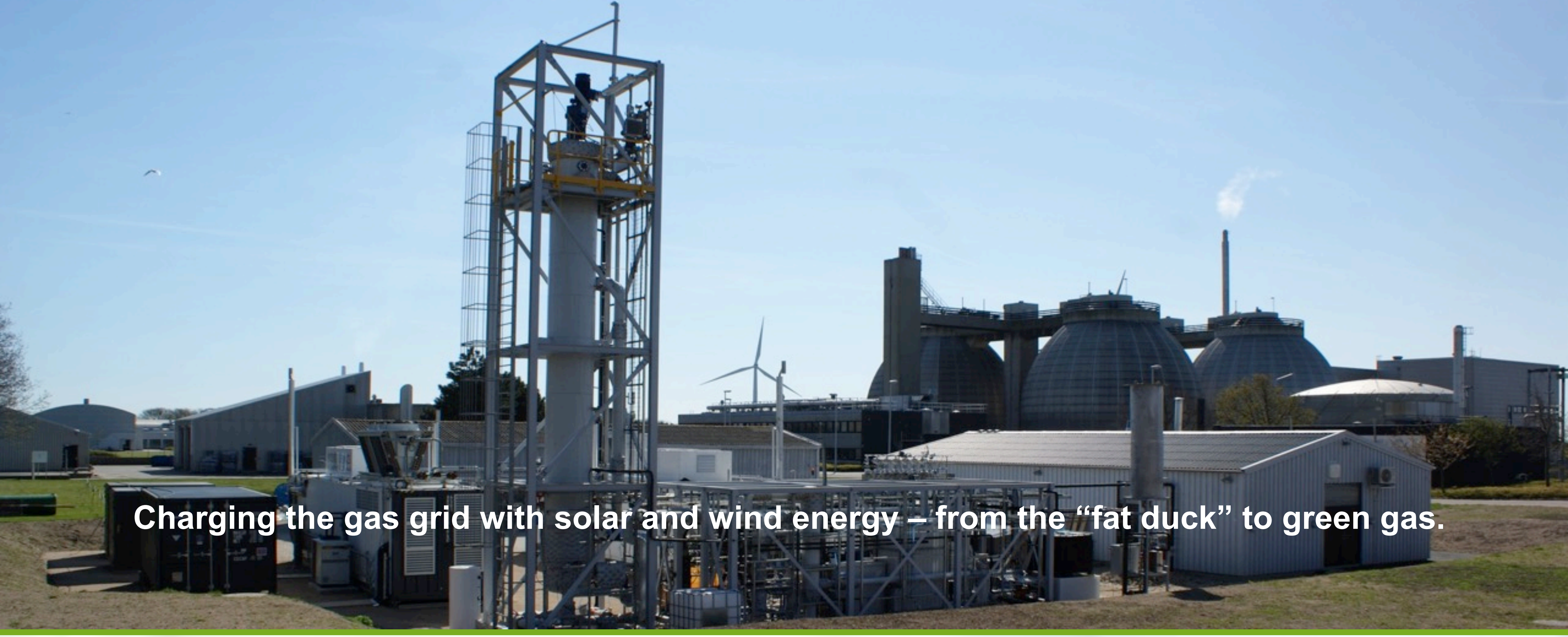


Charging the gas grid with solar and wind energy – from the “fat duck” to green gas.

Electrochaea

2nd International SOLAR FUELS Conference
8 July 2017 San Diego CA

Charging the Natural Gas Grid

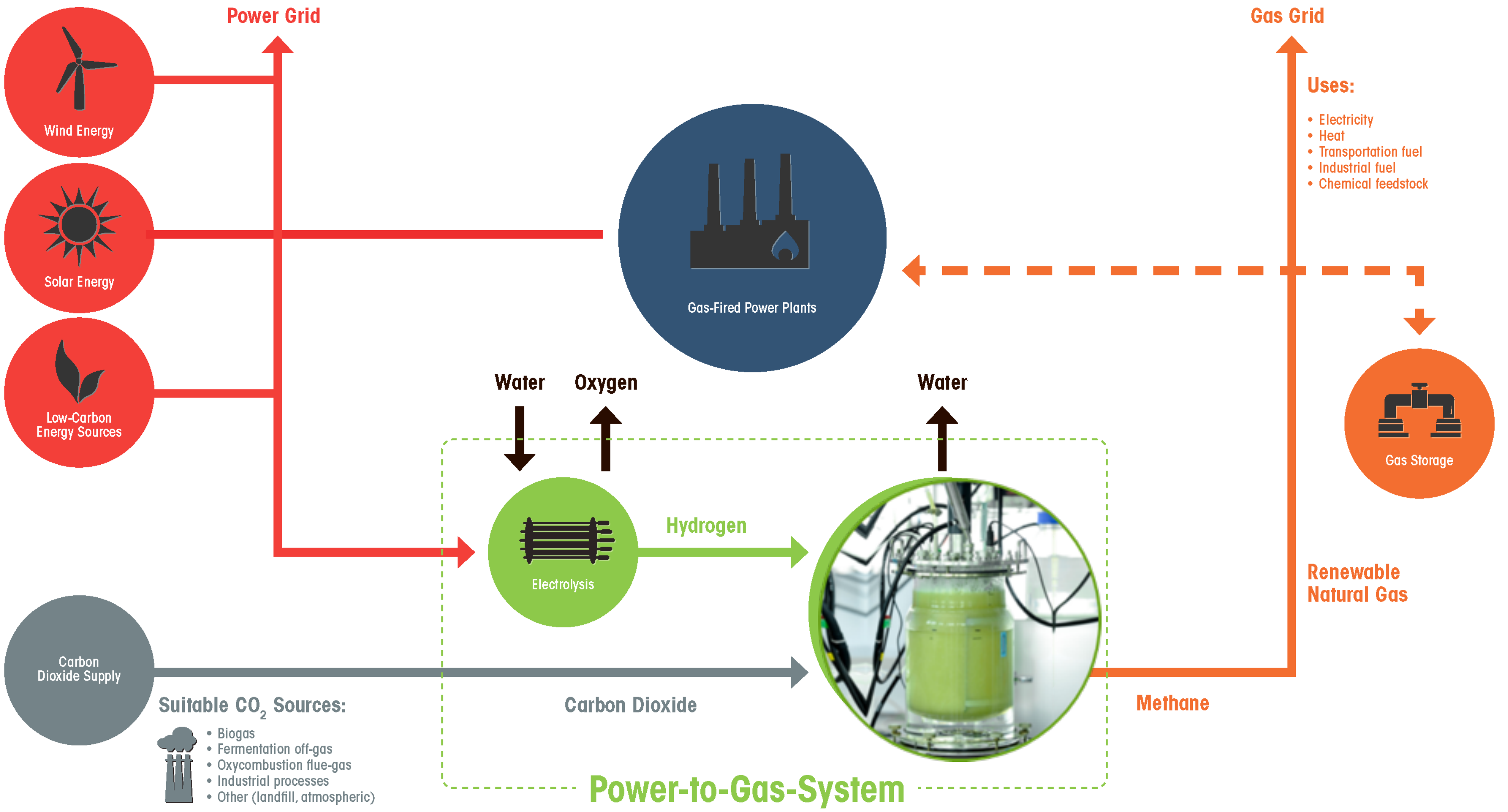
Challenge of Renewables:

- Renewable e- generation is intermittent, not responsive to demand
- Intermittency results in non-ideal economic and operational outcomes
- Storage can mitigate adverse outcomes of intermittency if scalable and available on demand

Power to gas as a solution:

- Renewable electricity can be converted to chemical energy in the C-H bonds of methane at grid scale
- Biological methanation is evolved for intermittency and is scalable to grid storage applications
- Biological methanation produces grid quality methane

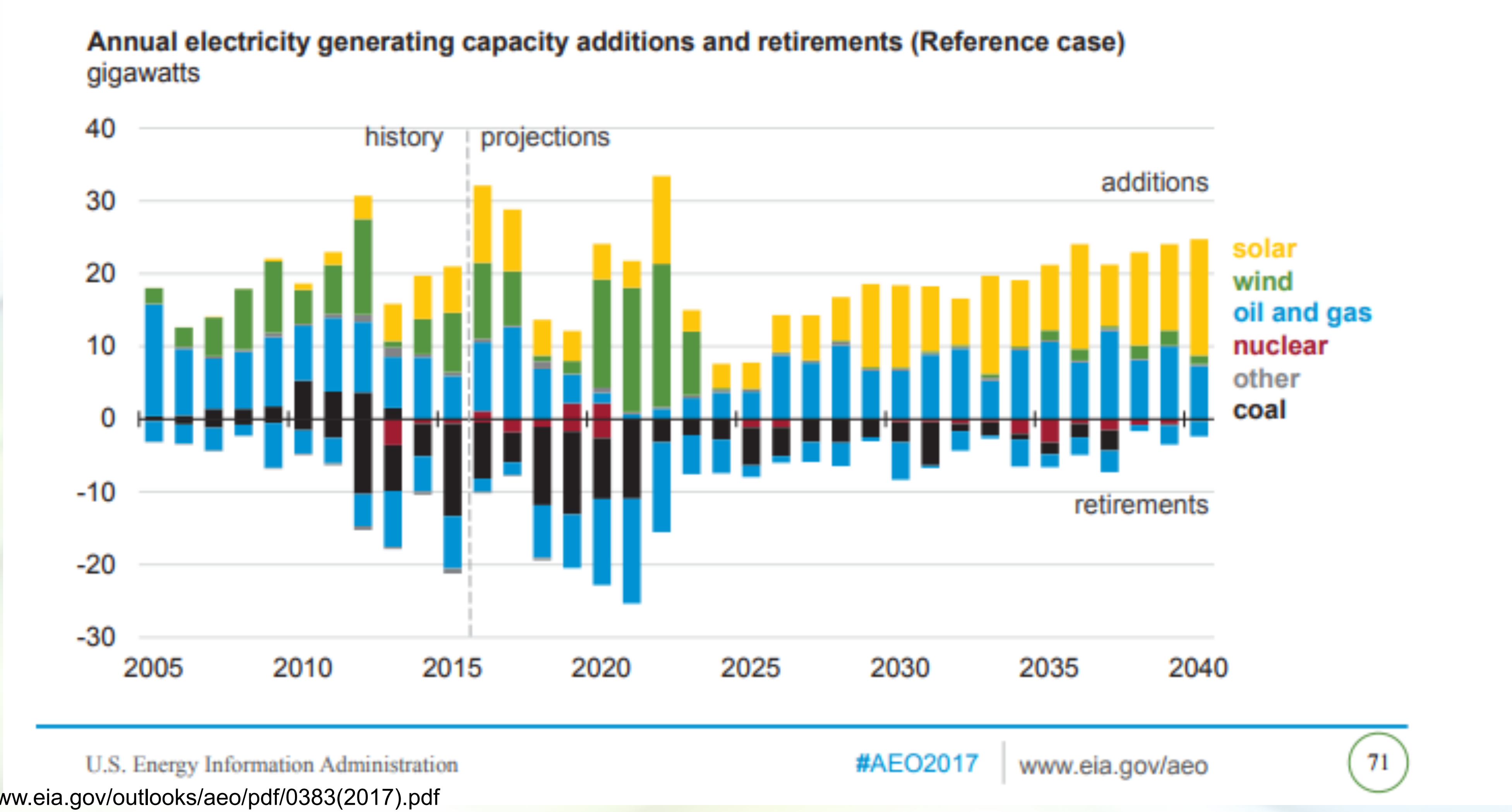
Energy Storage and Grid Integration



graphic adapted from Sterner, Specht, 2008

Energy Generation is increasingly Green and Intermittent

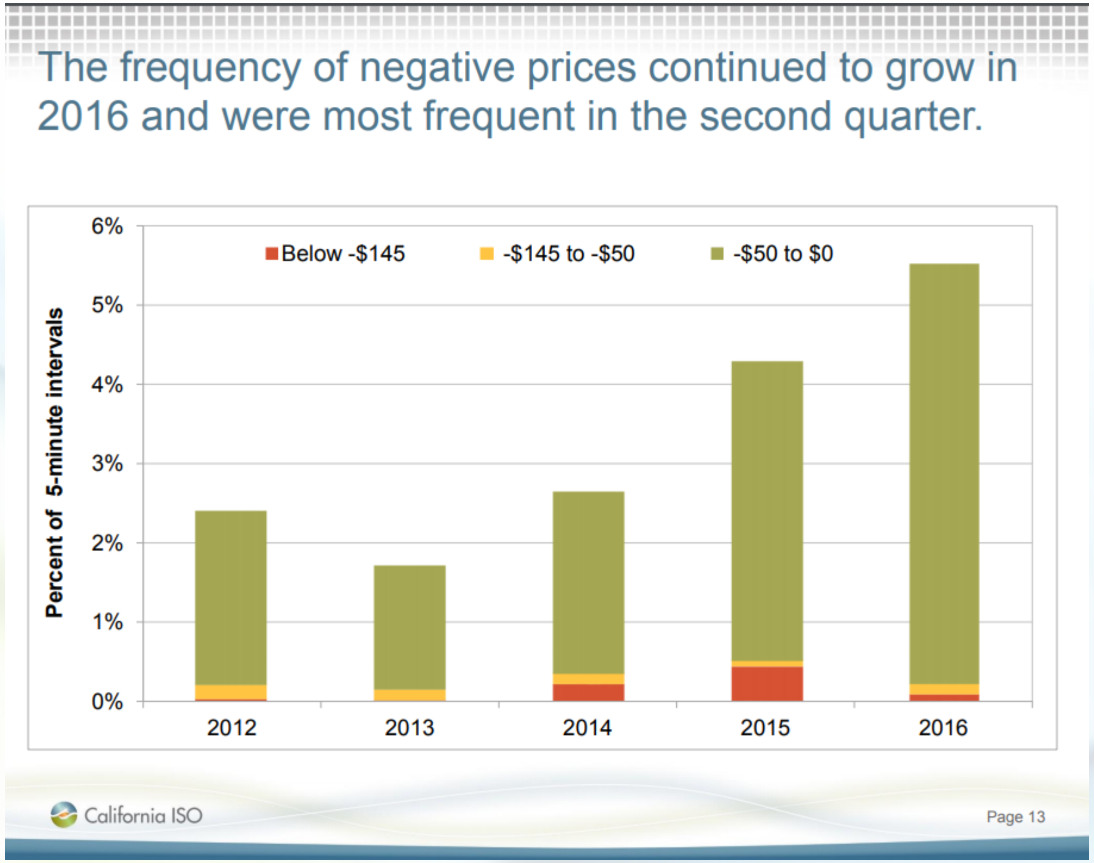
EIA electricity capacity generation addition Prognosis:



From https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf

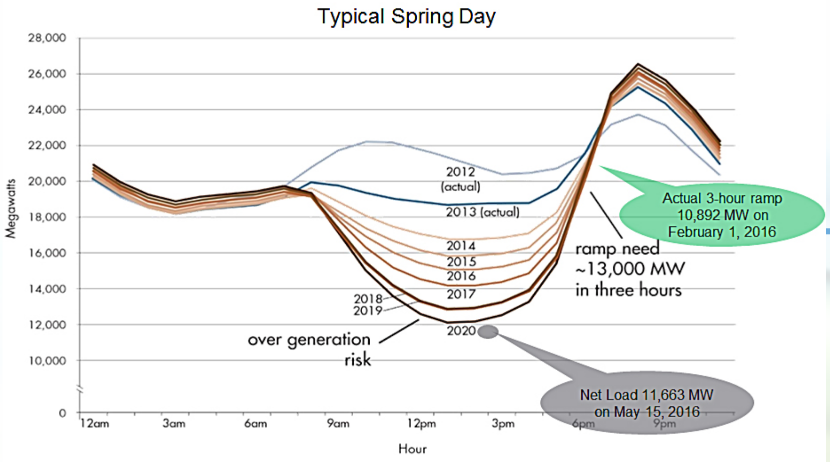
Intermittency of Power Supply provides Challenges and Opportunities

Intermittency results in challenges to grid reliability, Supply/Demand imbalances, fluctuating power prices, curtailment and increasing occurrences of low or negative pricing and reduced value of renewable generation assets

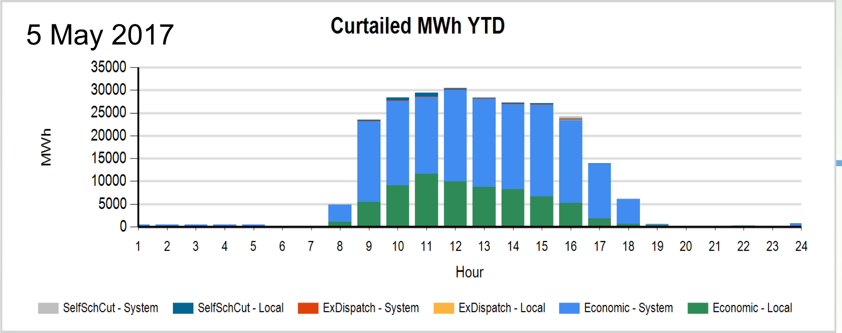


From http://www.caiso.com/Documents/Agenda-Presentation-2016AnnualReportMarketIssues-Performance.pdf

Power-to-gas can be scaled to meet grid scale storage demand



Curtailed Power



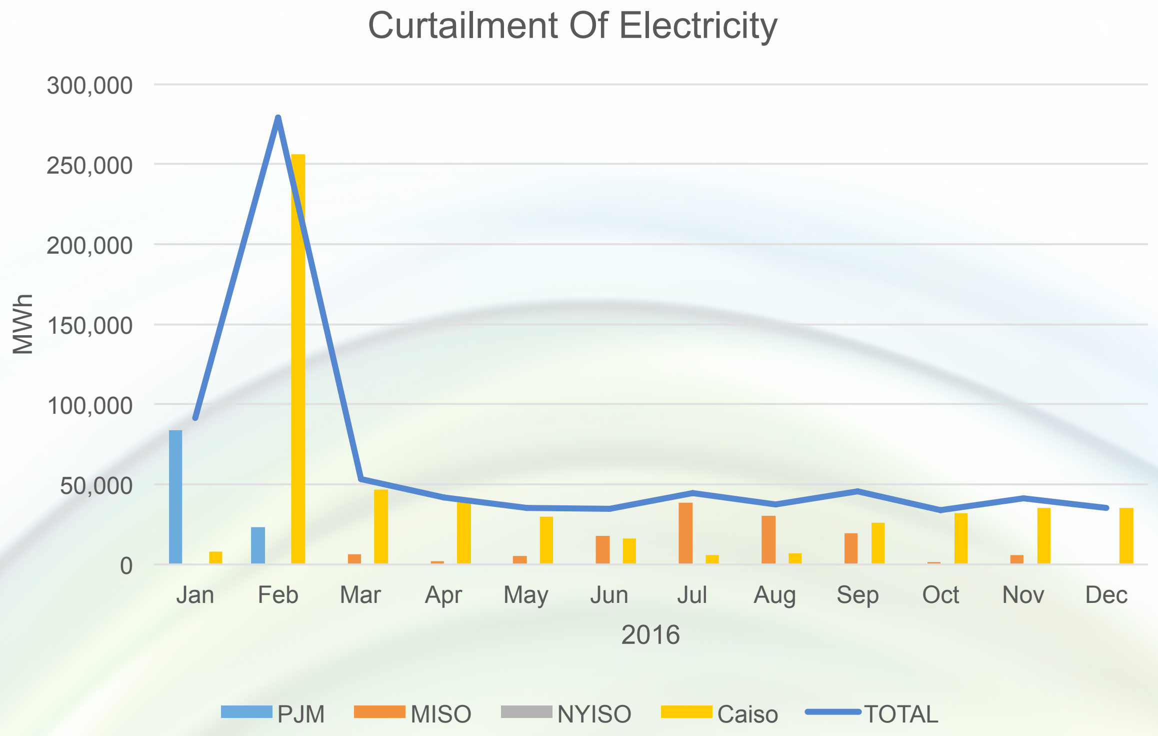
California ISO

BioCat System:

- Maximize revenue from renewables
- Store & redistribute energy and CO_2 to meet greatest need
- Stabilize power system with dynamic response

http://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf http://www.caiso.com/Documents/Wind_SolarReal-TimeDispatchCurtailmentReportMay05_2017.pdf

Curtailment of Renewable Energy



CURTAILMENT IN 2016 MWh				
PJM*	MISO*	NYSO*	Caiso**	TOTAL
106,848	127,785	216	538,243	773,091

Equivalent to 90MW P2G Plant

$85mio investment

Producing ~1,500,000 MmBTU of renewable natural gas

From *http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2016.shtml, Interchange transactions
**http://www.caiso.com/informed/Pages/ManagingOversupply.aspx, Production and curtailment data May 1, 2014 – May 31, 2017

Starting point

Renewable power supply & grid balancing

oxygen sink

$$4H_2O + e^- \rightarrow 4H_2 + 2O_2 + \text{Heat}$$

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

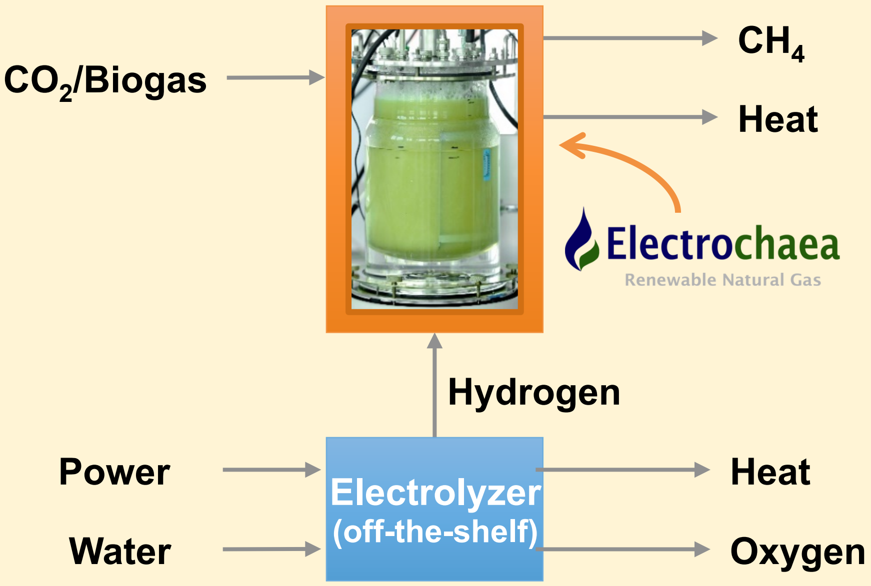
Biogas
Fermentation off-gas
Oxycombustion flue-gas
Industrial processes
Other (landfill, atmospheric)

gas sector

heat sink

System Design & Chemistry

System Design



Inputs

- Water
- Low-cost or stranded electricity or H_2
- CO_2 from biogas, fermentation, or other sources
- Electrochaea's proprietary biological catalyst

Outputs

- Pipeline-grade methane for direct grid injection
- Oxygen for industrial or medical applications
- Heat for on-site use or district heating grids

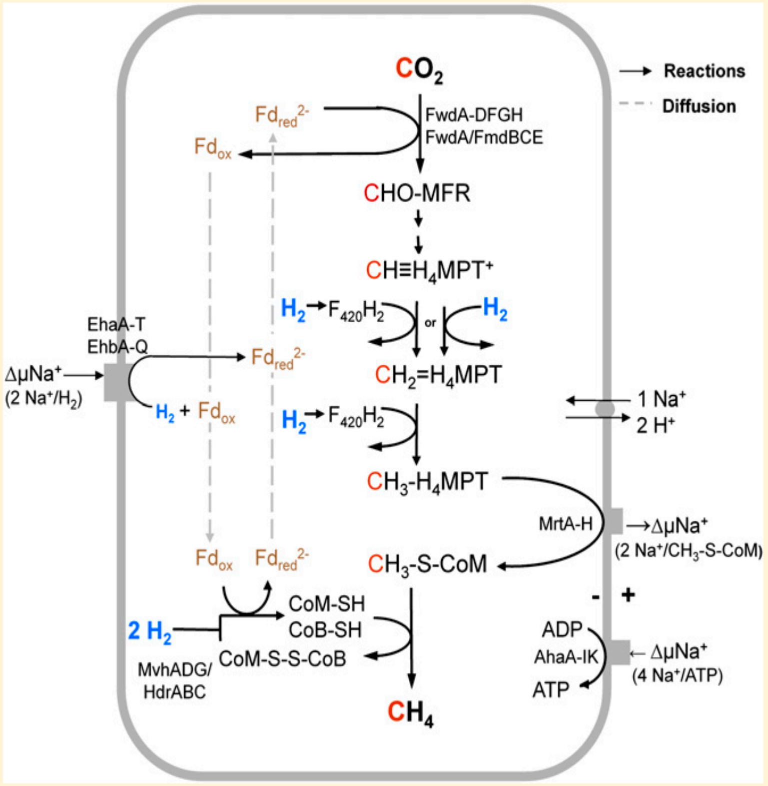
Chemistry & Biochemistry

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

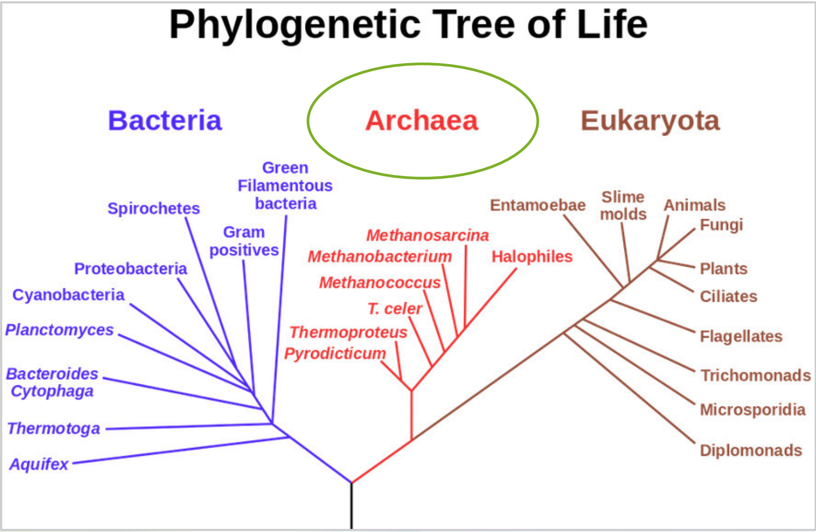
Net Reaction $CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$ + Heat η=0.60

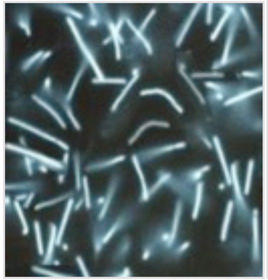


Kaster etal. 2011: www.pnas.org/cgi/doi/10.1073/pnas.1016761108

Proprietary Electrochaea Biocatalyst

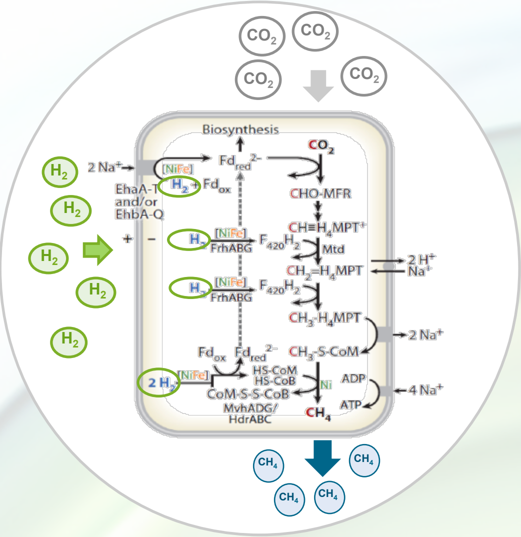
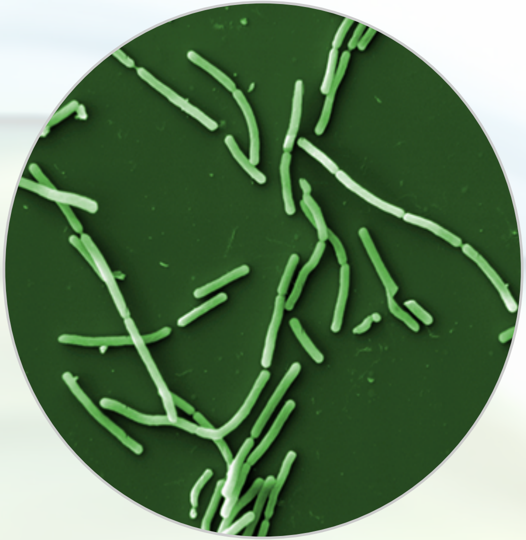
Electrochaea is using an optimized strain of methanogenic archaea (not genetically modified) to perform methanation at very high efficiency under industrial conditions





- Archaea are 3.5 billion year old single-celled organisms
- Identified only 30 years ago by pioneers Prof Carl Woese (Illinois) and Prof Karl Stetter (Regensburg)
- Specialized and self-contained „tiny manufacturing cells“
- „Archaeal diet“: CO_2 and H_2 (the only carbon and energy source needed)
- Make a single high energy product: „biomethane“

BioCatalyst System Productivity

1 enzyme complex		1 single cell		1.5L bioreactor		3500L bioreactor
	1 cell →		$5.5x10^{14}$ cells →		$1.83x10^{18}$ cells →	
Peak measured productivity*: Current productivity:		$8.3x10^{-14}$ Nm^3/hour nd		0.045 Nm^3/hour 0.007 Nm^3/hour		152 Nm^3/hour 31 Nm^3/hour

Thauer R.K. et al, Annual Rev Biochem 2010; 79. 507-537

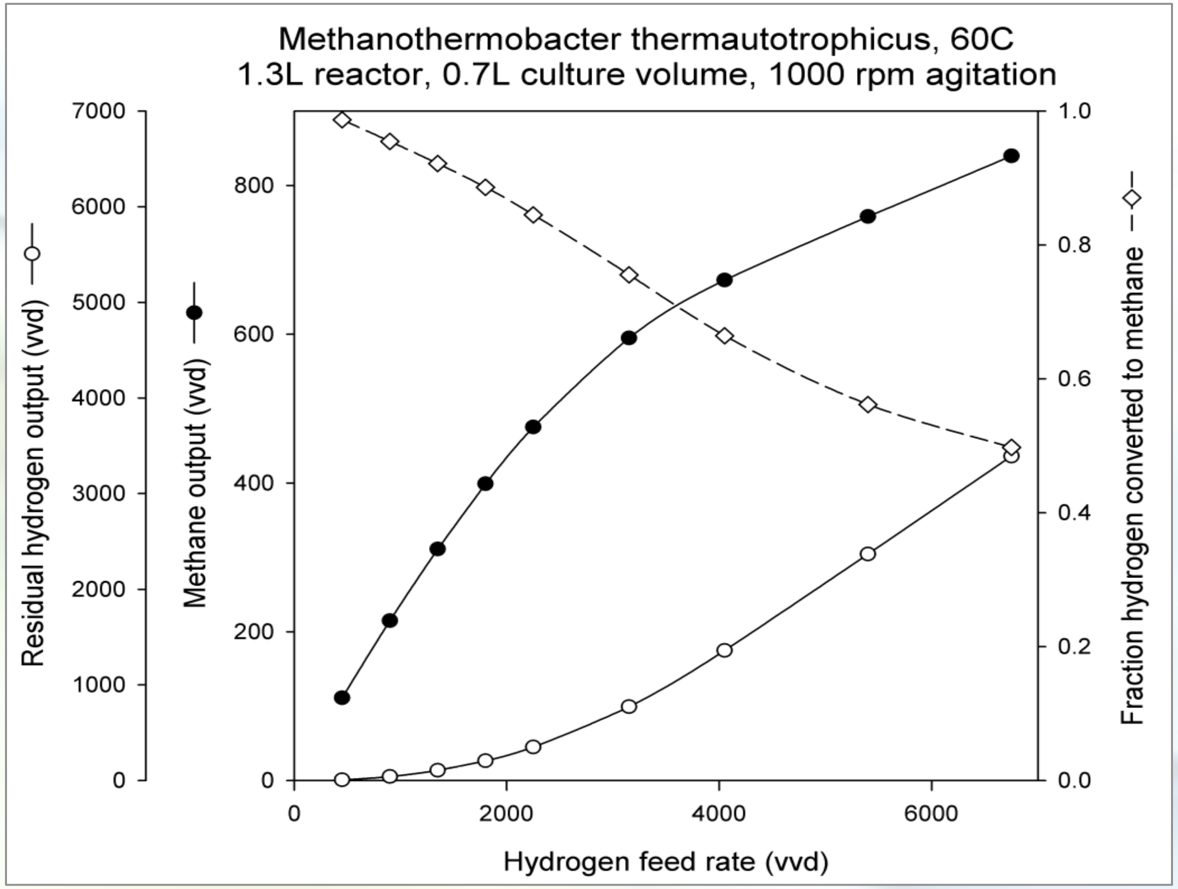
*assuming that vvd=800VolCH4/VolBioreactor/Day at a dry weight of 10g/L can be reached

Properties of Biological System

Conversion Rates & Volumetric Productivity

- Microbes display very high volumetric productivity and are not rate-limiting
- Conversion rate is significantly faster than in other bioenergy systems

- Conversion rate is measured by volume of methane produced per volume of culture per day ("vvd")
- Goal is to achieve vvd of 500 with 98% CO_2-to-CH_4 mass conversion efficiency at gas stoichiometry of 4/1 (H_2/CO_2)
  - To date in lab, vvd of 40 with conversion rate of ~100% and a vvd of >800 with a conversion rate of 55%
  - → **Microbes are not rate-limiting**



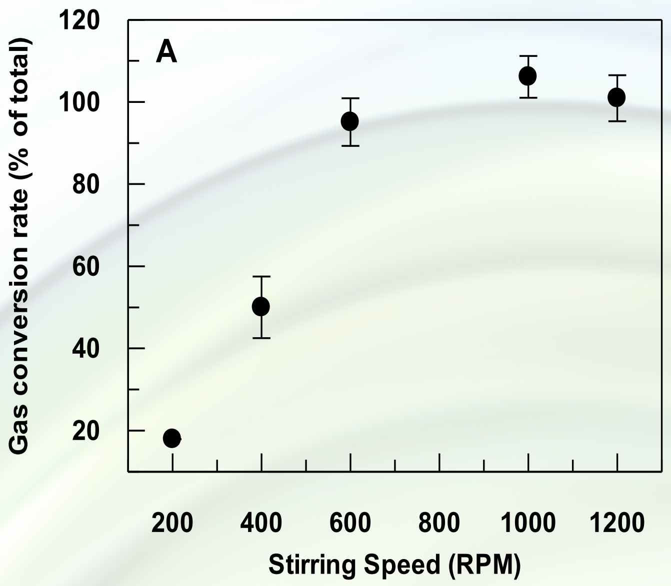
Hydrogen mass transfer is limiting

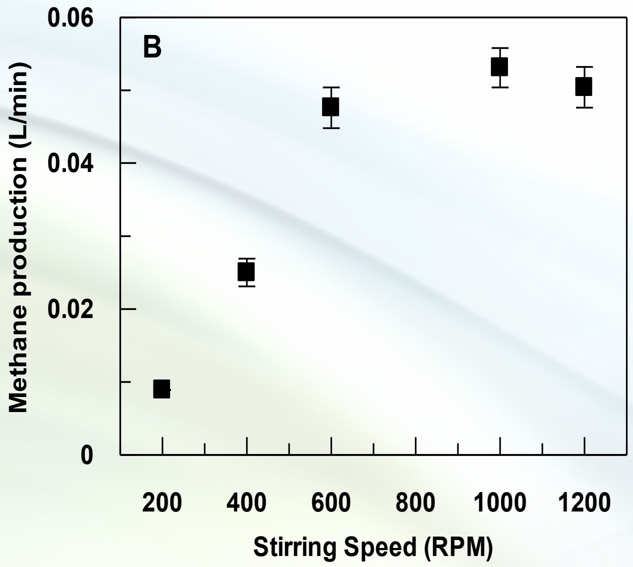
Electrochaea Lab - Conversion rates versus stirring speed (mixing energy)

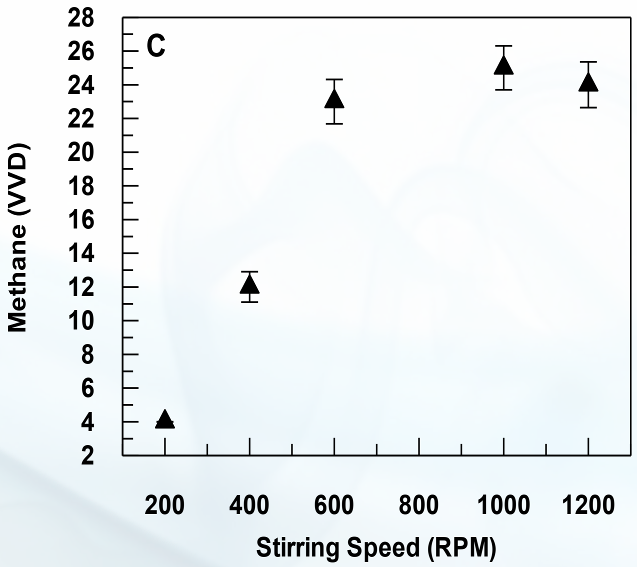
Gas conversion

Methane production

Methane vvd





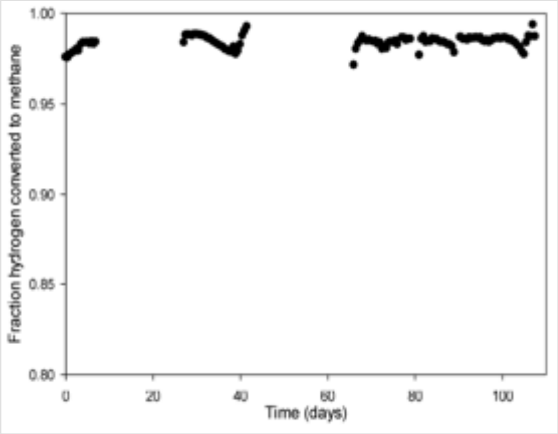


**Methanothermobacter* strain developed by L Mets, U Chicago

Unique features of Electrochaea Technology

Unique Biocatalyst
- Patented strain*
- Optimized methane productivity (20 x incease)
- Outstanding robustness
- Fast start/stop cycles
- Self-sustained

Scalable Bioreactor
- Mild operating conditions
- Optimized and proprietary design
- Broad range of applications



Efficient	▶	**98.6%** of carbon from CO_2 converted into **methane**
Productive	▶	**VVD** of 800**, H_2 mass-transfer limited
Responsive	▶	**Quick** return to methane production – ideal for intermittent duty cycles and load following
Selective	▶	**100% methane**, no intermediates in gas product
Robust	▶	**Self-maintaining and tolerant to oxygen, H_2S, CO, Sulfate, Ammonia, particulates**
Simple	▶	**Moderate** temperature range (60-65°C)

**Methanothermobacter* strain developed by L Mets, U Chicago
**VVD = volumes of gas per volume of reactor per day (24-hr)

From Benchtop to MW Scale

1 MW

Commercial-Scale Field Trial

Preparing for market entry with a commercial-scale demonstration unit, using an optimized reactor, Avedøre (DK)

50 kW

Pre-Commercial Field Trial

Process demonstration in a 5m³ stirred tank bioreactor using raw biogas, Foulum (DK)

1 kW

Lab-Scale Field Trial

Biocatalytic capability test with raw biogas

n/a

Power Input

Basic Research

In Dr. Mets' laboratory at the
University of Chicago, USA

BioCatProject
POWER-TO-GAS VIA BIOLOGICAL CATALYSIS

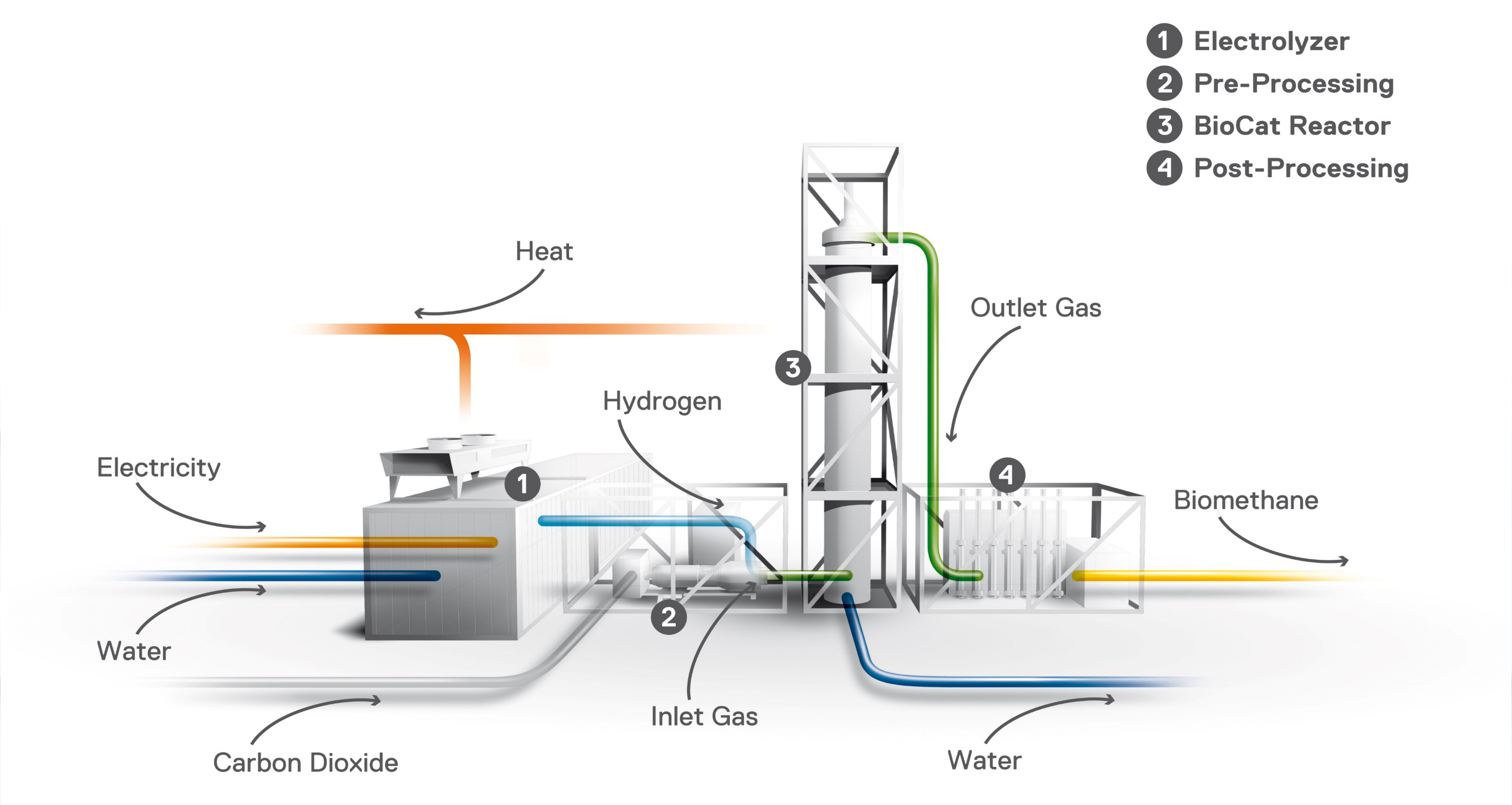
Building phase: 2014 – 2016
Operation: since 04/2016
Financed until: 12/2018

2013

2011 - 2012

2006 - 2010

Electrochaea‘s BioCat Methanation System Design



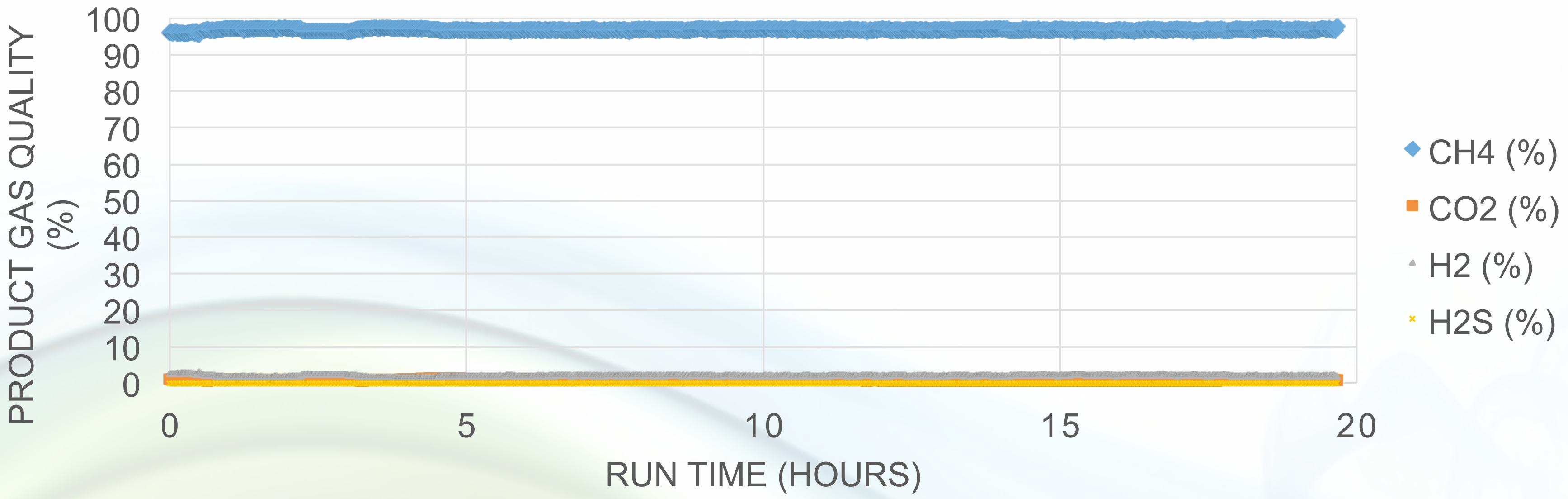
Successful Commissioning and Operation of BioCat

Operational schedules and programs:
- 14 months of intermittent operation with scheduled campaigns
- Typically 6-12 hrs of operation 5 days per week
- Continuous operations campaigns for ~500hrs with >94% plant availability
- Total operational hours ~ 3000hrs

Grid quality product gas:
- 97-98.5% CH_4
- 0.2-1% CO_2
- 1-2% H_2

Operating conditions:
- 8 bar pressure
- 62°C
- 55-70 Nm^3/hr biogas (37% CO_2, 63% CH_4)
- 80-105 Nm^3/hr H_2

Stable Gas Quality

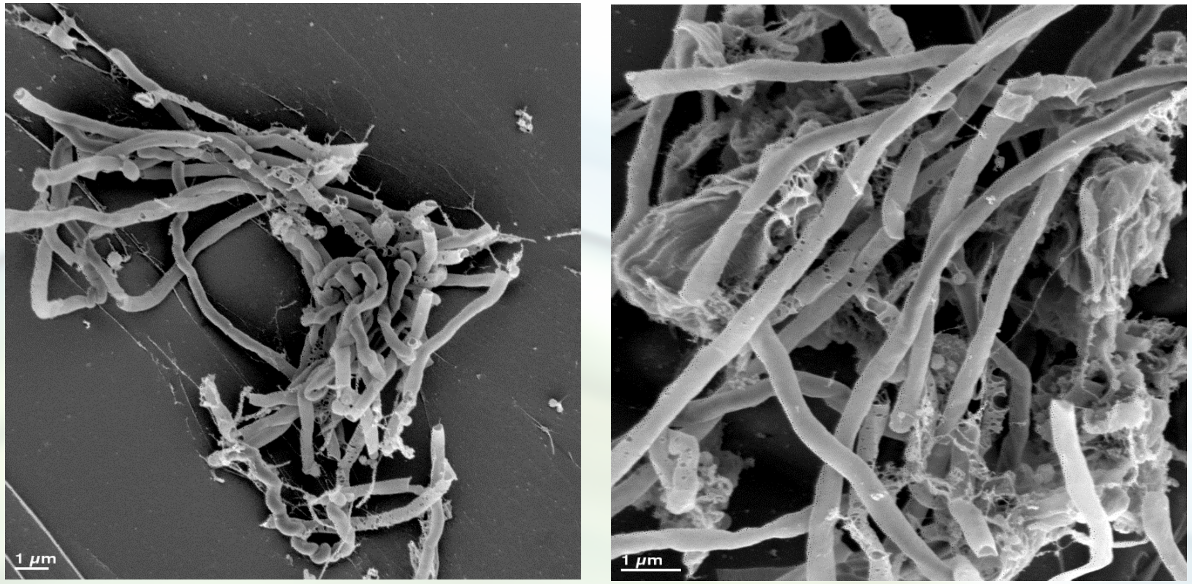


Grid gas quality

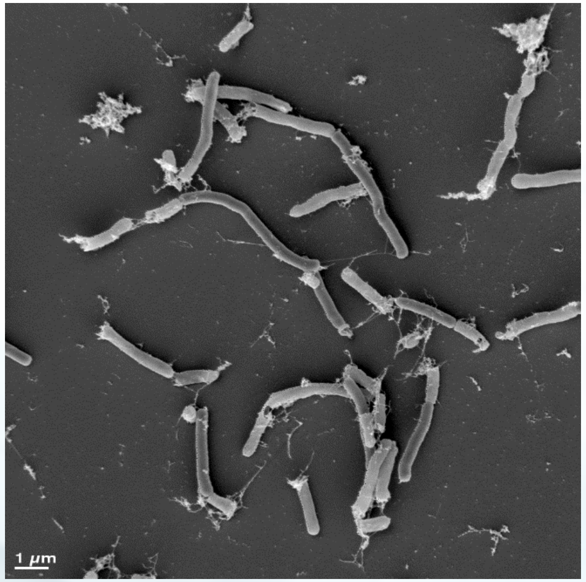
CH4 production: 777 Nm³ CH4/ day

Measurement	Required value for Grid Injection	Average product gas BioCat
CO_2 mole % (Carbon dioxide)	**Max. 3,0**	**1**
Methane mole %	**Min. 97**	**97**
H_2S (Hydrogen Sulfide) mg/ m_n^3	**Max. 5**	**0**
Hydrogen % vol.	**Max. 2**	**2**

Morphological differences of biocatalyst cultures – Raster Electron Microscopy – LMU, Prof Andreas Klingl



BioCat culture



Lab reactor culture

Achieving Grid Scale Production

1 MW BioCat Plant in Avedøre (DK)

1 MW electrical power → 200 Nm^3/h H_2

50 Nm^3/h CO_2 (from Biogas)

Heat 320 kW

Biomethane 50 Nm^3/h → grid

BioCat
Biological methanation system in megawatt scale

- Conversion of excess renewable power into biomethane
- Proprietary Bio-Catalyst (4 patents), in-house system design & operation
- Competitive advantage: dynamic operation, high tolerance to impurities
- Scaling: to 10 MW and 50 MW systems and in worldwide markets

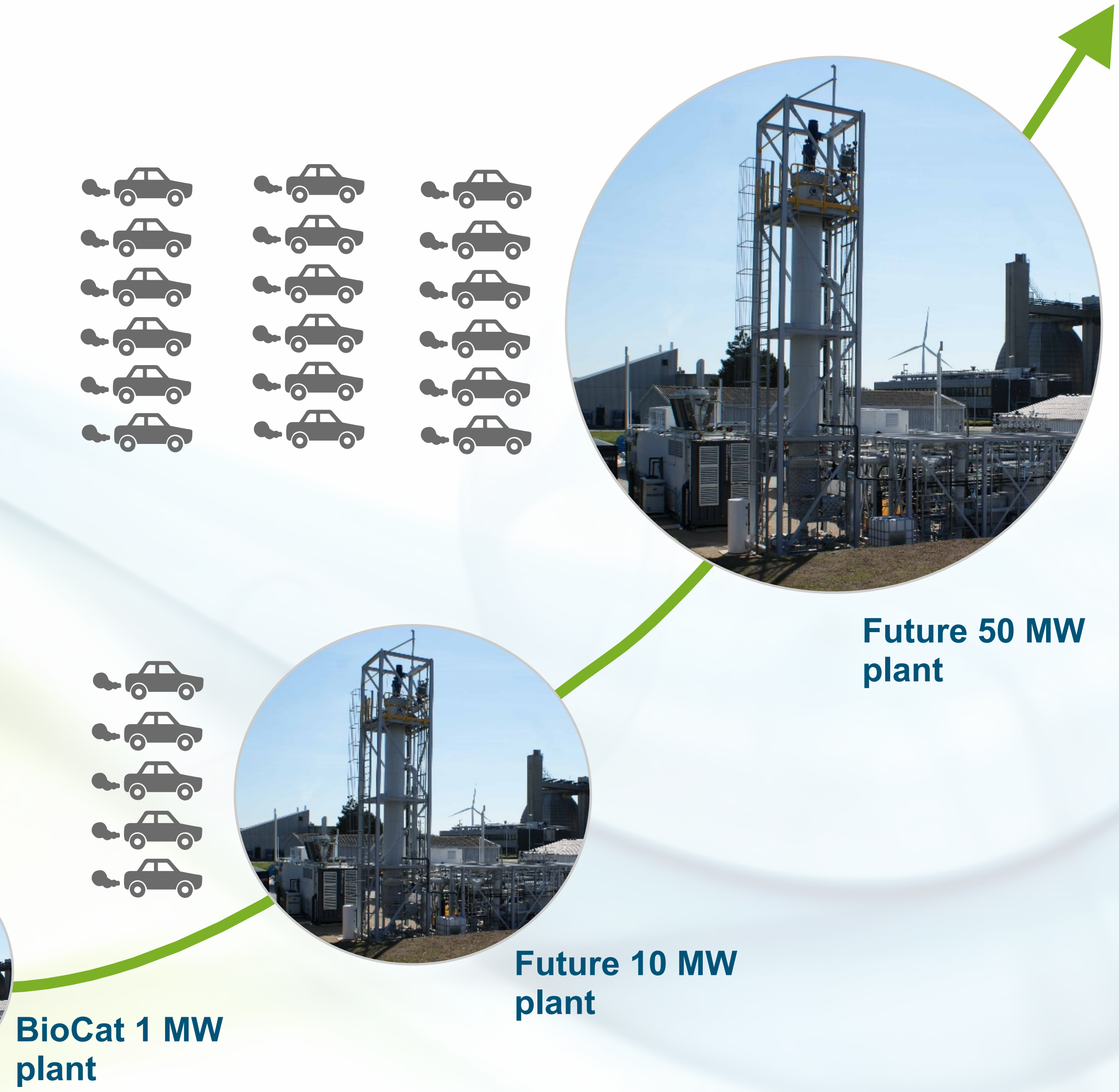
BioCatProject POWER-TO-GAS VIA BIOLOGICAL CATALYSIS · HMN GASHANDEL · Audi Vorsprung durch Technik · FORSK EL · BIOFOS · HYDROGENICS

Strong Impact of a 50 MW BioCat System

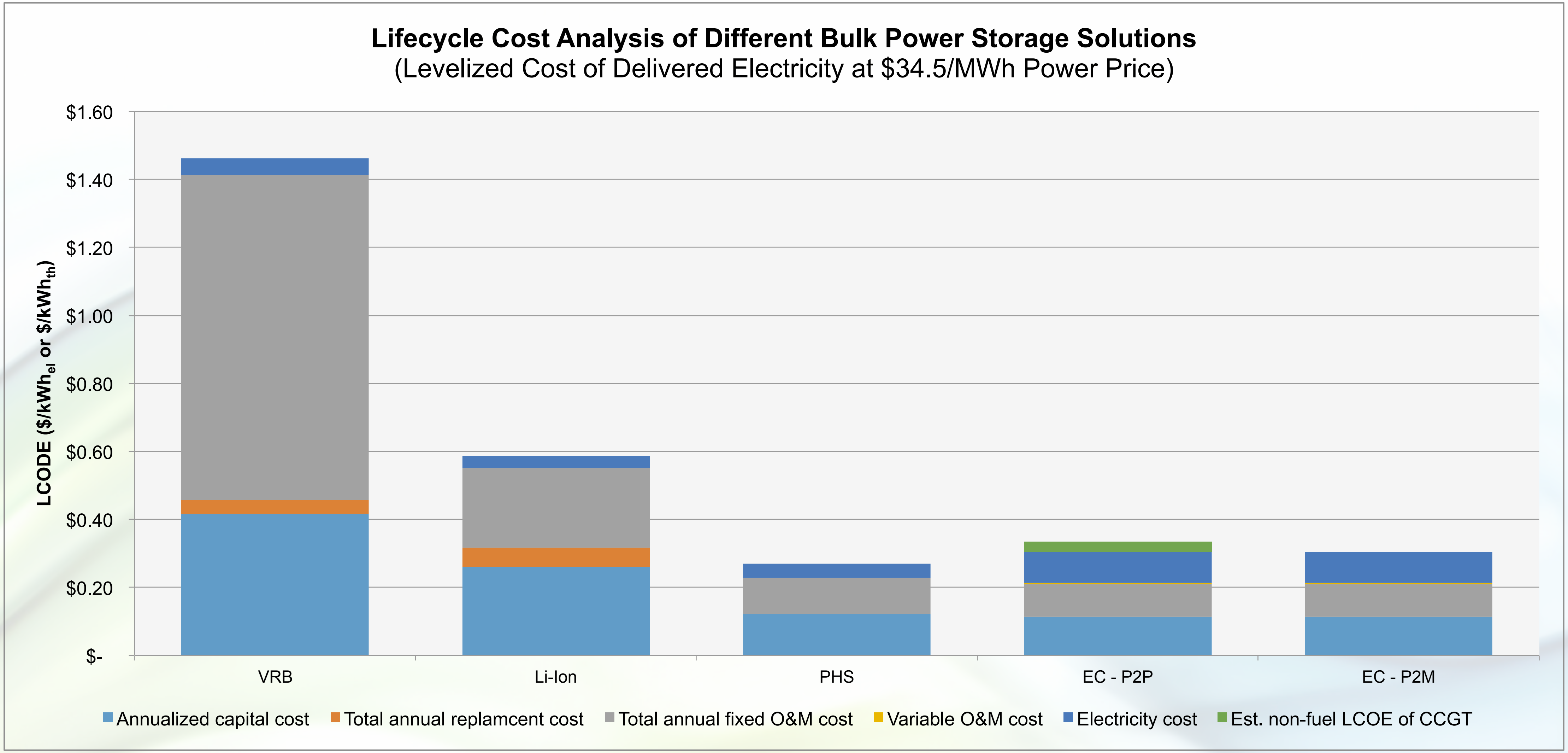
Capabilities of a 50 MW BioCat System

Storing 400 GWh/a of electrical energy*	=	More than 125,000 households consumption per year
Achieving a CO_2 sequestration of 37,000 tons/a*	=	Emissions of ~20,000 cars per year

*assumptions:
- Heat and electricity for one year 3,200 kWh in a household with 4 person in Germany (2013)
- 132.6 gr/km emission per car and 14,000 km driving average km per year in Germany (2014)
- 8,000 h/a of operation, electrolysis included



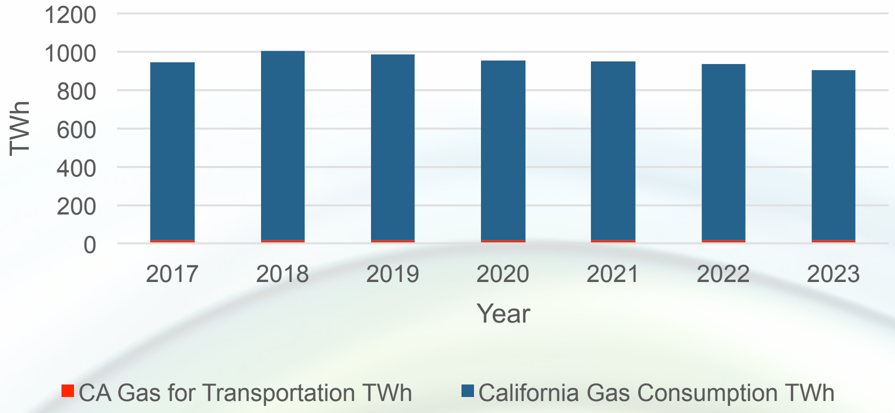
Levelized Cost Of Delivered Electricity (LCODE)



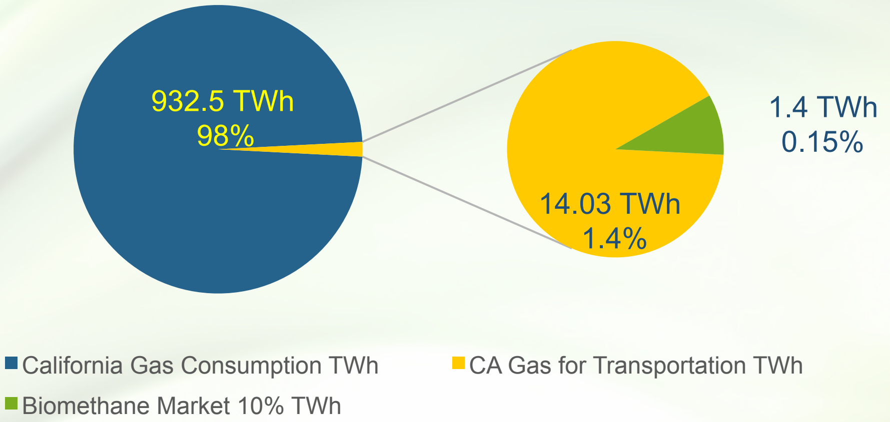
Own elaboration, from [1] L A Z A R D ' S L E V E L I Z E D C O S T O F S T O R A G E — V E R S I ON 2 . 0,
[2] Schoenung (2011), Energy Storage Systems Cost Update - A study for the DOE Energy Storage Systems Program, SANDIA REPORT (SAND2011-2730), April 2011
[3] Electrochaea'sassumptions

California Biomethane Market

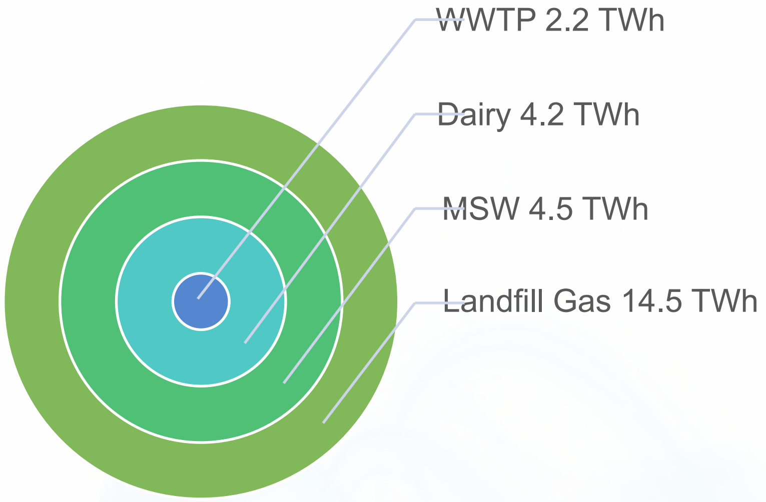
California Transportation Gas Consumption is <2% of Total CA Gas Consumption*



Electrochaea's goal for CA transportation biomethane is 1.4TWh (10% of transport gas market)



Biomethane Production Potential**



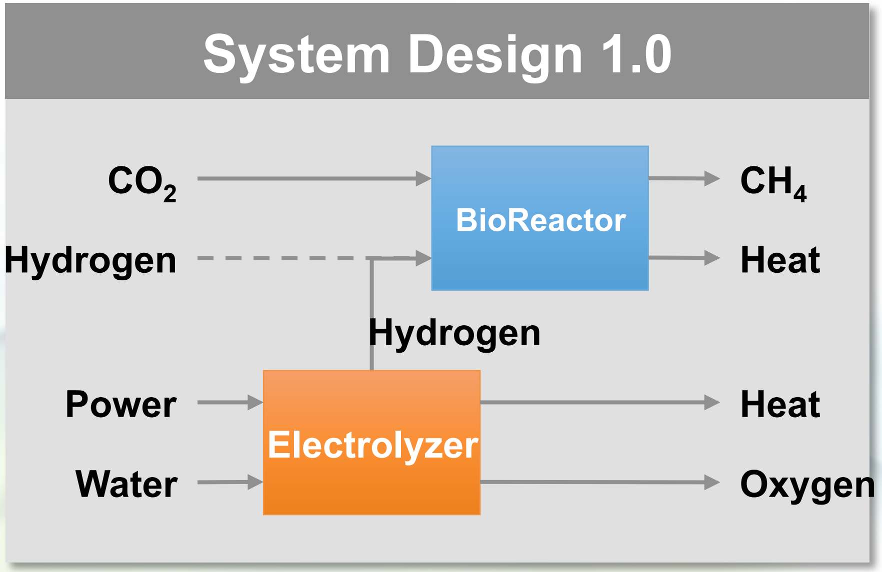
Sector**	Price Supplement $/MWh (LCFS + RINs)
WWTP (waste water treatment plant)	$105
Dairy	$232
MSW (municipal solid waste)	$122
Landfill	$92
Average Price	$138

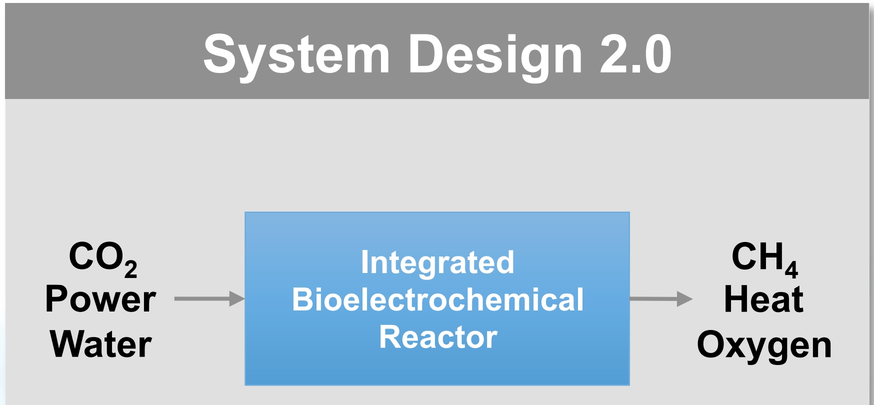
Natural Gas Price ~ $10 MWh

*Adapted from the EIA https://www.eia.gov/outlooks/aeo/data/browser/#/?id=2-AEO2017&region=1-9&cases=ref2017~ref_no_cpp&start=2015&end=2050&f=A&linechart=ref2017-d120816a.3-2-AEO2017.1-9~ref_no_cpp-d120816a.3-2-AEO2017.1-9~ref2017-d120816a.80-2-AEO2017.1-9~ref_no_cpp-d120816a.80-2-AEO2017.1-9&map=ref_no_cpp-d120816a.3-2-AEO2017.1-9&sid=ref2017-d120816a.65-2-AEO2017.1-9~ref_no_cpp-d120816a.65-2-AEO2017.1-9&sourcekey=0

**Adapted from the Air Resource Board California

Second Generation with Improved Efficiency





Rationale: higher efficiency, lower capital cost
Status: lab-scale proof of concept

Power-to-RNG Efficiency

System Design 1.0
- 58% (RNG Only)
- 78% (RNG + Heat)

System Design 2.0
- 67% (RNG Only)
- 84% (RNG + Heat)

Electrobiological Methanogenesis

Net equation: $CO_2 + 2\ H_2O \rightarrow CH_4 + 2\ O_2$

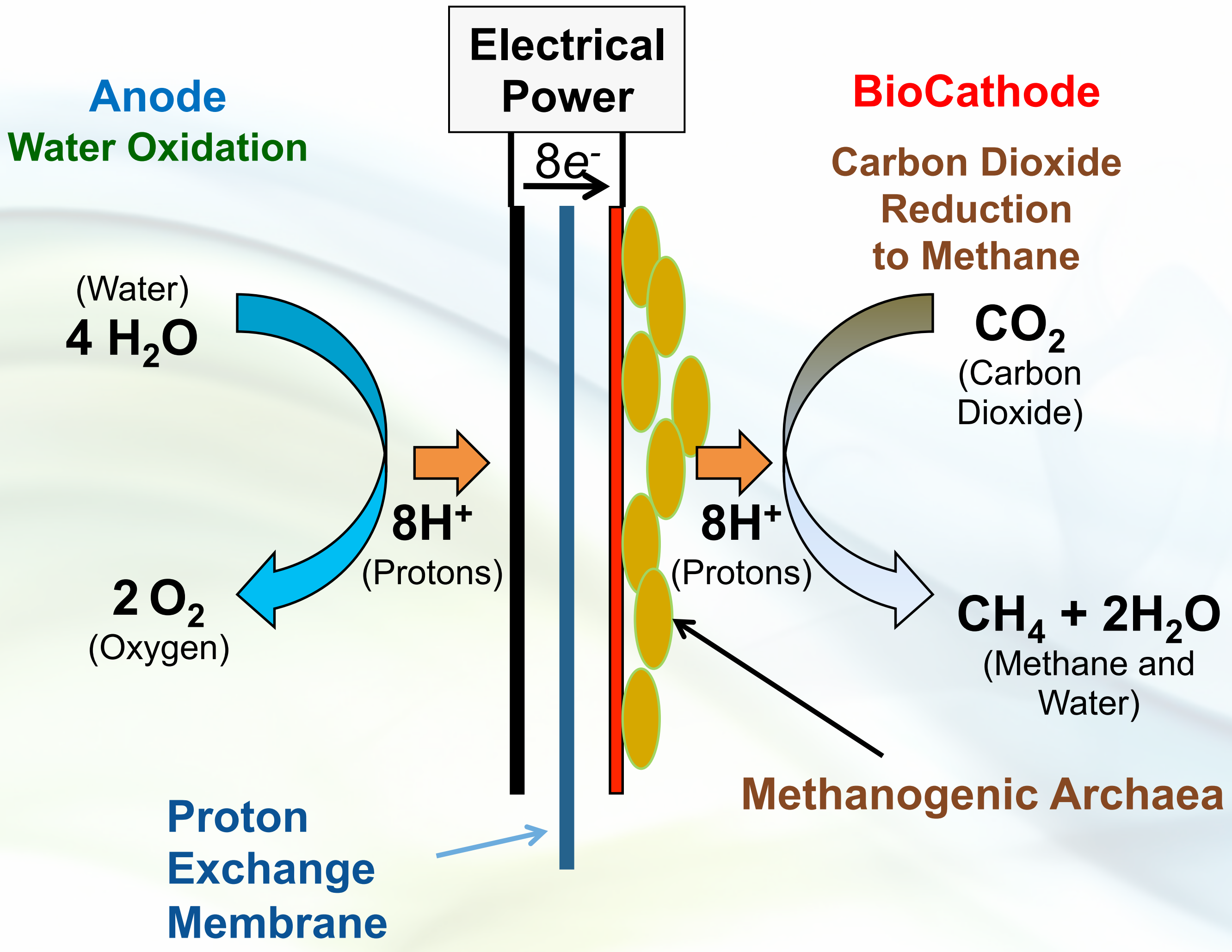
Cathode: $CO_2 + 8e^- + 8\ H^+ \rightarrow CH_4 + 2\ H_2O$

PEM: --

Anode: $4\ H_2O \rightarrow 8\ H^+ + 8e^- + 2\ O_2$

Biological Cathode Catalyst: 60-90°C; carrier-mediated or direct electron transfer

Integrated System with BioCathode



What's next?

- First Grid Scale Project 'events' to demonstrate scalability, flexibility and reliability to incumbents
- Regulatory changes to make power for storage available at marginal cost of production to induce capital to fund energy storage at grid scale
- Next generation innovations – bioelectrochemical cells for scalability and cost-down,ong term cavern replenishment with renewable CH_4, colocation and integration with WWTP, MSW, fermentation industries to close carbon cycle
- Sector coupling (power, heat, gas, transportation) for system efficiency gains

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2014 Global Cleantech 100 TOP 100 COMPANY Cleantech Group

ECOSUMMIT AWARD
Fame and Fortune for the Best Smart Green Startups

Bronze medalist 2016 in early stage start-up category