://www.nrel.gov/esif

Hydrogen and Biomethanation Systems

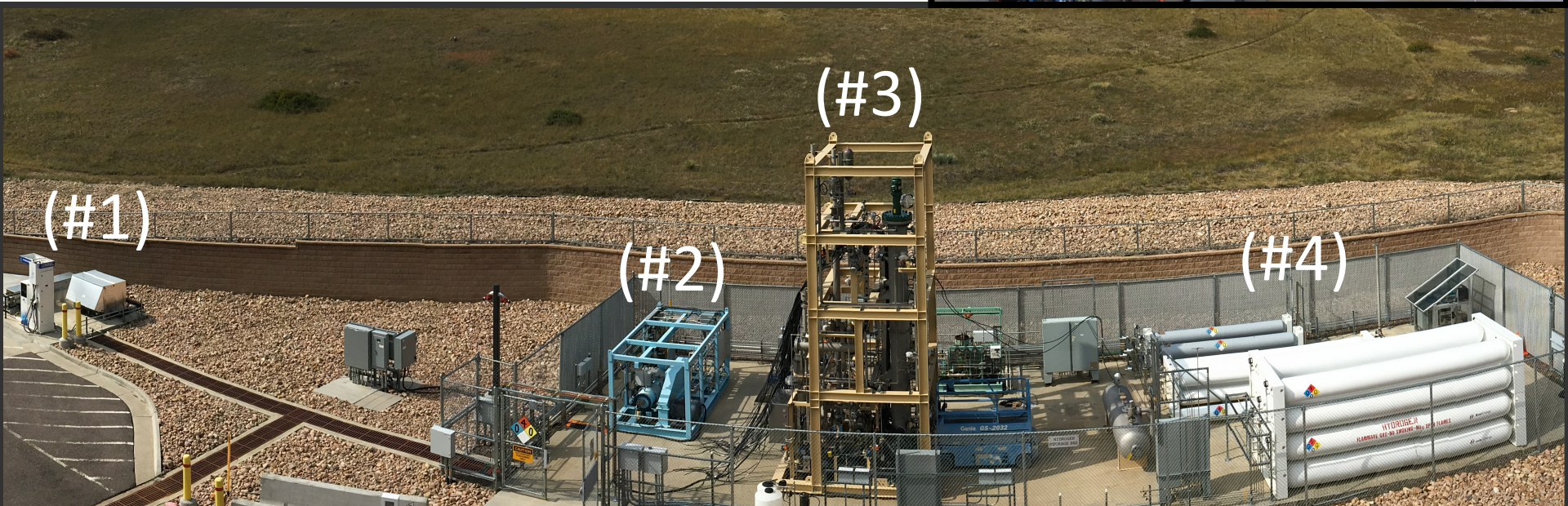
NREL's designed and built electrolyzer ——→

- 20 – 70 bar, 4000A at 250Vdc, < 5 ppmv H_2O_v
- Today, 5 kg/hr, 250 kW PEM stack at 20 bar



NREL's Outdoor Research & Demonstration Site

1) 350/700 bar dispensing system
2) Compression
3) 25' tall bioreactor skid combines H_2 and CO_2 to produce pipeline quality methane
4) 200, 400 & 875 bar storage (350 kg Total)



Bench Scale (5 L) Learning

Varying H_2:CO_2 Ratio

(1) Lowered H_2 flow rate (3.8:1 H_2:CO_2)

(2) Increased H_2 flow rate (4.0:1 H_2:CO_2)

(3) Lowered H_2 flow rate (3.8:1 H_2:CO_2)

(4) Increased H_2 flow rate (4.0:1 H_2:CO_2)

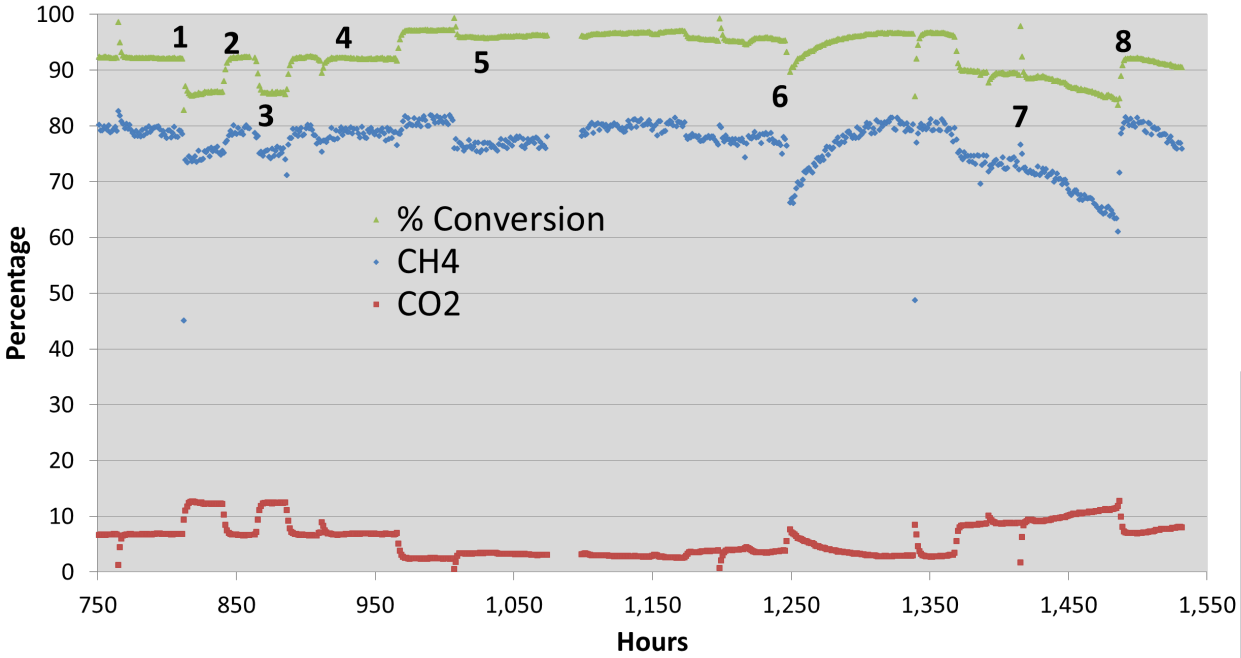
(5) Increased H_2 flow rate (4.2:1 H_2:CO_2)

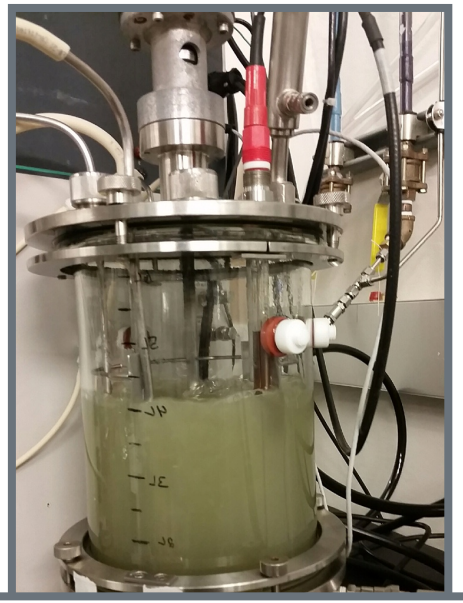
Varying Vessel Volume

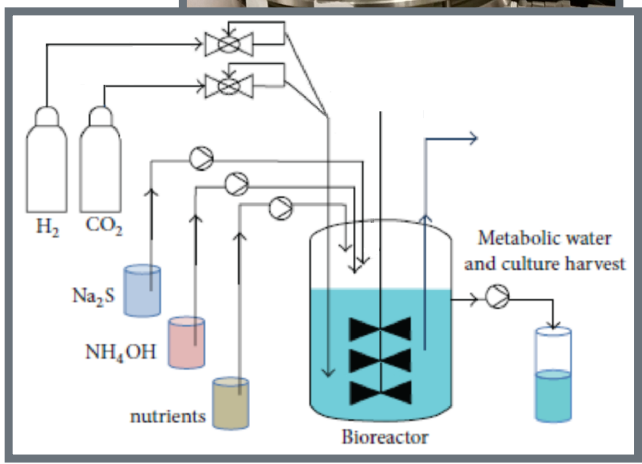
(6) Removed 1/3 of the vessel volume

(7) Increased CO_2 flow rate (4:1 H_2:CO_2) and increasing volume to 5L

(8) Increased agitation







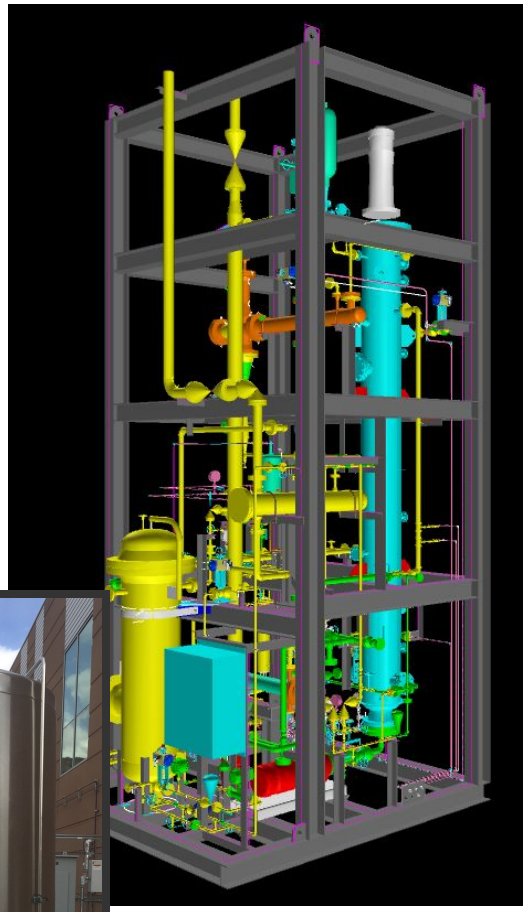
- Over 70 days of continuous operation
- Ambient pressure and 60°C
- 85 – 95% conversion efficiency **(Green above)**

SoCal Gas Bioreactor

Specifications:

$$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O + Heat$$

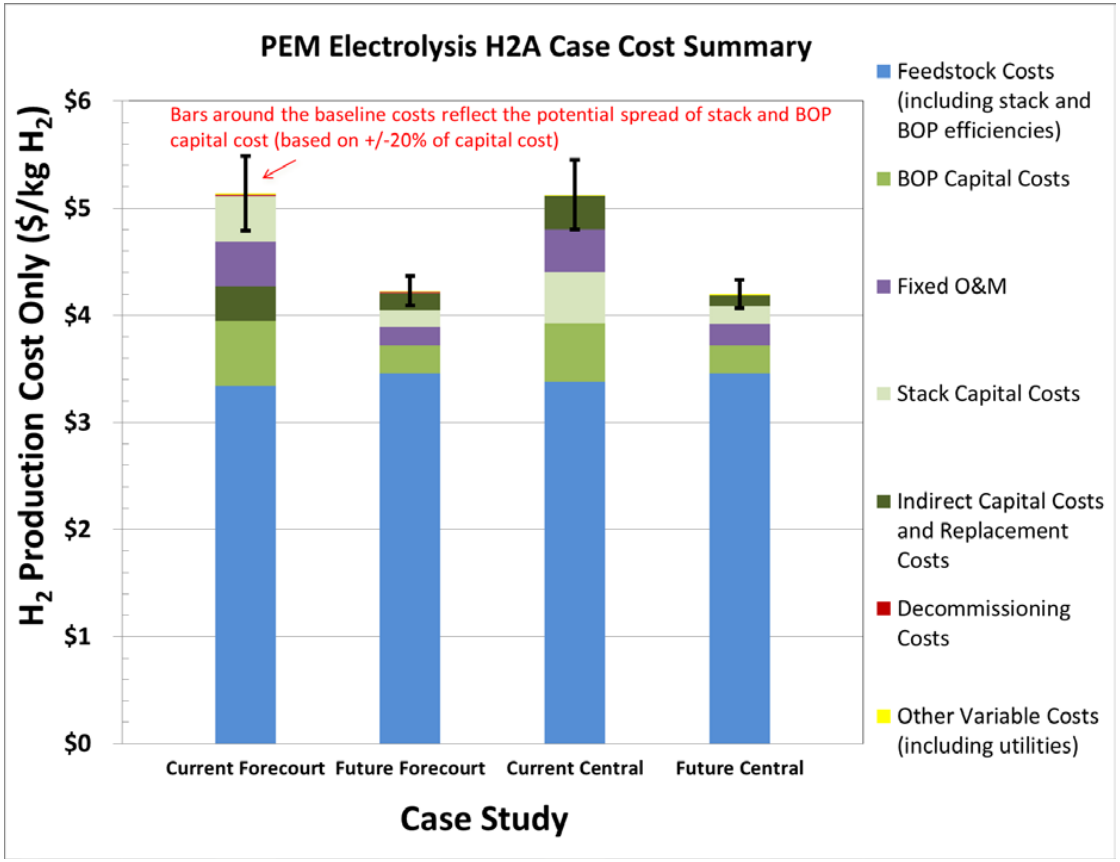
- 700 L water volume mounted on 12’x12’x25’ Tall skid
- Reactor (18” dia. x 17’ Tall) sized to accept the H_2 output from 120 kW electrolyzer (2.5 kg/hr)
- Separate nutrition skid provides Sulfur, Nitrogen and nutrients to maintain cell health and production
- Up to 18 bar operation and 75°C
- H_2S clean-up using absorbent method
- VFD control over agitation and recirculation
- CO_2 sourced with dewar



Goals:

- Demonstrate daily operation under varying hydrogen production via solar PV profile
- Optimize electrolyzer and bioreactor systems
- Characterize system performance under steady-state and variable gas flow modes
- Generate pipeline quality natural gas

MW-Scale Low-Temperature Electrolyzer Systems



ProtonOnsite and Nel Hydrogen Solutions, have received a purchase order of $8.3 million on a combined hydrogen PEM electrolyser and H2Station® fueling solution for SunLine Transit Agency in California.

http://www.protononsite.com/news-events/nel-asa-awarded-worlds-largest-hydrogen-electrolyser-fueling-station

10MW REFINERY HYDROGEN PROJECT WITH SHELL

1st September 2017

ITM Power is pleased to note the announcement today from Shell concerning a joint project to install a 10MW electrolyser to produce hydrogen at the Wesseling refinery site within the Rheinland Refinery Complex in Germany.

http://www.itm-power.com/news-item/10mw-refinery-hydrogen-project-with-shell

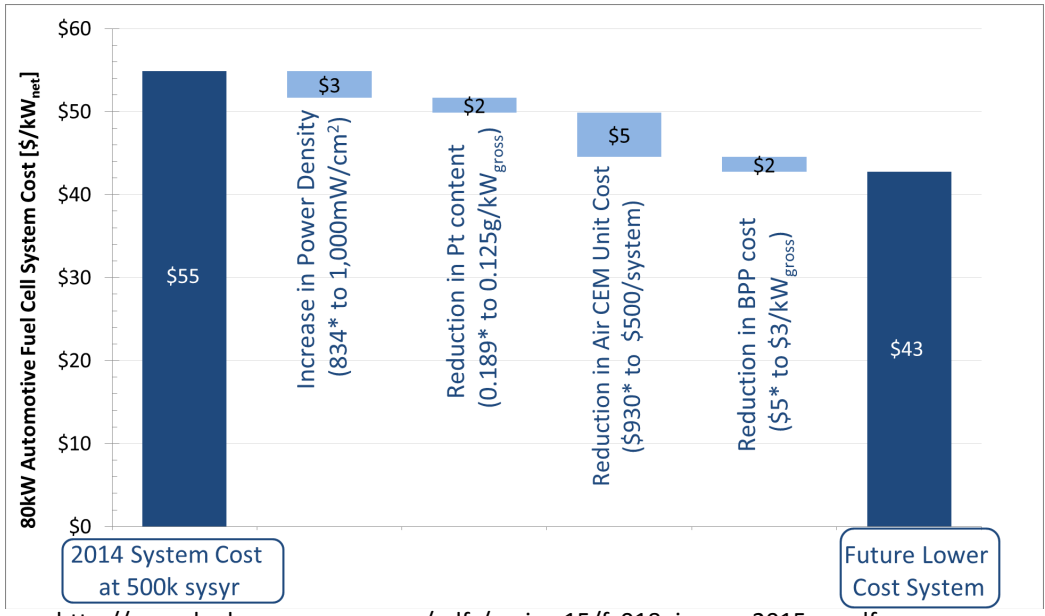
Economic Analysis of PEM Electrolysis

- Capital cost of electrolysis systems based on industry questionnaire approach (no DFMA-up type models)
- Current and future cost estimates

Uninstalled 2012$/kW	Current Forecourt	Future Forecourt	Current Central	Future Central
Total Capital	$940	$450	$900	$400

http://www.hydrogen.energy.gov/pdfs/review14/pd102_james_2014_o.pdf

And similar scale PEM FC

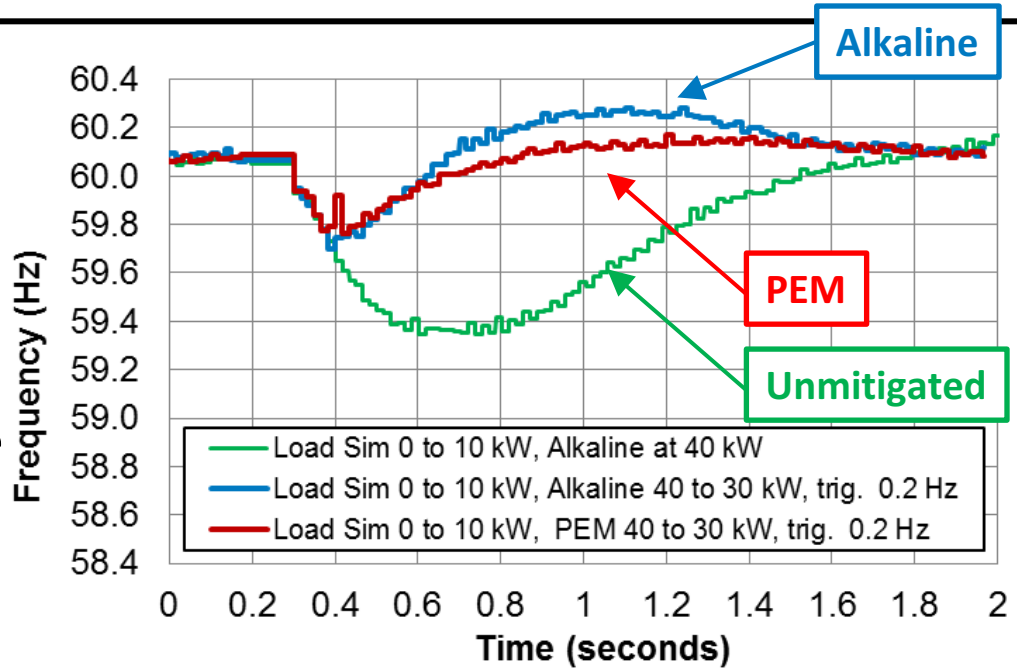


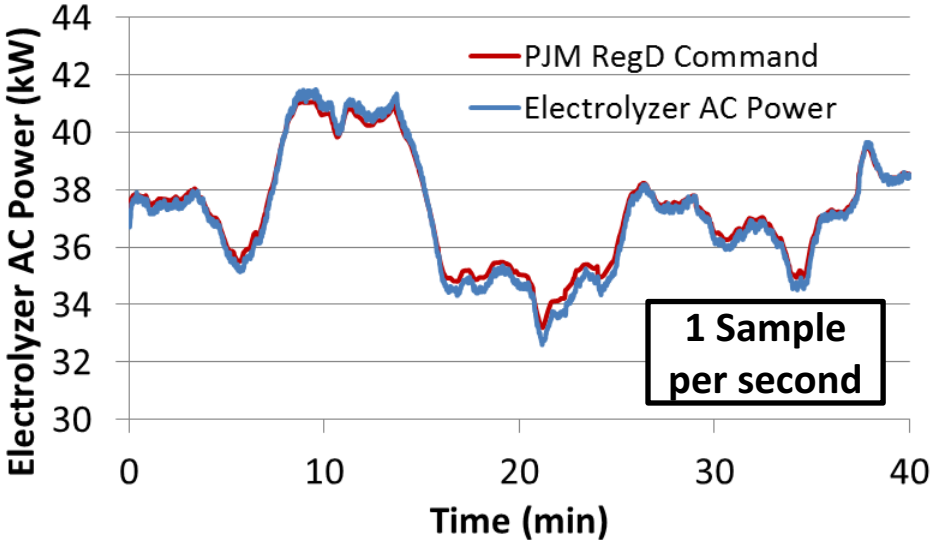
http://www.hydrogen.energy.gov/pdfs/review15/fc018_james_2015_o.pdf

Grid Support – Systems Integration

Microgrid – Freq. Response

- Sensed local frequency drop
  - 10 kW resistive load
- PEM and Alkaline tests ran separately
- Both responded quickly to mitigate disturbance once freq. ≤ 59.8 Hz





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

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

Questions/Discussion

Thank You

www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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