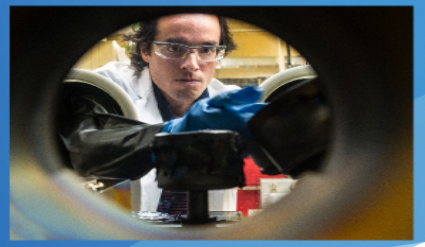
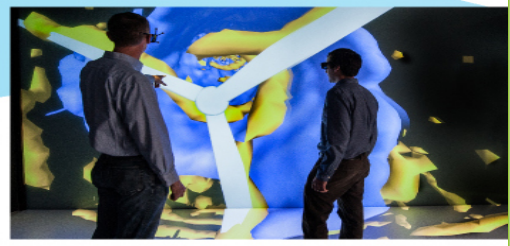
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

40
1977 – 2017

Power-to-Gas

Biomethanation: A Unique and Sustainable Approach to Renewable Natural Gas and other products

Kevin Harrison & Nancy Dowe

National Renewable Energy Laboratory

AGA/EPA 2019 Renewable Natural Gas Workshop

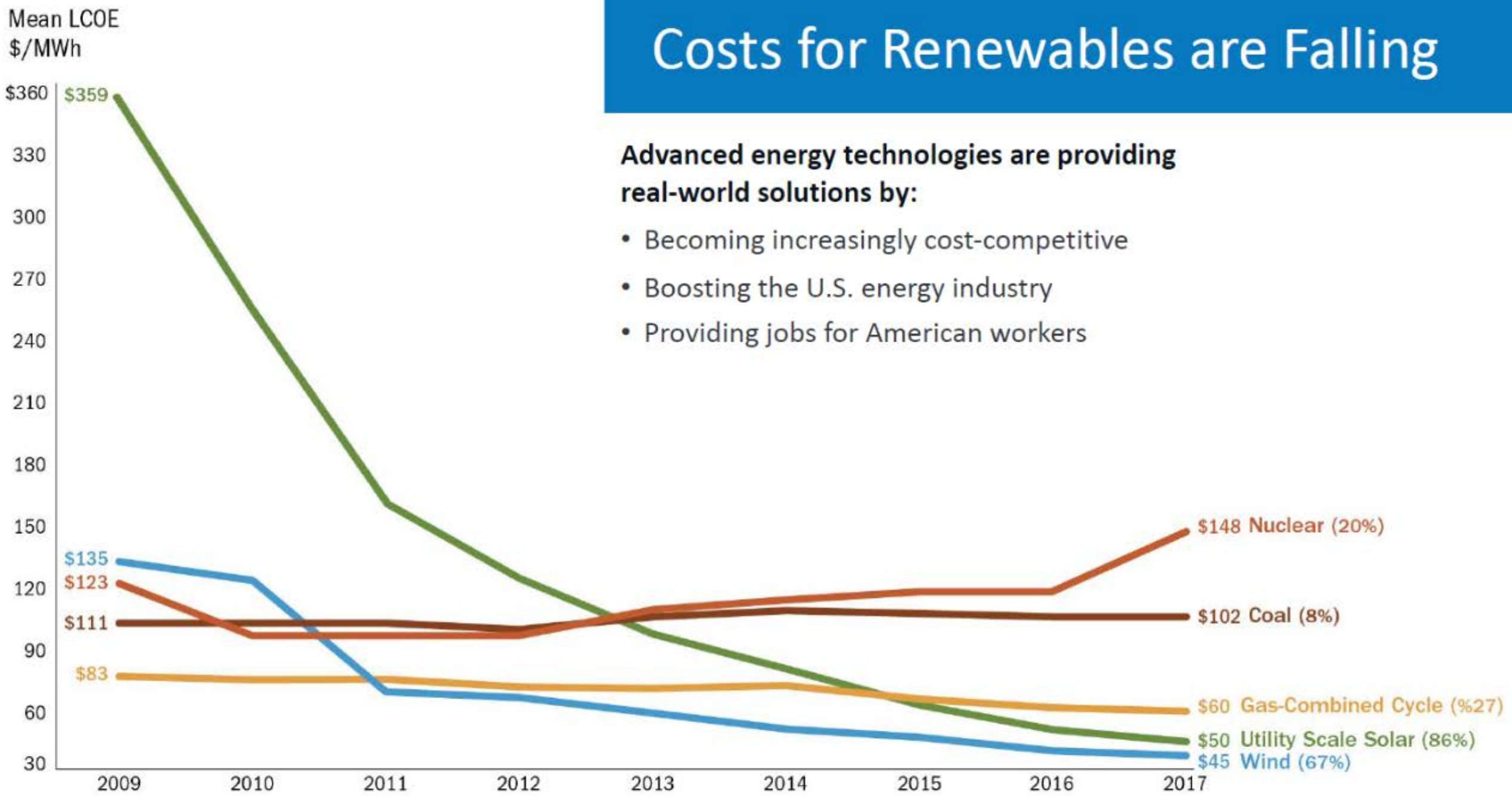
Peppermill Reno – Reno, NV

September 24, 2019

Costs for Renewables are Falling

Advanced energy technologies are providing real-world solutions by:

- Becoming increasingly cost-competitive
- Boosting the U.S. energy industry
- Providing jobs for American workers

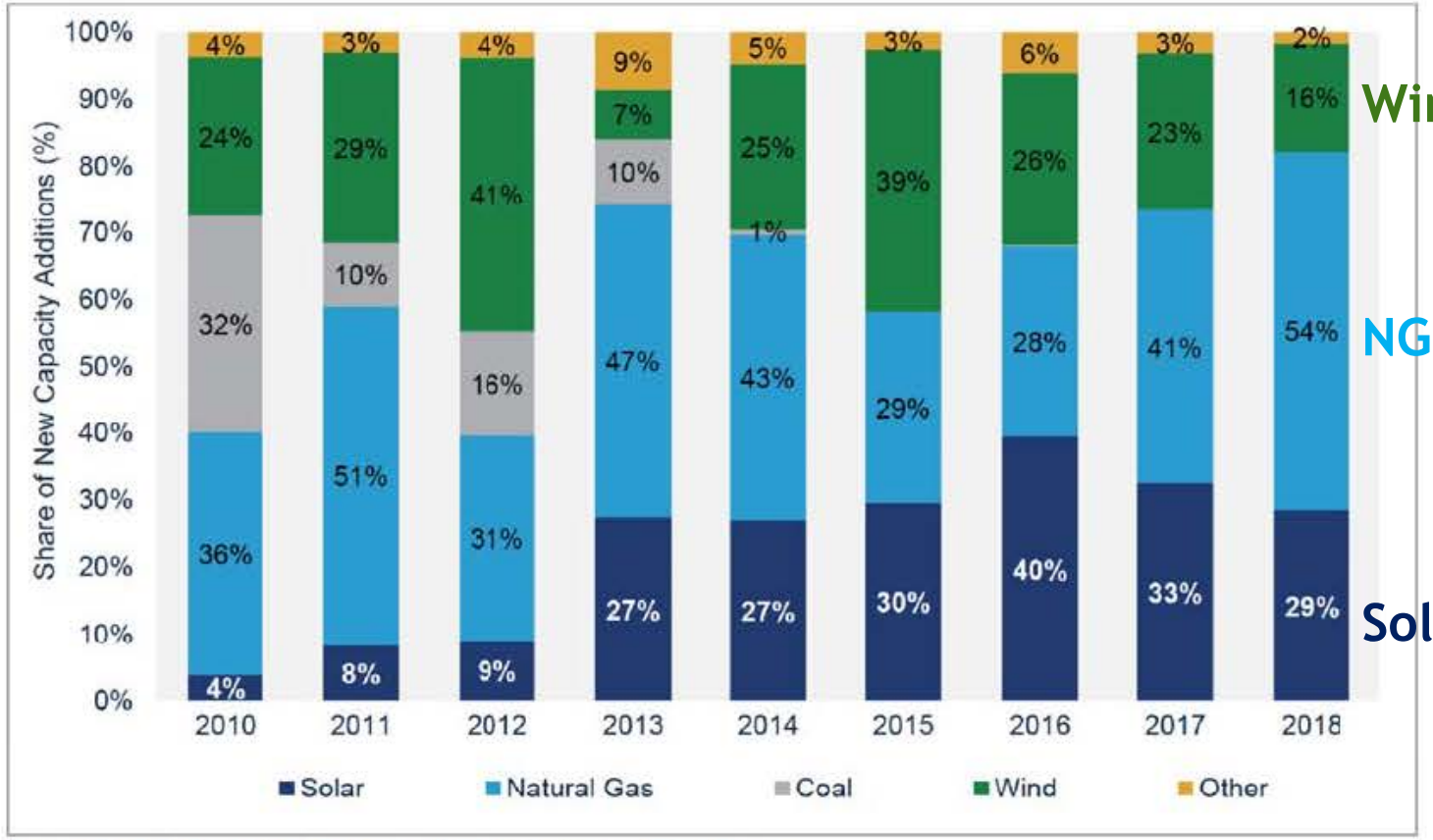


Source: *Lazard's 2017 Levelized Cost of Energy Analysis*, Version 11, 2 November 2017

https://www.lazard.com/perspective/levelized-cost-of-energy-2017/

Recent U.S. Electricity "New Capacity"

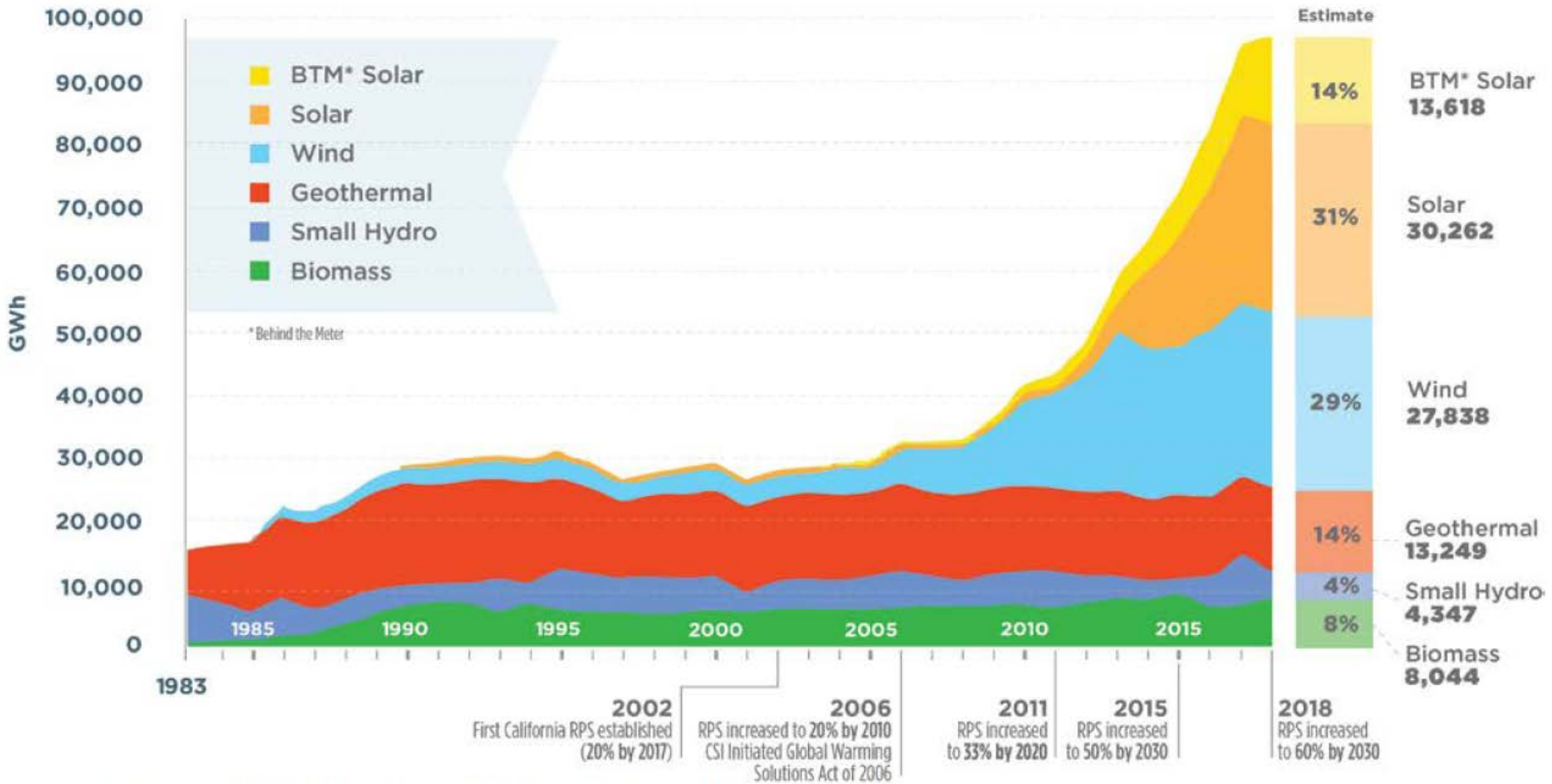
Far from "alternative," **renewable energy and natural gas is the new normal** in the United States



Source: Wood Mackenzie Power & Renewables, FERC (All other technologies)

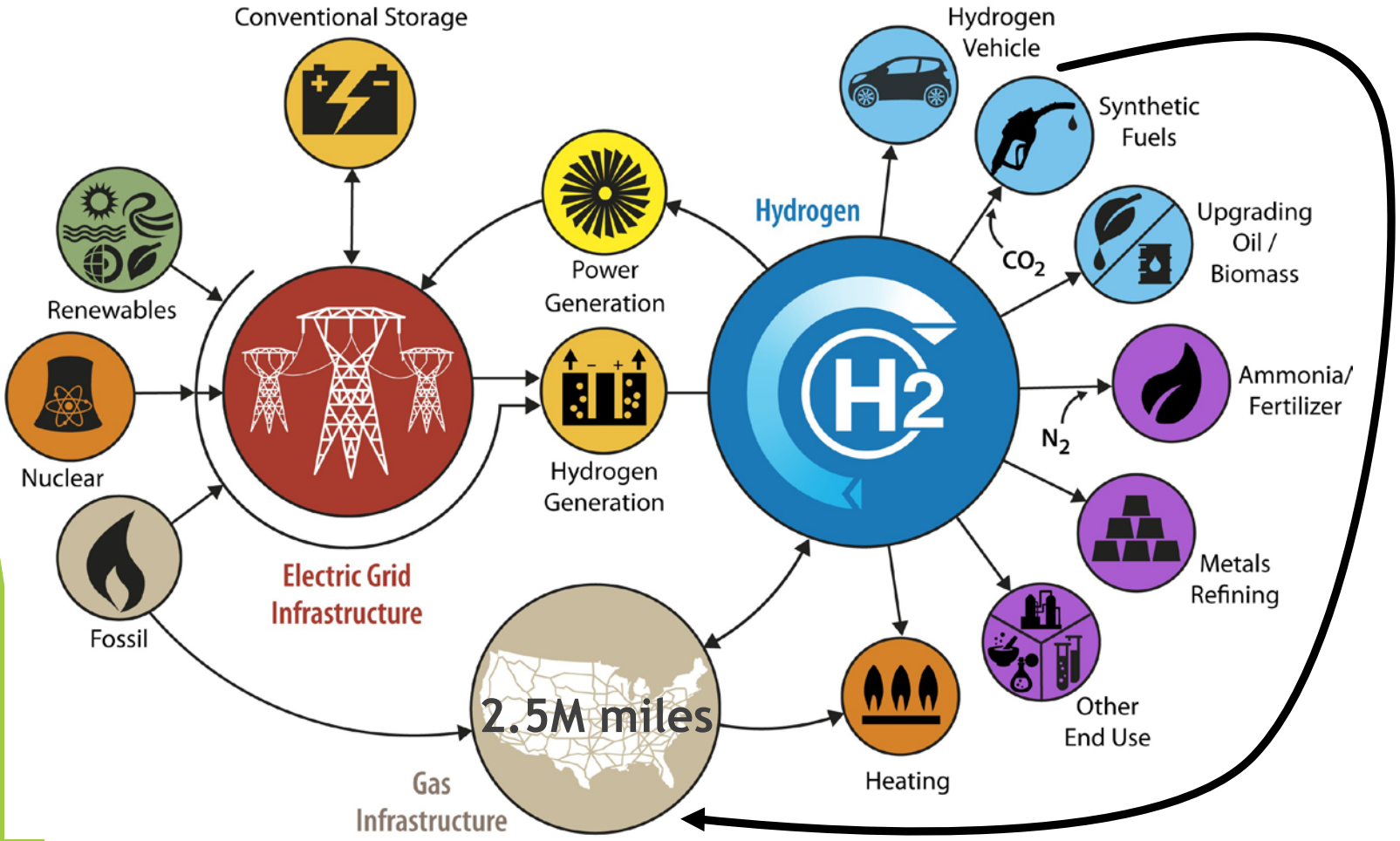
The Need for Long-Duration Energy Storage

Figure 4. Total Renewable Generation Serving California Load by Resource Type



Source: California Energy Commission, staff analysis November 2018

H_2@Scale Initiative



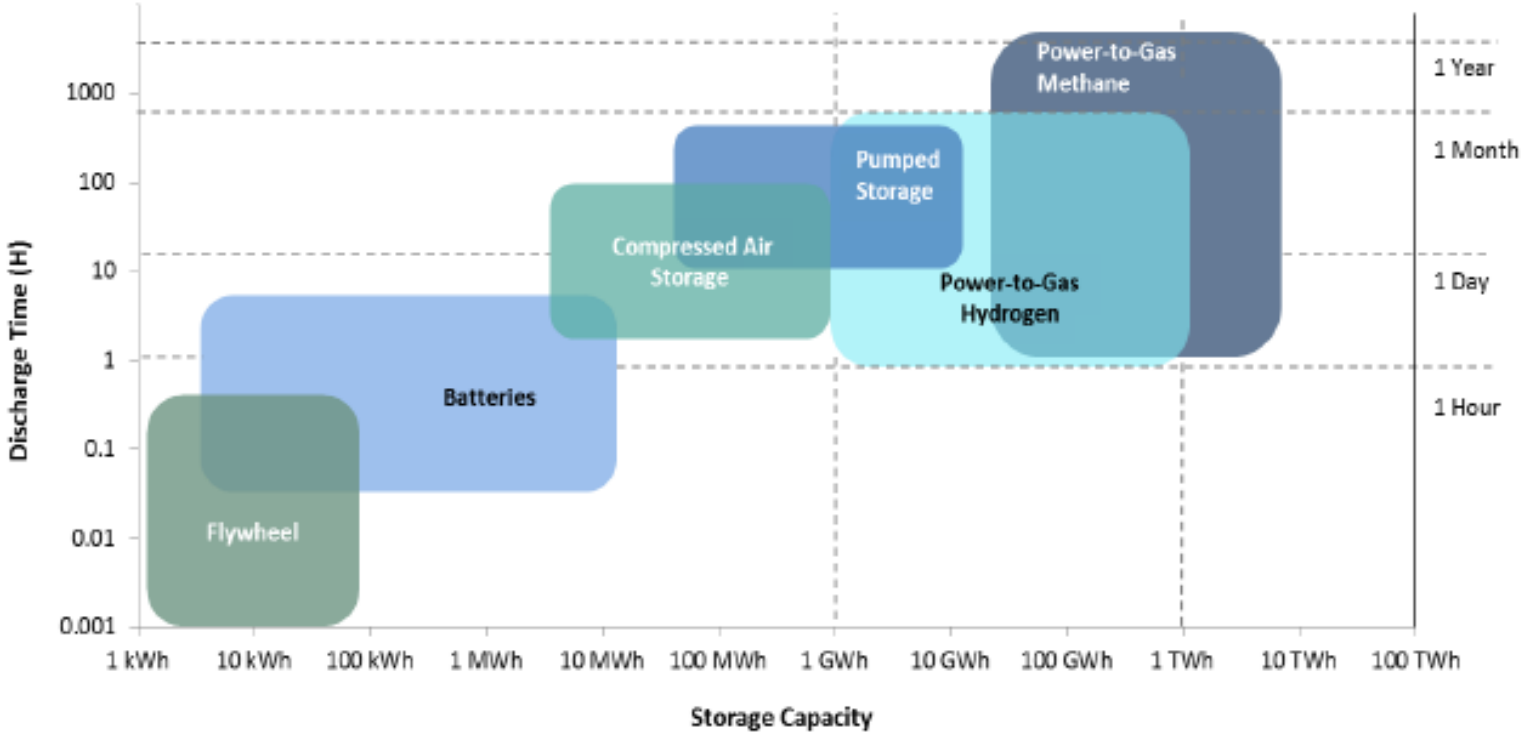
Benefits of Renewable H_2

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

10 MM tons H_2 /year in U.S.

https://www.energy.gov/eere/fuelcells/h2scale

Storing Renewable Electricity as Molecules



Over 130 billion cubic feet of natural gas storage capacity exists in Southern California.

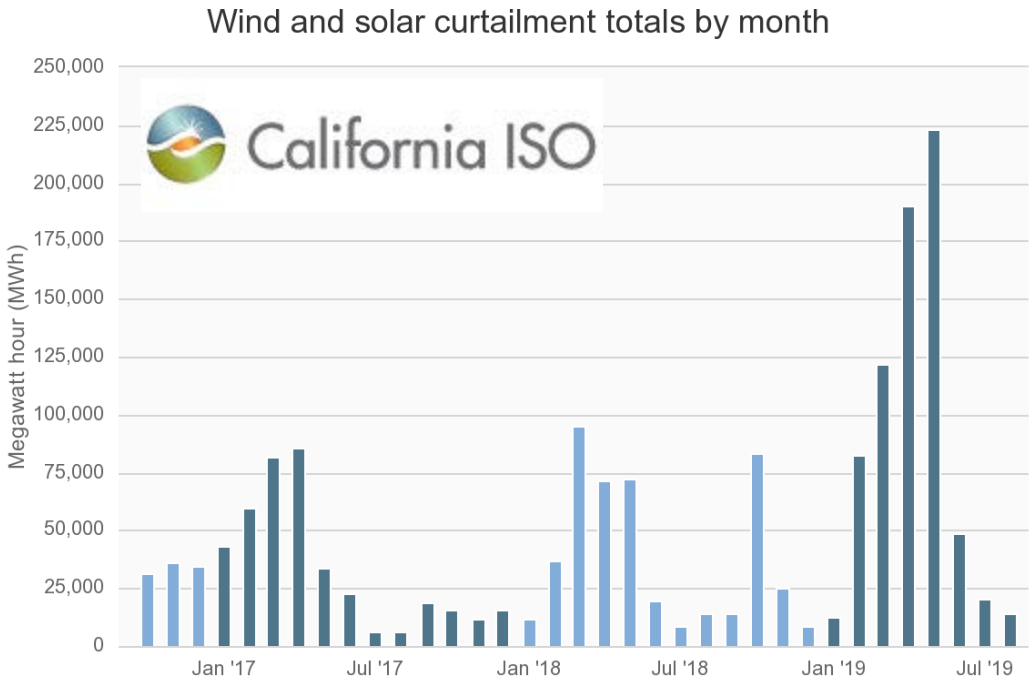
To put this in perspective, this is enough to supply all of the gas-fired generation in the region for more than two months.

- SoCalGas

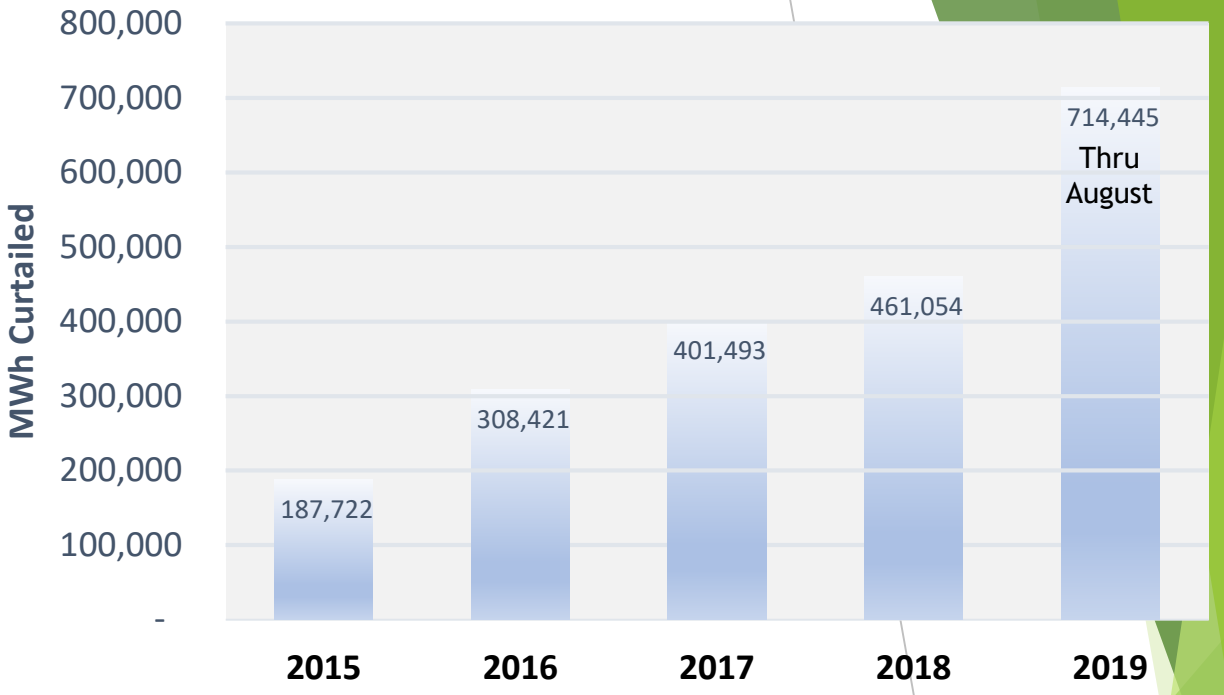
Electricity, transportation, feedstock and heat

- NG has high energy density ~7x greater than H_2
- Existing national energy transmission system
- Flexibility in energy use
- Shifting RE with seasonal energy storage
- High scalability of P2G and RNG Production

Wind and Solar Curtailment Totals



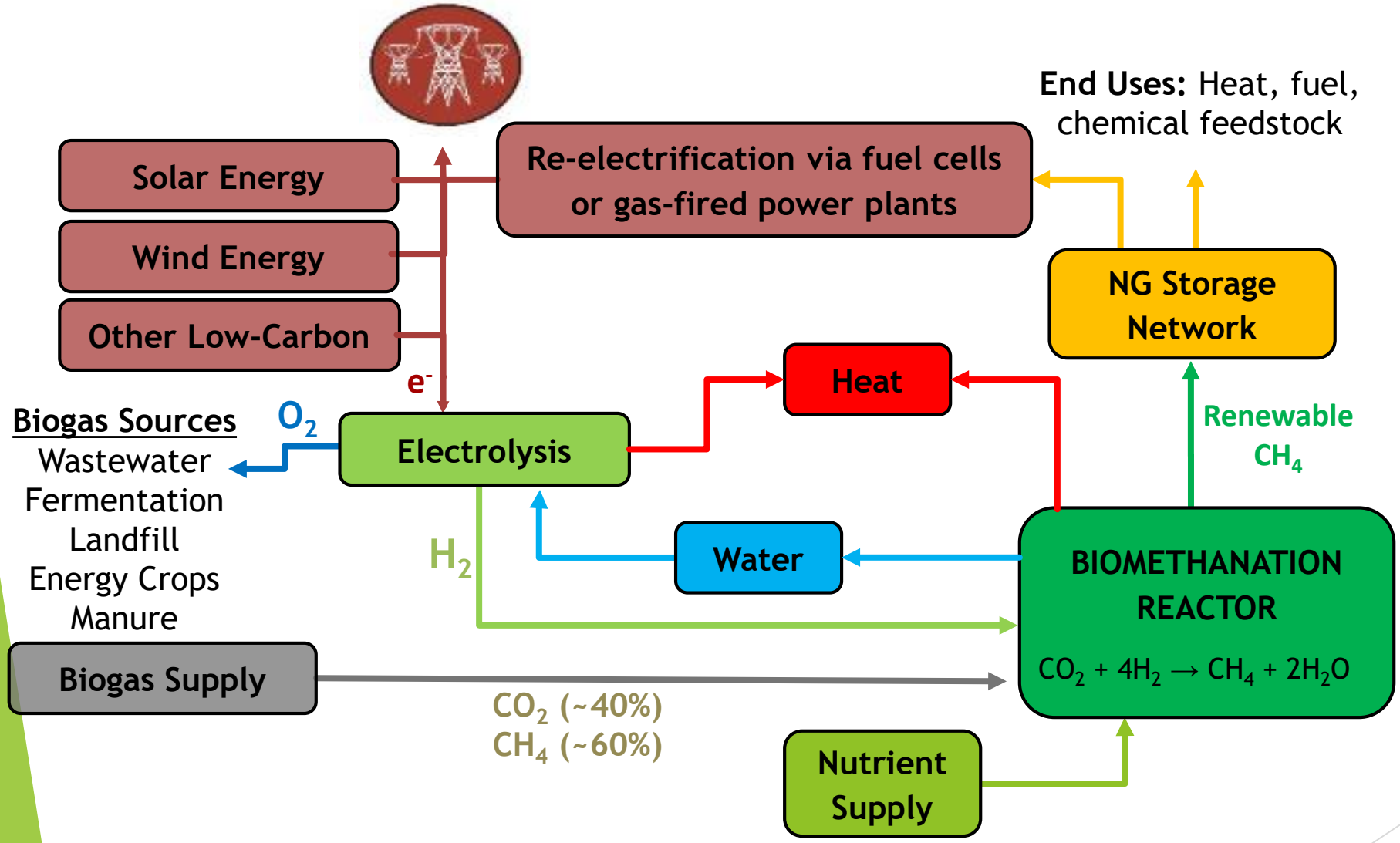
http://www.caiso.com/informed/Pages/ManagingOversupply.aspx



- Solar and wind curtailed by year
- Production only assume: 50 kWh/kg H_2
- Thru August of 2019 alone, over 76,000 Metric Tons of CO_2 could have been recycled!

Year	MWh	MT kg H2	MT CO2
2015	187,722	3,754	19,992
2016	308,421	6,168	32,846
2017	401,493	8,030	42,757
2018	461,054	9,221	49,100
2019	714,445	14,289	76,085

Waste-to-Energy: Biogas Sources of CO_2

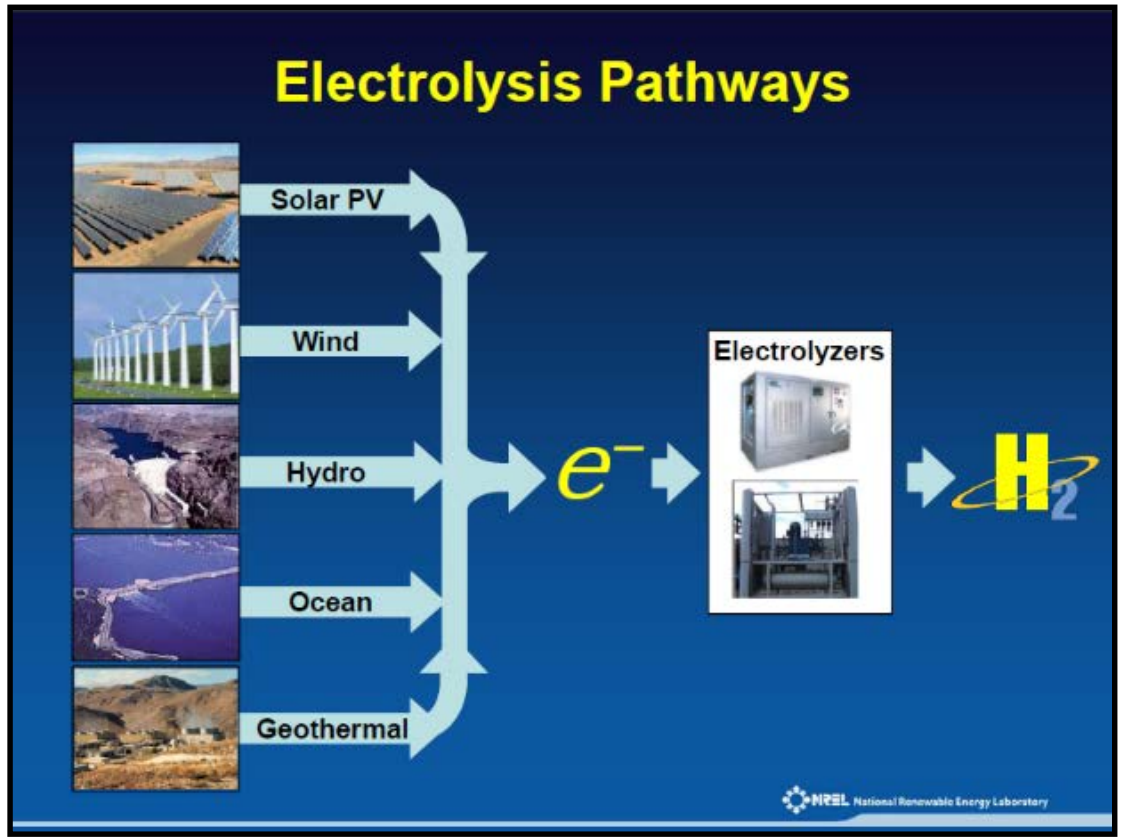


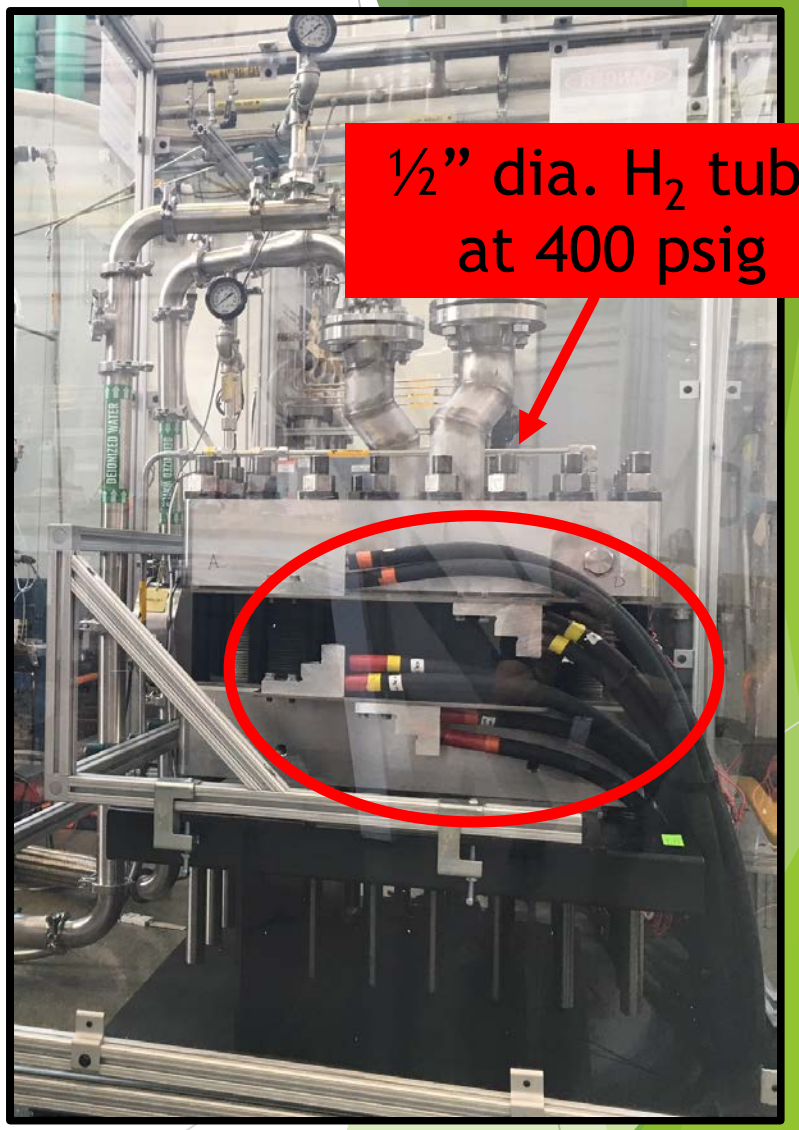
Meets SoCalGas' Rule 30 gas quality standard

HHV R30: 970-1150
CO_2 R30: 3% max
H_2 R30: 0.1% Trigger*
*SoCalGas doe not have a shut-off limit, but this level triggers additional study/testing.

Renewable Hydrogen Production

Step 1: Using renewable electricity to split water into hydrogen and oxygen in an electrolyzer



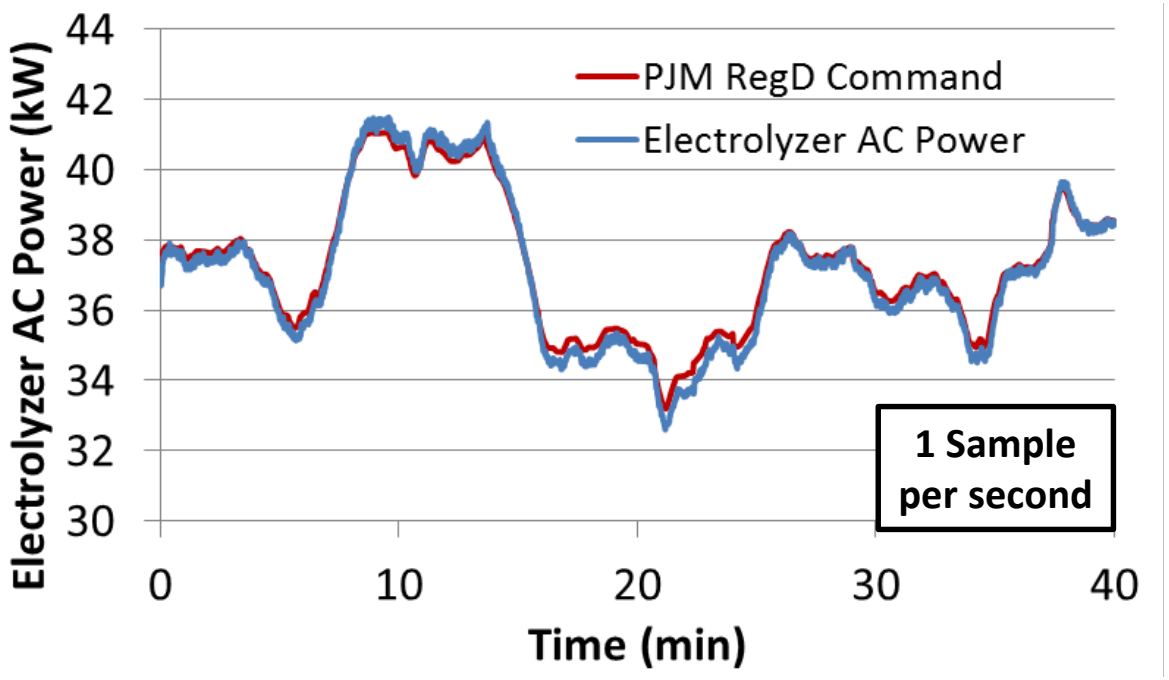


Rules of Thumb

- MW-scale: 50 – 55 kWh make 1 kg of H_2
- 1 MW_e electrolyzer, ~400 kg /day
- 1 kg H2 ~1 gallon of gasoline (gge)

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

Electrolyzer – Electricity Grid Support



Electrolyzer systems are flexible electrical loads that can help stabilize the electrical 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

Biomethanation – RNG Production from CO_2

Step 2: Using the renewable H_2 (from Step 1) and CO_2 in a downstream biomethanation process to produce renewable methane and water

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

Benefits of Biomethanation

- Recycles CO_2 …. As well as the CH_4
  - Ethanol, dairies, wastewater, breweries, fossil
- Meets (SoCalGas') pipeline quality standards
  - 998 BTU/CF, 0.89% CO_2, 0.4% H_2
- Scale-able, non-toxic, self-replicating biocatalyst,
- Low temperature (65˚C) systems

Rule of Thumb: 10MW_e of electrolysis feeding a bioreactor can produce ~500 scfm (12,000 Nm^3 or 440 MMBTU per day/6 g/L-hr) of methane and recycles ~20 tons of CO_2 per day

H_2 & RNG Systems at NREL

Electrolyzer System

- Today, 250 kW PEM stack
  - 5 kg H_2 / hr
- 30 bar H_2 Pressure
  - Up to 70 bar max
- (4) Power Supplies
  - Current-sharing mode
  - 4000 A_{dc} at 250 V_{dc}

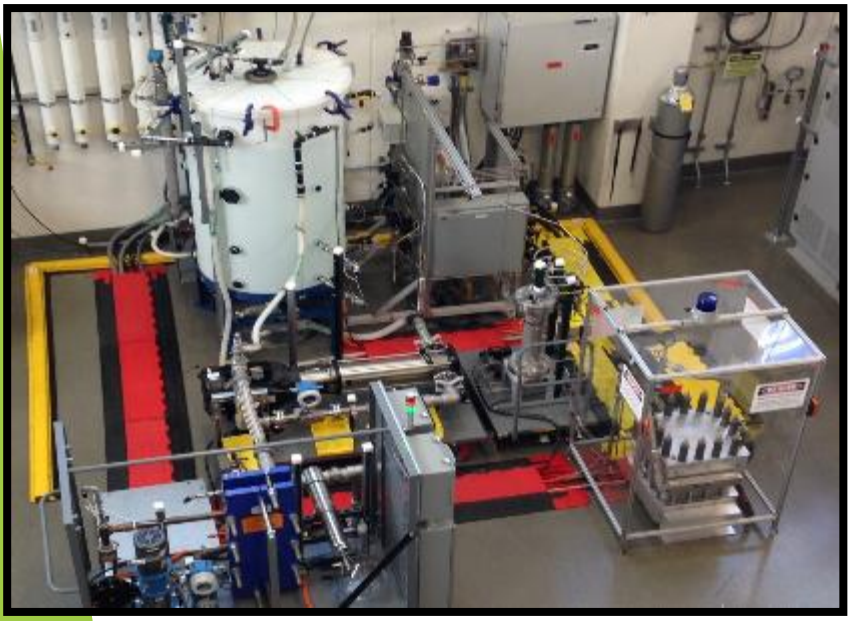
H_2 and RNG R&D Site

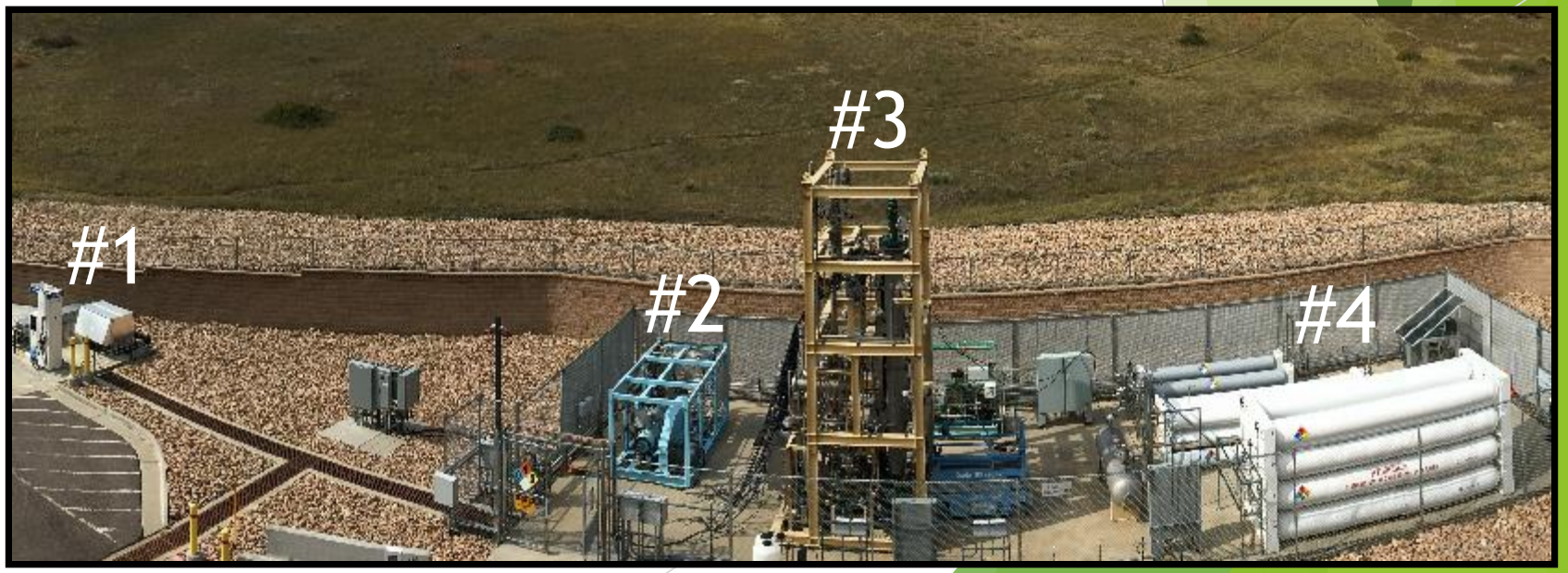
#1) 350 and 700 bar pre-cooled H_2 dispensing system

#2) Diaphragm and piston compressors

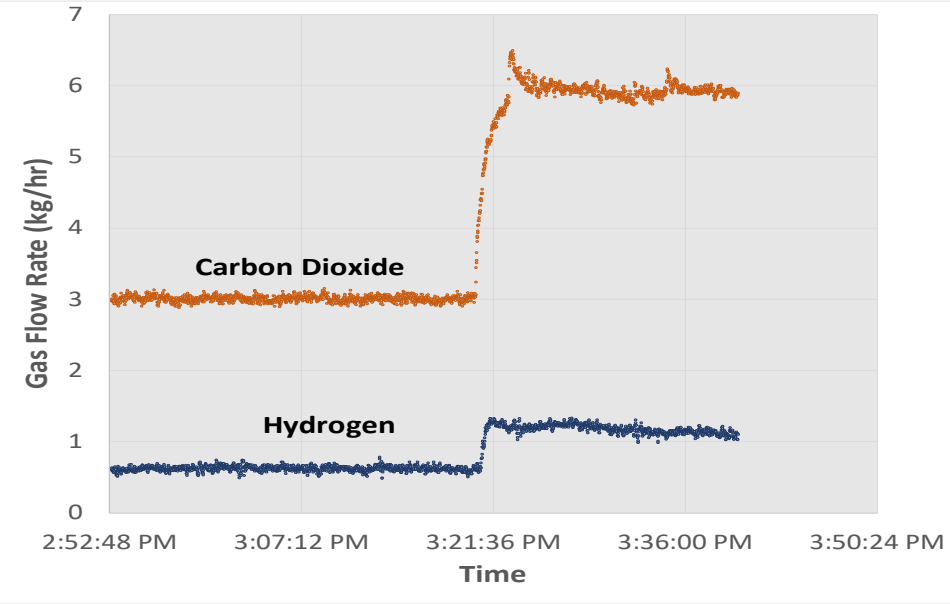
#3) 700 L bioreactor – operates at 18 bar (260 psig) and 60 - 65°C with agitation, recirculation loop and cell recycle

#4) 200, 400 & 900 bar storage - 350 kg Total



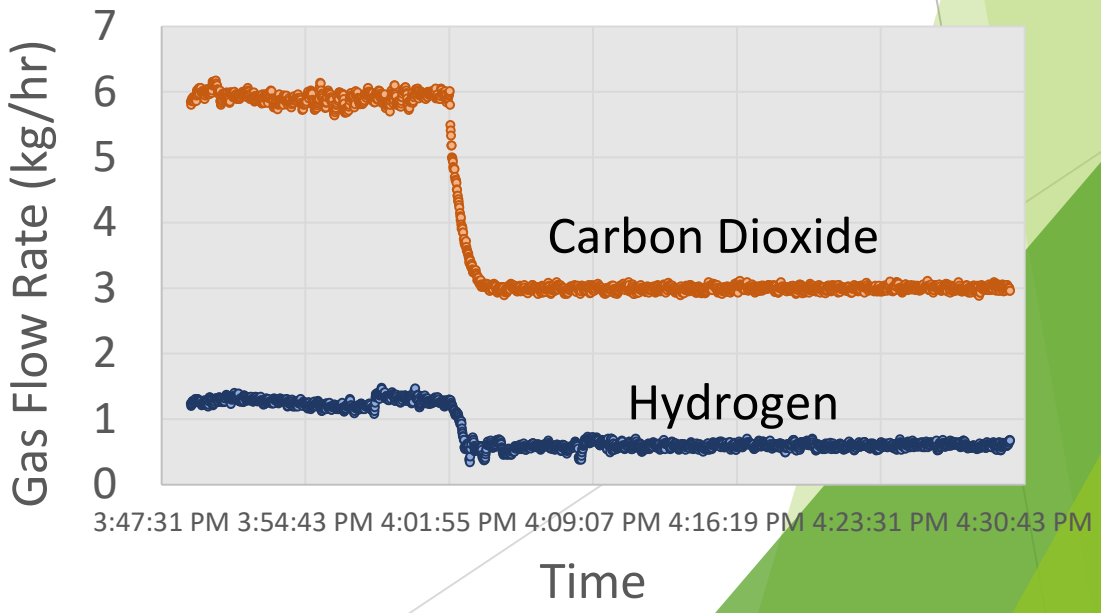


Varying Input Gas Flows

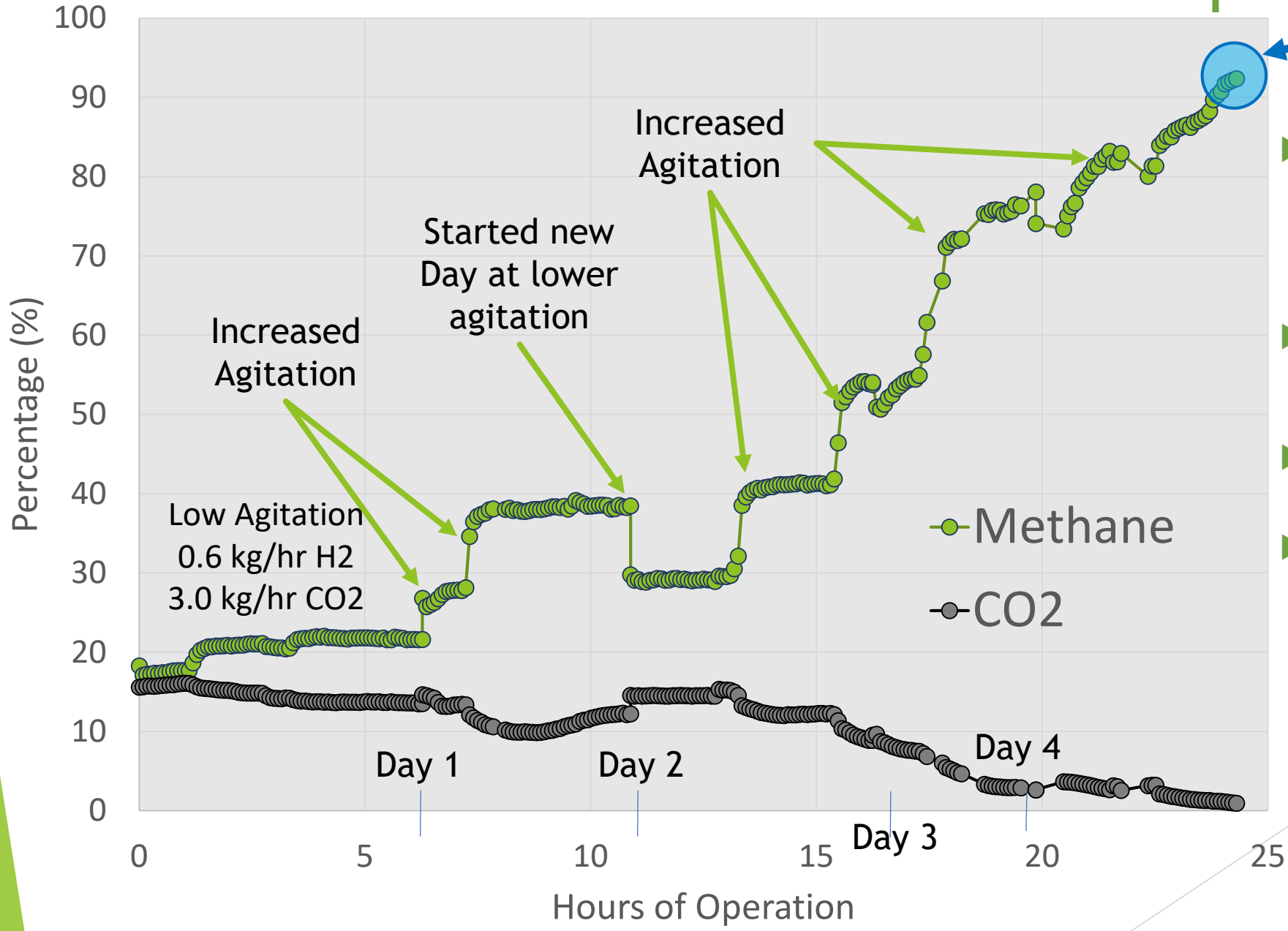


- Step-up and step-down response shown
- Bioreactor can load follow like an electrolyzer
- **Challenge:** Low density gas, like H_2, is difficult to monitor

- **Goal:** Maintain > 98% methane production under varying input gas flows
  - Trace CO2, H2 and H2S remaining
- Maintain H:C Ratio
  - Ideally 4:1 H_2 to CO_2



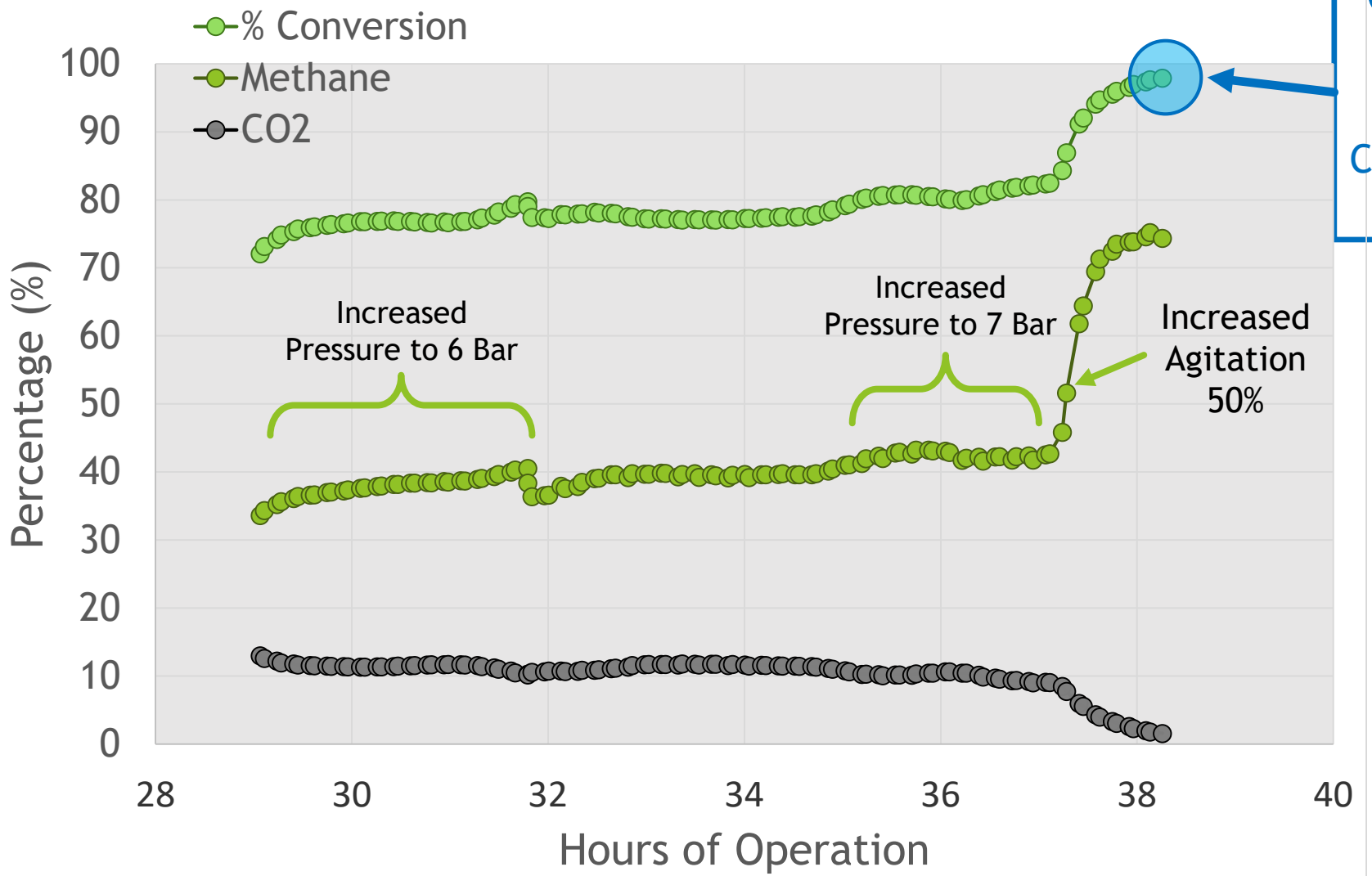
SoCalGas – 700L Bioreactor Start-up



After 24 hours of total operation conversion reached 92%

- During this start-up phase the biocatalyst grew to 10x the initial population
- Agitation reached 50% of maximum RPM
- Flow rates 20% of rated
- Reactor pressure 4 bar during this time
  - 18 bar (260 psig) max.

Increasing Pressure to Improve Conversion



Conversion reached 98%

$$\text{Conversion} = \frac{\%\ CH_4}{\%\ CH_4 + \%CO_2}$$

Operational State

- Start pressure 5 bar
- Returned to low agitation rate
- 0.6 kg/hr H_2
- 3.0 kg/hr CO_2

Biocatalyst – Methanogenic Archaea

Growth Requirements

- Seawater environment
- Salts and minerals
- 60 – 65°C
- Anaerobic conditions
- Feedgas: CO_2 and H_2

Long Term Stability

- Capable of daily startup
- "Load" following
- Robust
- Self-replicating
- Fast recovery during start/stop cycles

Methanothermobacter thermautotrophicus

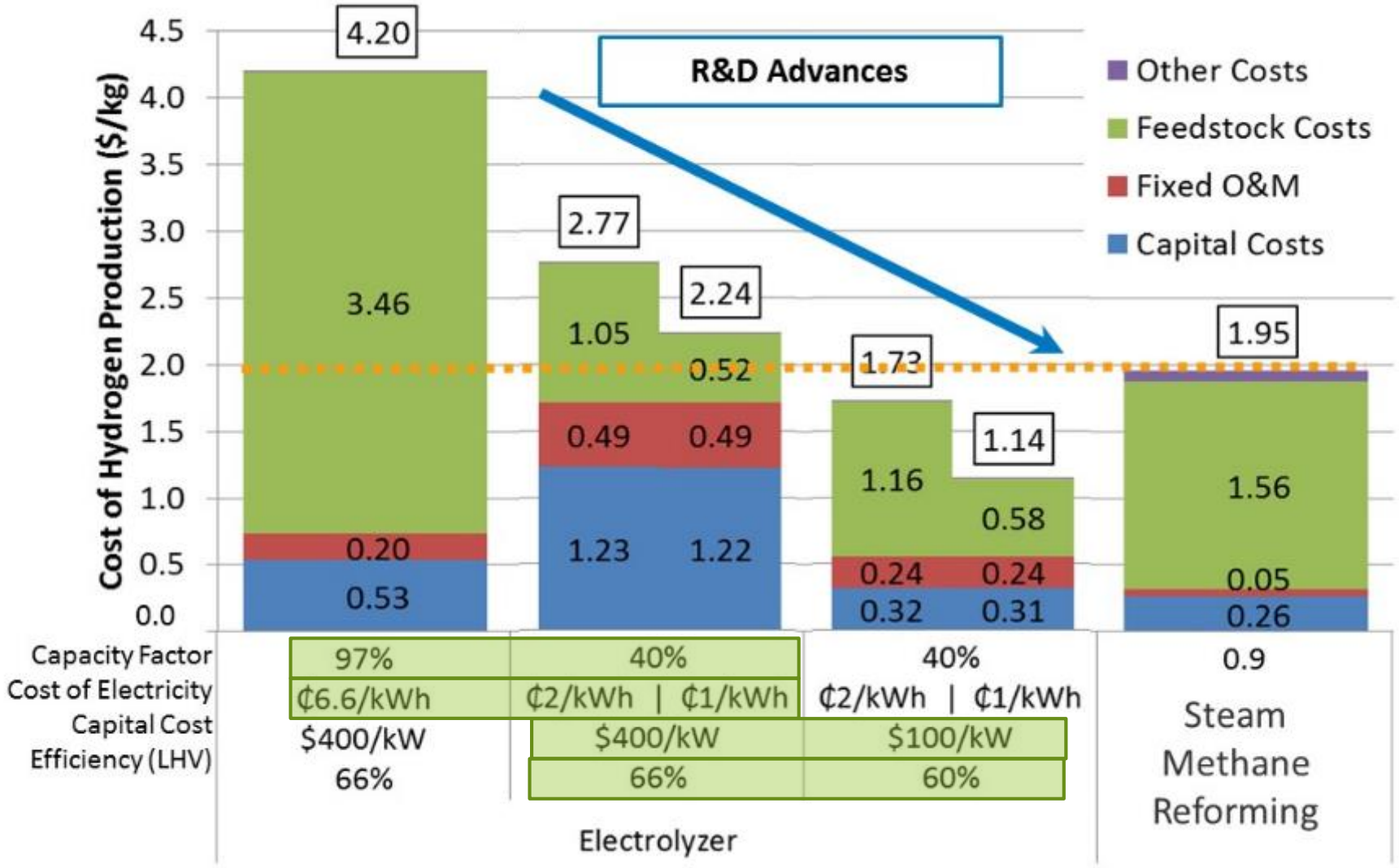
Efficient	98.6% of carbon goes into methane
Productive	VVD* of 800, H_2 mass-transfer limited
Responsive	Quick return to methane production within seconds/minutes
Selective	100% methane, no intermediates
Robust	Tolerant to oxygen, H_2S, CO, Sulfate, Ammonia, particulates
Simple	Moderate temperature range (60 – 65°C)

Electrochaea's proprietary biocatalyst is a selectively evolved – not genetically modified – strain of *methanogenic archaea*, a single-celled microorganism that has populated Earth for billions of years

http://www.electrochaea.com/technology/

Electrochaea

Challenge – Reducing the Cost of H_2



Upcoming Projects

- DOE Bioenergy Technology Office, SoCalGas and Electrochaea
  - **Biopower:** Upgrade biogas to pipeline quality RNG
  - Design and build a scaled-down mobile bioreactor
  - Analytical development

- SoCalGas, Bioenergy and Fuel Cell Technology Offices
  - **H2@Scale:** Systems integration and optimization
  - IP development
  - Gas mixing and mass transfer

Biomethanation – Bulk Energy Storage and…

- Recycles CO_2 in addition to the CH_4
- Sector Coupling – Electrons-to-Molecules
- Biogas and pure CO_2 are potential sources
- Uses the existing NG network (2.5 Million miles)
- Produces a "Drop-in" replacement for fossil NG
- Heat and oxygen are (also) produced in this two-step process
- Enables higher penetrations of solar- and wind-generated electricity
    - Shifts, in time and space, the production of renewable electricity

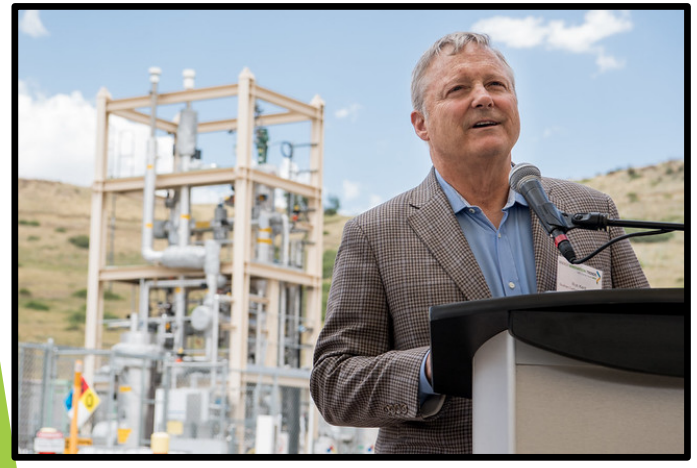
Meets SoCalGas' Rule 30 gas quality standard

Higher Heating Value: R30: 970-1150 BTU/CF Carbon Dioxide: 3% max. Hydrogen: R30 - 0.1% Trigger for more testing and study, SoCalGas does not have a shut off limit set.

Partners

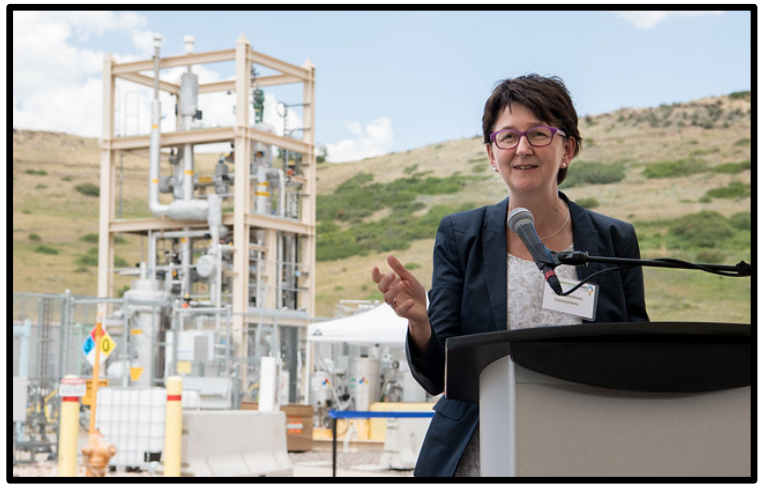
Southern California Gas Company

A Sempra Energy utility®



Ron Kent

Electrochaea



Doris Hafenbradl, CTO

Mich Hein, CEO

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

Bioenergy

H_2 & Fuel Cells

Solar Energy

Pictures taken on August 13, 2019 at NREL's 3rd Partnership Forum during the SoCalGas bioreactor dedication ceremony

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System Comparison

	P2G - BioCat	P2G - SoCalGas
Location	Copenhagen, DK	NREL - Golden, CO
Volume	3,500 L	700 L
Electrolyzer	1 MW – Alkaline	125 kW - PEM
Production	30.4 scfm CH_4	4.1 scfm CH_4
CO_2 Source	Avedøre WWTP	Delivered
Pressure	9 bar	18 bar

"The core of our power-to-gas system is a selectively evolved microorganism – **a methanogenic archaea** – that excels through unprecedented catalytic ability and industrial robustness."

http://www.electrochaea.com/about/

Renewable Methane Production

Scientific Approach

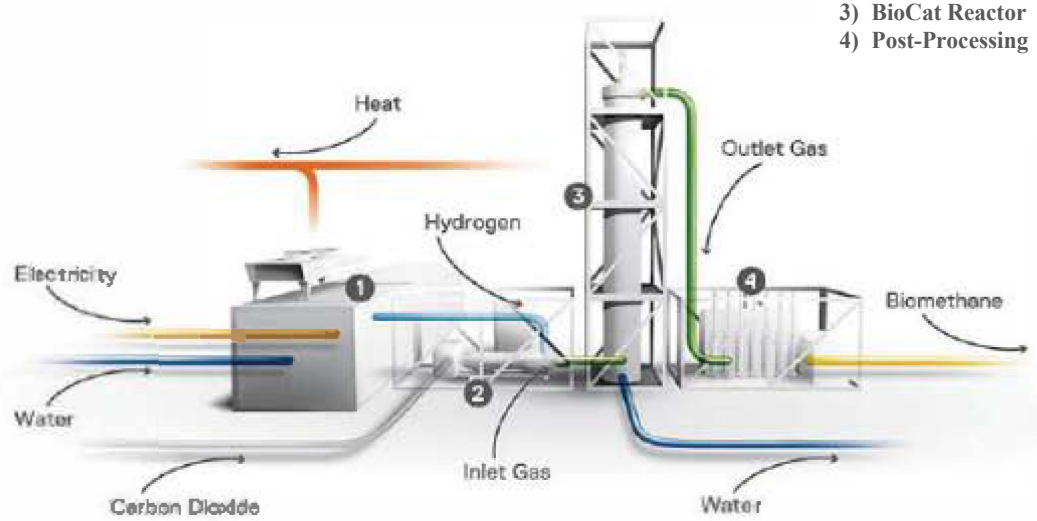
- Utilize excess electricity production for the electrolysis of water to H_2 and O_2
- Optimized strain of methanogenic archaea to perform methanation under industrial conditions
- 98% Carbon efficiency of CO_2 to CH_4
- Post-processing for pipeline quality natural gas

Significance and Impact

- Potential long term storage strategy via conversion of electricity & CO_2 to CH_4
- High efficiency CO_2 capture and conversion strategy
- Demonstrated route to renewable methane

BioCatProject
POWER-TO-GAS VIA BIOLOGICAL CATALYSIS

1) Electrolyzer
2) Pre-Processing
3) BioCat Reactor
4) Post-Processing



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

NREL
Transforming ENERGY

SoCalGas
A Sempra Energy utility

Electrochaea