2020 NARUC Annual Meeting and Education Conference
Bridging the Divide

Staff Subcommittee on Clean Coal & Carbon Management
Staff Subcommittee on Gas

Joint Session: **"The Future of Blue Hydrogen"**

This session will begin at 3:00 pm ET

2020 NARUC Annual Meeting and Education Conference
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"The Future of Blue Hydrogen"

Co-Moderators:
James Branscomb, Senior Rate Engineer, Wyoming Public Service Commission

Andreas Thanos, Gas Policy Specialist, Massachusetts Department of Public Utilities

Participants:
John Litynski, Deputy Director for Advanced Fossil Technology Systems, Office of Fossil Energy, U.S. Department of Energy

Sharon Tomkins, Vice President, Strategy and Engagement and Chief Environmental Officer, Southern California Gas Company

Ron Kent, Advanced Technologies Development Manager, Southern California Gas Company

Chris San Marchi, Hydrogen and Metallurgical Science, Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY | Office of Fossil Energy

NARUC Annual Meeting - The Future of Blue Hydrogen

NARUC Blue Hydrogen Panel

John Litynski
Deputy Director
U.S. DOE Advanced Fossil Technology Systems

Nov 5, 2020

State of Hydrogen Production Today

Currently 99% of 10 MMT in the U.S. supplied by fossil fuels – least cost

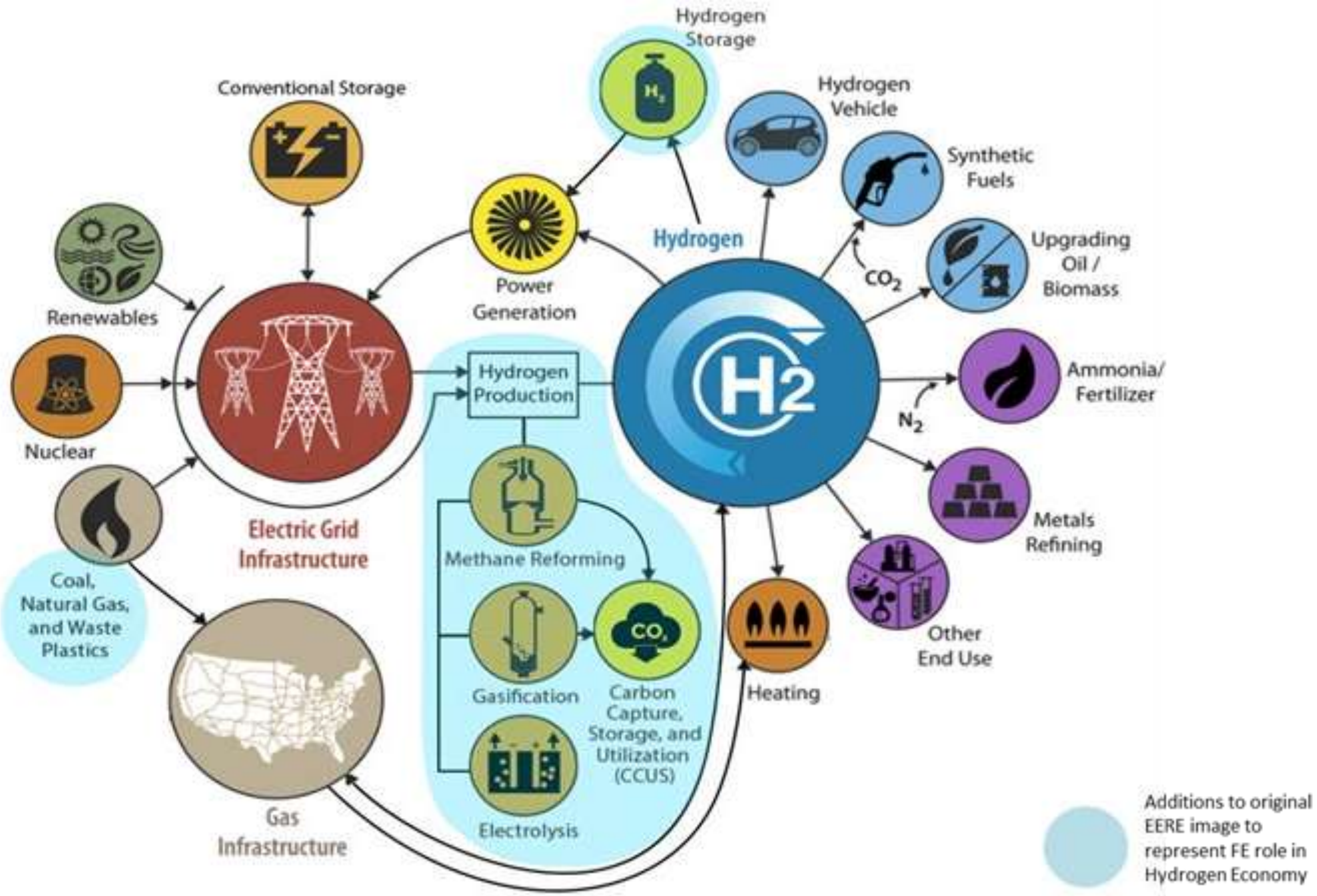
- **96% by SMR**
- **3% by gasification**
- **1% by electrolysis**

70 MMT generated globally

- **76% by SMR**
- **22% by gasification**
- **2% by electrolysis**

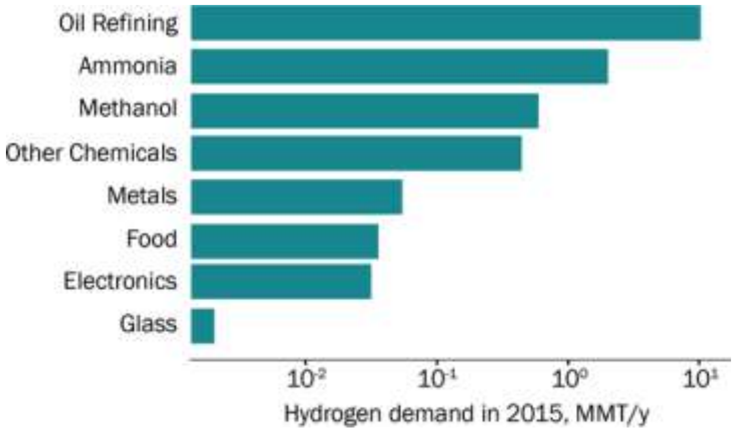
Small fraction includes CCUS

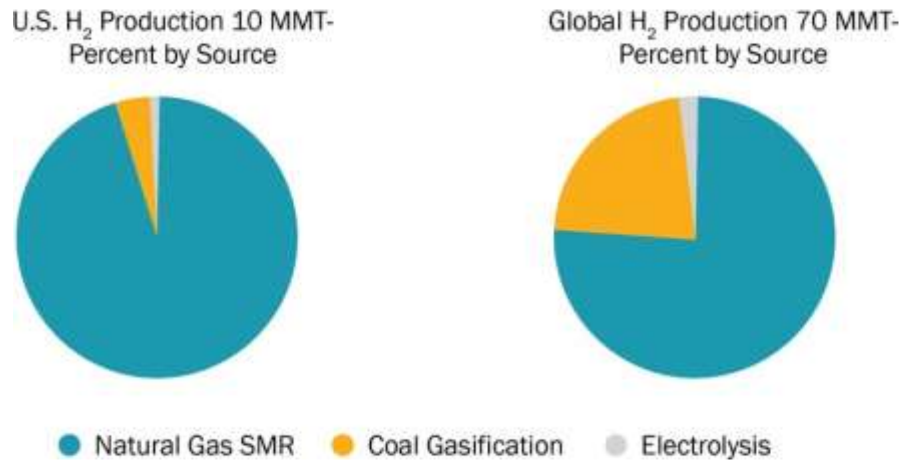
Economics dominates generation mix

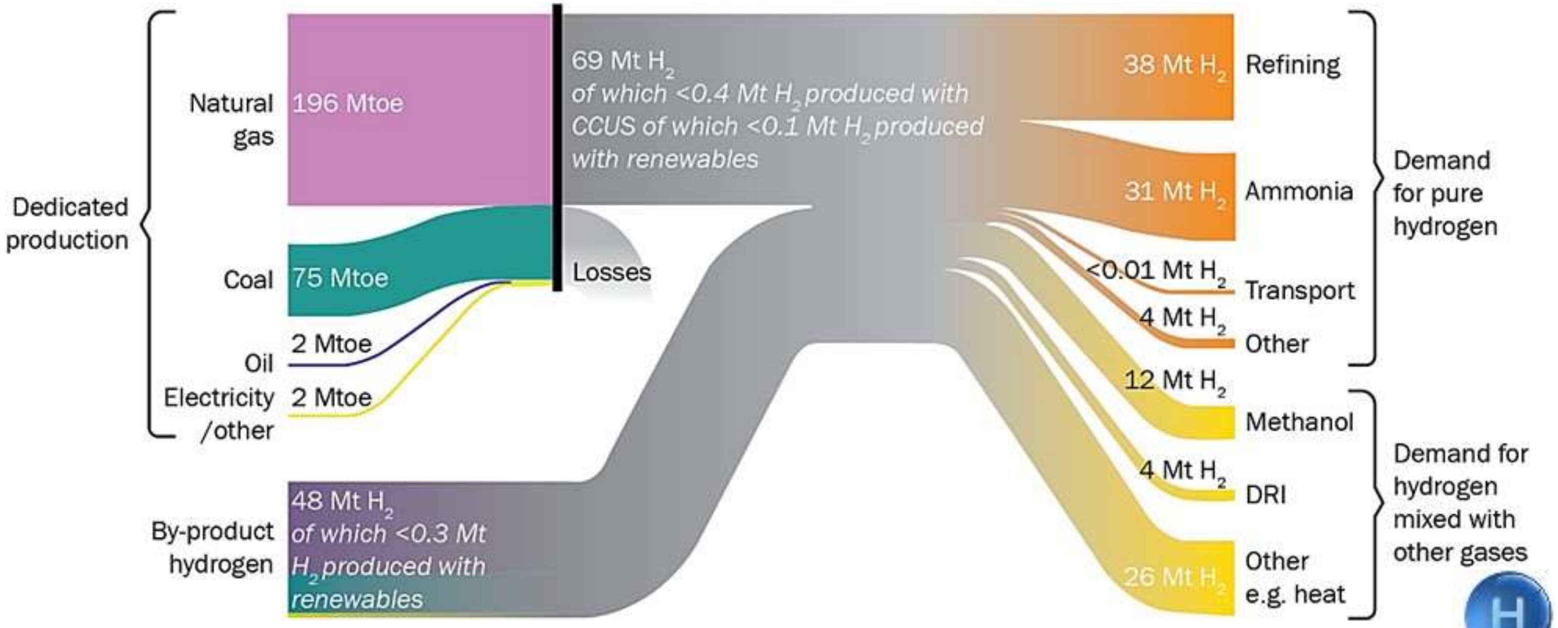


Current Hydrogen Demand

- Current demand is mostly for oil refining and chemical production.
- Metals, electronics and glass production are main industrial sources of demand.
- Food production is main consumer source of demand.
- Transportation, building heating and electricity generation are areas of demand growth for a decarbonized economy.



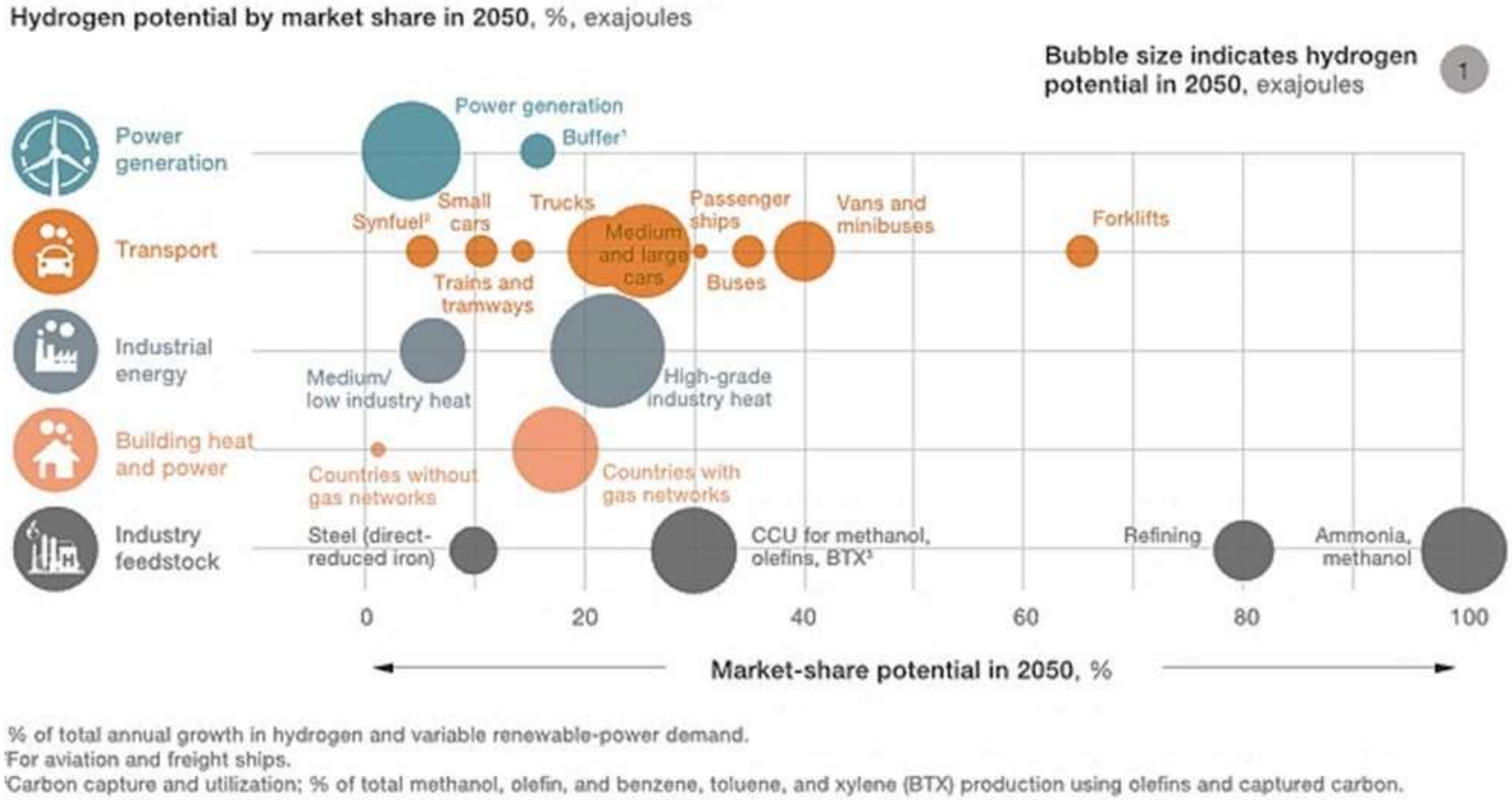




Potential Hydrogen Demand in 2050

- Transport, buildings, and power sectors all have the potential to use cost-competitive hydrogen.

- Fossil fuels with CCUS will support emerging carbon free market opportunities with low-cost hydrogen.
  - Utility scale hydrogen based power generation/energy storage
  - Steel and advanced alloys manufacturing
  - Cement, fertilizer and chemicals production
  - Fuel for marine, rail, and heavy-duty vehicle applications



Examples of Scale:

1- Hydrogen for the U.S. transport sector would require 200 MMT of hydrogen - 20X current US production

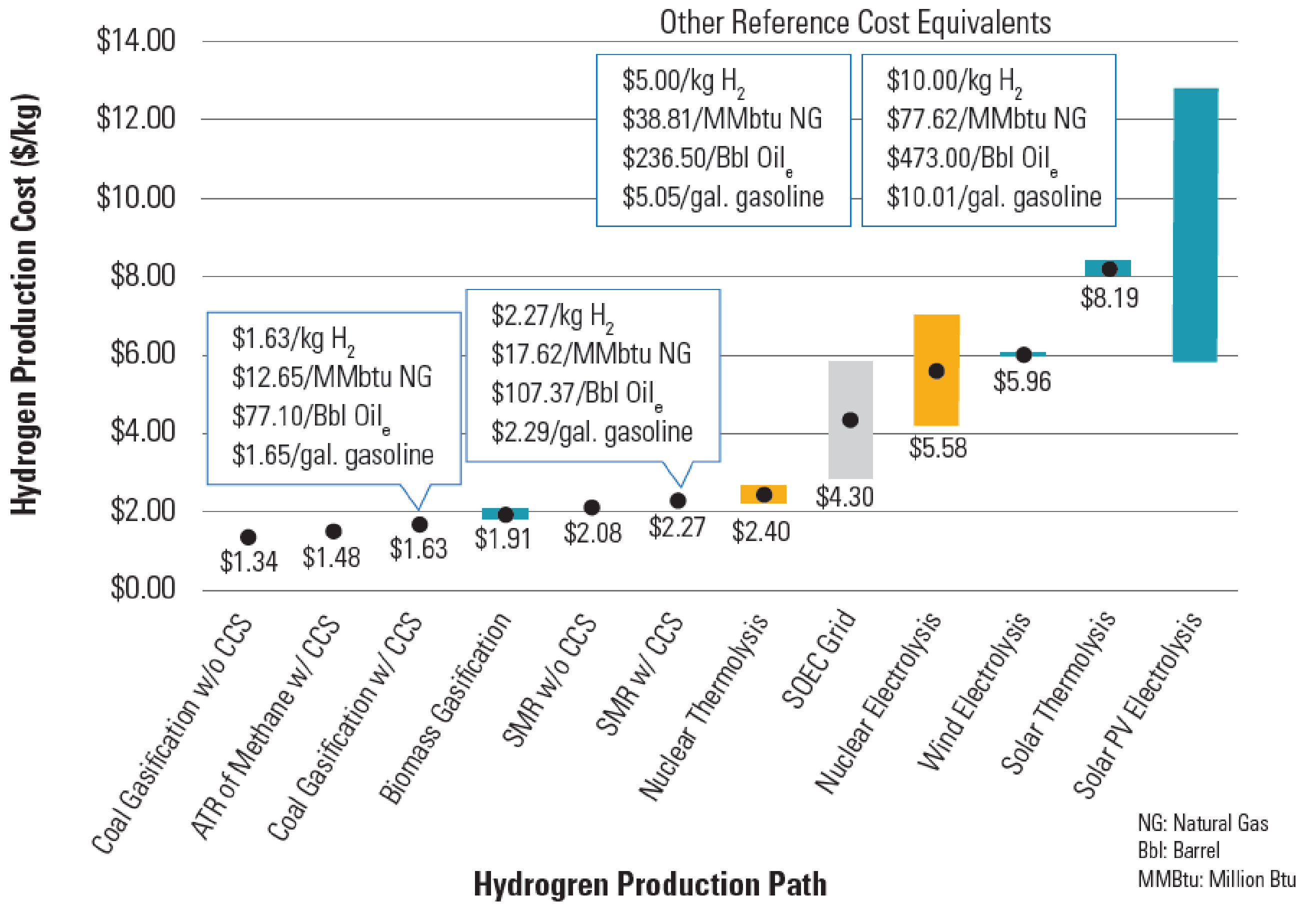
Transportation fleet expected to increase 2-3X by 2050

2 - Replacing all NG power in NE requires ~10MT of hydrogen

Economics of Hydrogen Production

- H_2 production from fossil fuels is the least expensive source, even with CCUS
- Gasification with CCUS could be carbon neutral or even negative when co-firing biomass
- R&D advances could significantly reduce SMR and gasification costs further

Figure 5. Current Hydrogen Production Cost Ranges and Averages by Technology and Equivalent Prices for Fossil Sources with CO_2 Capture and Storage[9,10]



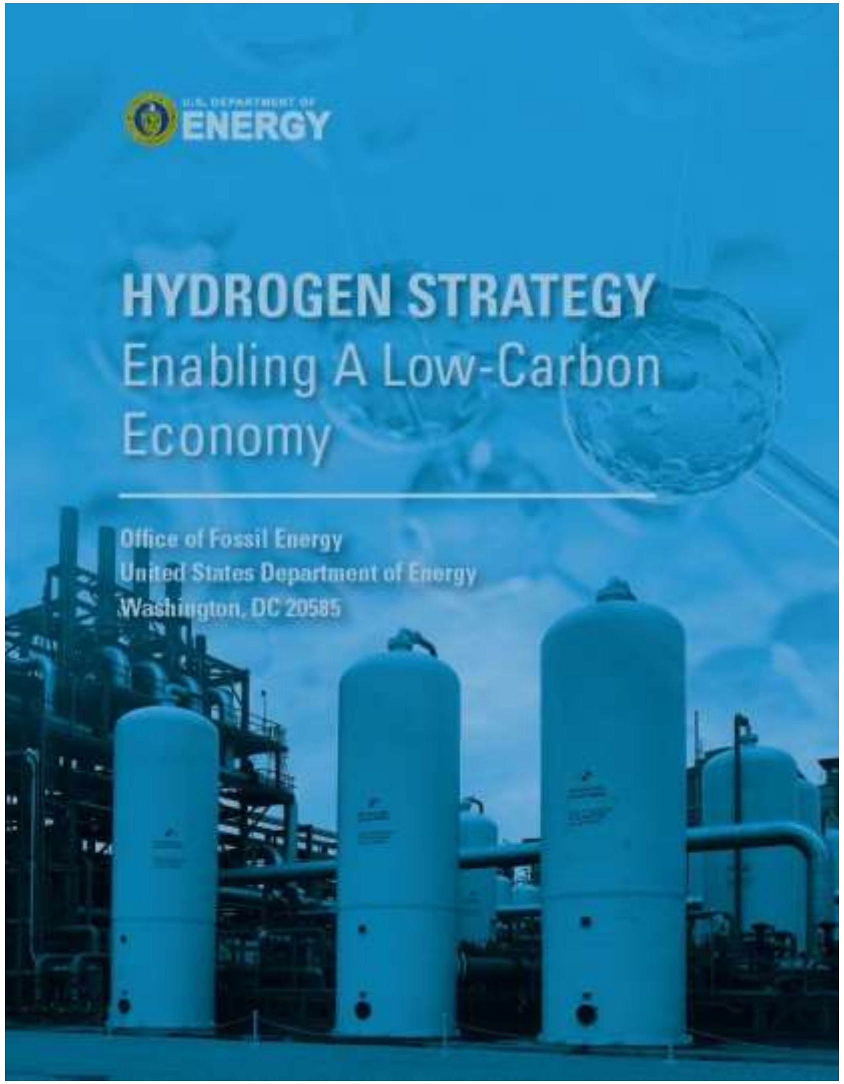
Solar Hydrogen Production: Processes, Systems and Technologies, 1st Edition. Editors: Francesco Calise, Massimo Dentice D'Accadia, Massimo Santarelli, Andrea Lanzini, Domenico Ferrero. Academic Press. August 2019.
PNNL "H2 Hydrogen Tools." Accessed online: https://h2tools.org/hyarc/calculator-tools/energy-equivalency-fuels

DOE Fossil Energy Investments in Blue Hydrogen R&D

Over the past two decades FE has invested ~$1.3B in low-cost, carbon neutral hydrogen production technologies, including Turbines, Gasification, Solid Oxide Fuel Cells, and Pre Combustion R&D

Aligning H2 R&D in Office of Fossil Energy

- Carbon-Neutral Hydrogen Production Using Gasification and Reforming Technologies
- Large Scale Hydrogen Transportation Infrastructure
- Large Scale On-site and Geological Hydrogen Storage
- Hydrogen Use for Electricity Generation, Fuels, and Manufacturing.



FE Program Elements Supporting Hydrogen Strategy

Hydrogen Production – Coal FIRST

Reforming and Gasification Design

Pre-combustion Carbon Capture

Advanced Turbines

Reversible SOFC Systems

Bulk H_2 Storage

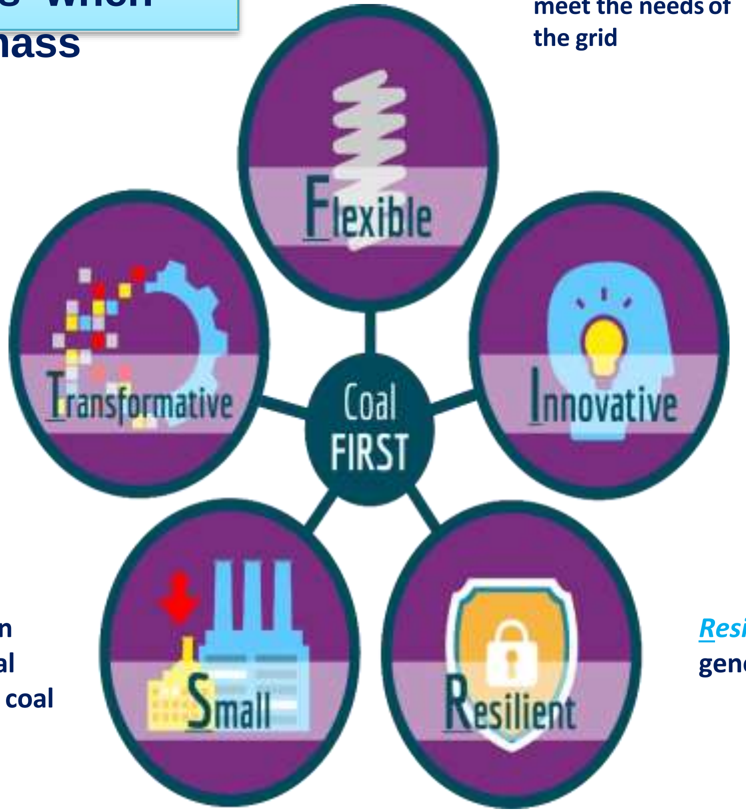
Hydrogen Transport

21st Century Power Plants - Coal FIRST: Enabling a Carbon Free Hydrogen Economy

(Flexible, Innovative, Resilient, Small, Transformative)

- **Carbon neutral, including net negative CO_2 emissions with co-firing coal and biomass,** power plant **R&D effort in the world**
- **Capable of producing power and/or hydrogen** for polygeneration
- **Coal, biomass, and plastics with CCUS excellent and economical feedstocks for hydrogen**
- **Contributes to IEA minimum cost scenario** for deep CO_2 emissions -- **carbon capture**
- Provides **low cost power generation**; economically competitive
- Potential to **sustain U.S. coal communities**; provide a source of **high value exports**

Carbon neutral Emissions Negative CO_2 emissions when co-firing biomass



Flexible coal plant operations to meet the needs of the grid

Transforms how coal technologies are designed and manufactured

Innovative and cutting-edge components; improved efficiency and carbon neutral emissions

Smaller than conventional utility-scale coal plants

Resilient power generation

Hydrogen Production Gasification Project FEED Studies – Net Negative Emissions

Electric Power Research Institute, Inc. (Palo Alto, CA)

- *Gasification of Coal and Biomass: The Route to Net-Negative-Carbon Power and Hydrogen* – Integrated design study on an oxygen-blown gasification system coupled with water-gas shift, pre-combustion CO2 capture, and pressure-swing adsorption working off a coal/biomass mix to yield high-purity hydrogen and a fuel off-gas that can generate power.
- Nebraska Public Power District
- CO_2 Storage: enhanced oil recovery and saline sequestration
- Co-feed corn Stover and possibly other biomass and waste plastics

Wabash Valley Resources, LLC (West Terre Haute, IN) - *Wabash Hydrogen Negative Emissions Technology* –

Complete System integrated design study for redeveloping the existing Wabash Valley Resources coal gasification site in West Terre Haute, Indiana, into a Coal FIRST power plant for flexible fuel gasification-based carbon-negative power and carbon-free hydrogen co-production.

- Facility: Wabash Gasification Facility
- CO_2 Storage: Saline sequestration
- Co-feed woody biomass and/or agricultural residue and petroleum waste plastics

Production - Reforming, Gasification, and Pre-combustion Capture

Autothermal reforming

Alternative Feedstocks

- Waste Plastics as Gasifier Feedstock
- Net Negative CO_2 w/ Biomass Blending

Advanced Technologies

- Ultra High-Pressure Gasifier
- Microwave assisted gasification systems
- Materials development (materials and catalysts)

Pre-combustion Capture

- Integrated sulfur and CO_2 removal
- Advanced membranes and Sorbents

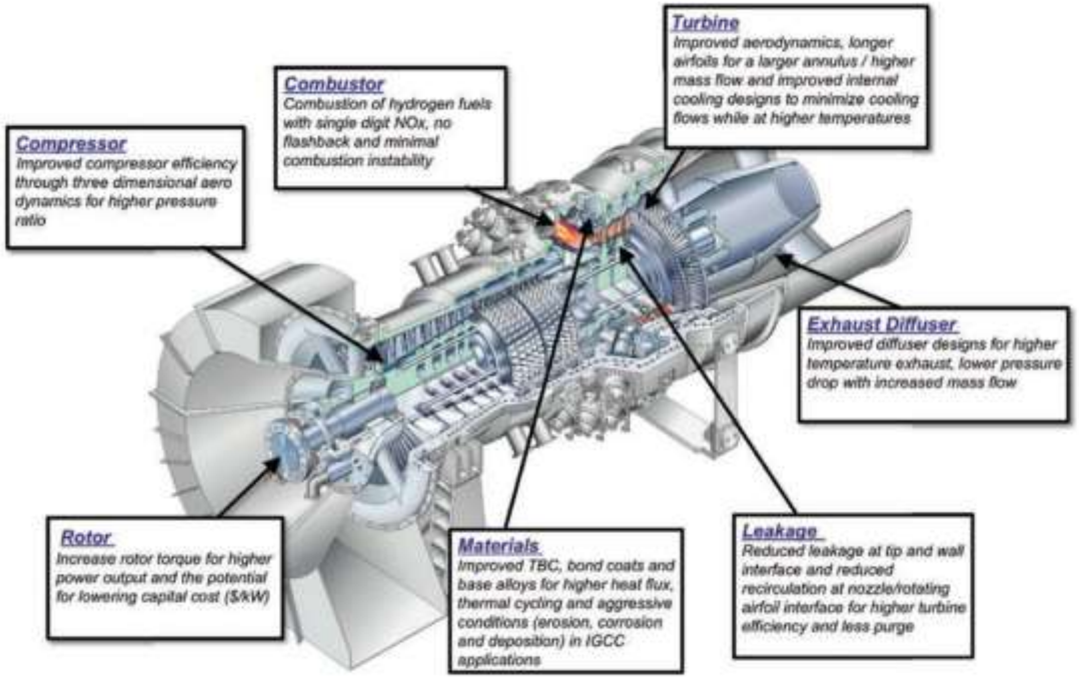
Polygeneration Systems – Flexible operation to meet demand

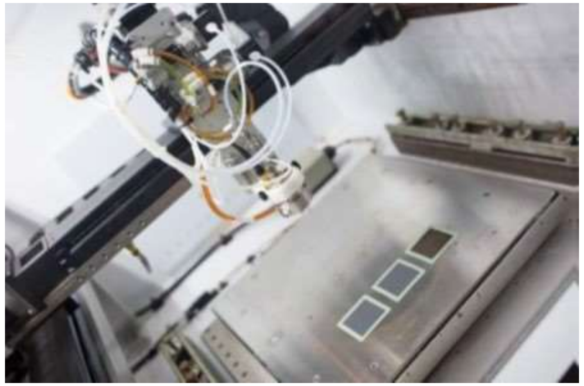
Hydrogen Use - Turbines and Reversible SOFCs

Future work – reduce CAPEX and OPEX

- Science and engineering knowledge of stable high temperature, low NO_x hydrogen combustion.
- Combustion of carbon neutral fuels (i.e. NH_3, ethanol vapor).
- Apply H_2 combustion engineering to utility scale and aero derivative machines – new and retrofit
- Aim for 100% hydrogen machine.
- Prior and on-going SOFC R&D supported by FE will provide the technology basis for SOEC development going forward
- Potential for hybrid systems to produce hydrogen in SOEC mode and electricity in SOFC mode

<u>Meeting the demand for flexible low carbon power</u>





Hydrogen Storage Technologies

SOTA - High pressure tanks and as a liquid requires cryogenic temperatures (-423°F) – physical storage

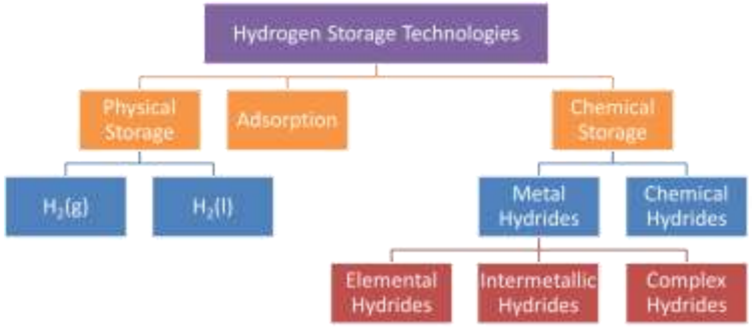
Hydrogen infrastructure could require geologic bulk storage to handle variations in demand throughout the year

And bulk onsite storage for emergency fuel supply during extreme events

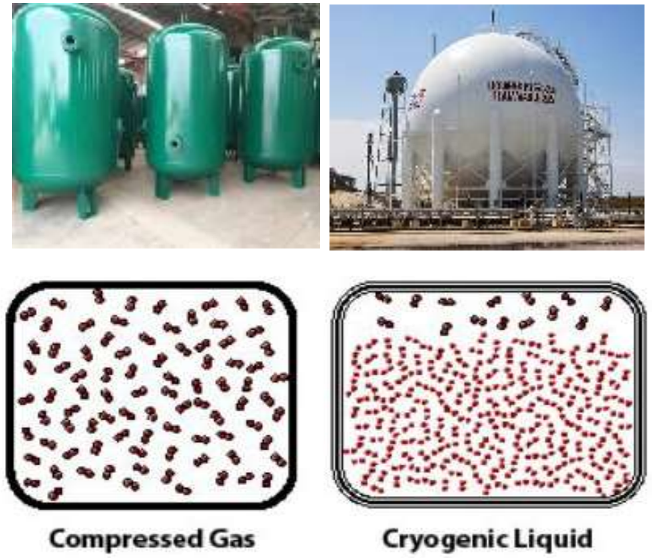
Technology Advancement necessary in physical and chemical storage

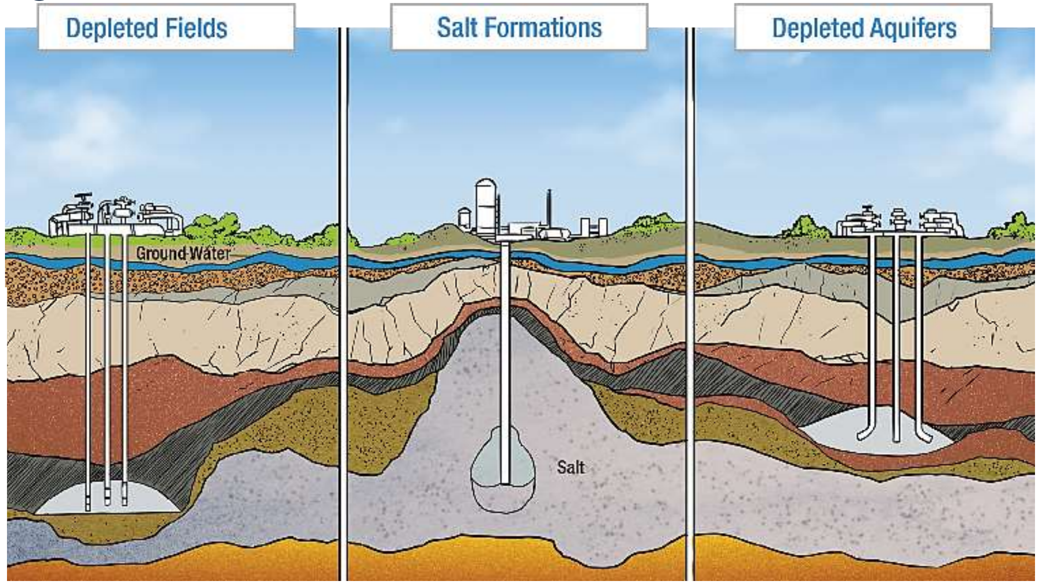
Underground geologic storage of low-pressure gaseous hydrogen necessary

- Salt caverns, depleted oil and gas reservoirs, aquifers, and hard rock caverns.
- Regional characterization and field laboratories to validate geologic storage



Ref: Andersson, J. and S. Gronkvist, 2019, "Large-scale storage of hydrogen." International Journal of Hydrogen Energy, Vol. 44.





Hydrogen Distribution

- Hydrogen is currently distributed through three methods:
  - **Pipelines:** While the least-expensive way to transport large volumes of hydrogen, there are only about 1,600 miles of U.S. pipelines dedicated for hydrogen delivery.
  - **High-Pressure Tube Trailers:** Transporting compressed hydrogen gas by truck, railcar, ship, or barge in high-pressure tube trailers is expensive and used primarily for distances of <200 miles.
  - **Liquefied Hydrogen Tankers:** Cryogenic liquefaction is an expensive process that enables hydrogen to be transported more efficiently over longer distances by truck, railcar, ship, or barge.



- Existing domestic natural gas pipeline infrastructure has the potential to expand the transportation of hydrogen.
  - Blending hydrogen into natural gas pipeline networks is a potential option for delivering pure hydrogen to markets – pipelines can handle up to 30% hydrogen blends without significant modifications or detrimental effects.

The Future of Blue Hydrogen

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11/05/2020

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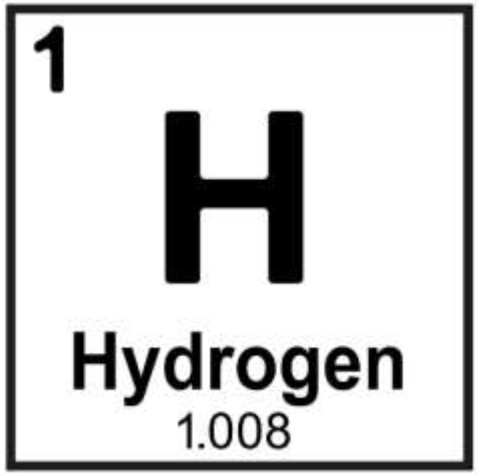
Hydrogen Drivers



GHG emissions mandates

FCEVs

Curtailment of wind and solar electricity

SoCalGas Renewable Gas Goals

- ***California Law***
  - ***2030: 40% below 1990 levels*** (SB 32, 2015)
  - ***2050: 80% below 1990 levels*** (EO B-30-15 and EO S-3-05)
  - ***2045: Carbon neutrality and net negative thereafter*** (EO B-55-18)

- ***SoCalGas commitment:***
  - ***2022: 5% Renewable Gas***
  - ***2030: 20% Renewable Gas***

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SoCalGas' 40 Million Ton Challenge

SoCalGas Climate Registry CO_2 Emissions

- Unverified 2018 Scope 1 emissions: 1,789,720 $MTCO_{2e}$
- Unverified Scope 2 (from purchased electricity): 21,647 $MTCO_{2e}$
- Verified Scope 3 (CARB Subpart NN combustion emissions for gas delivered to customers): **39,890,211 $MTCO_{2e}$**
- 18.8 Mcf NG = 1 metric ton CO_2
- Global CO_2 Emissions = 40 Gt/yr

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National Hydrogen Scenarios

H2USA Locations Roadmap Working Group

DOE/NREL

National Hydrogen Scenarios 2035 Scenario

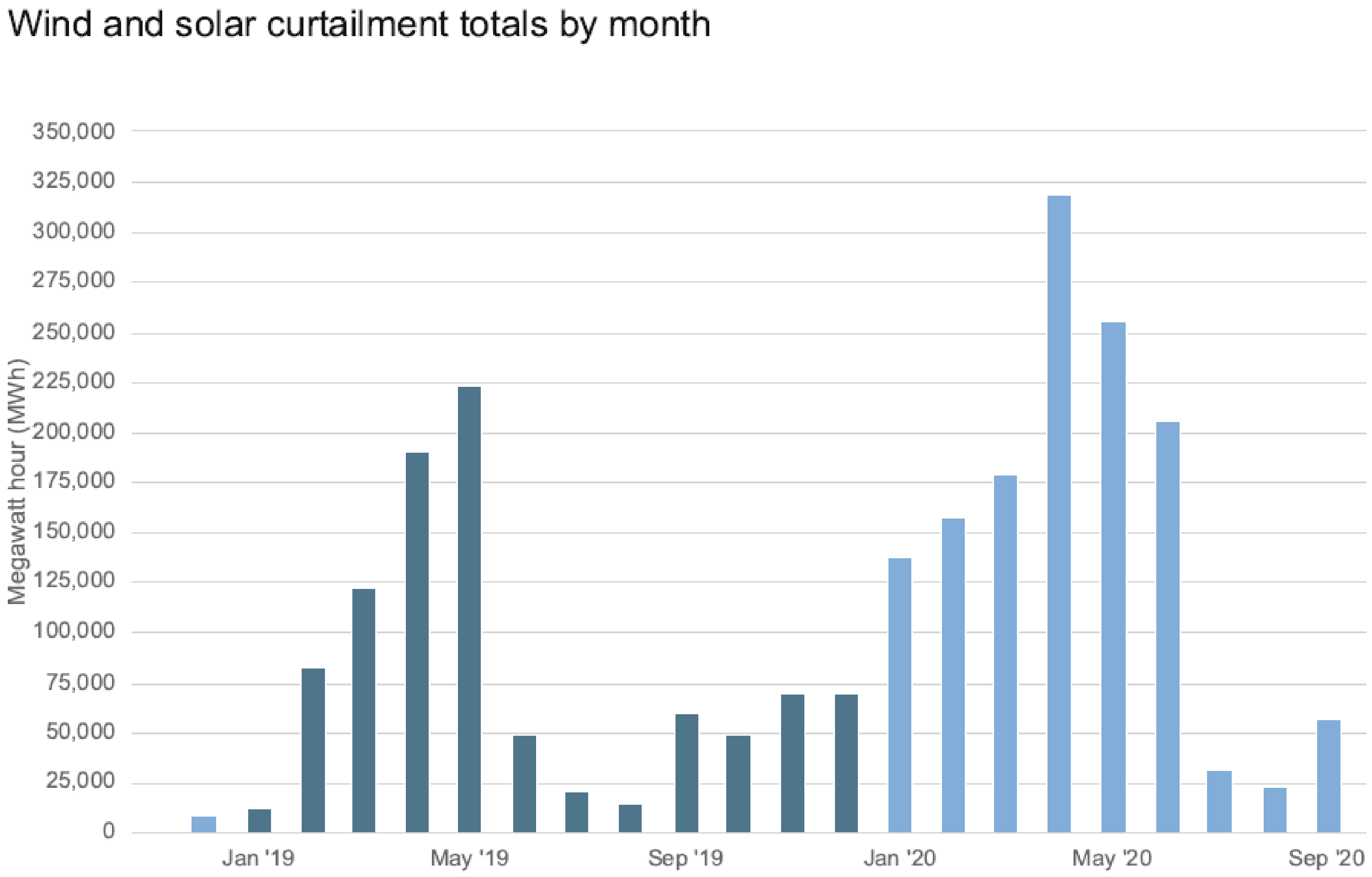
- 1,500–3,300 hydrogen stations nationally
- 1.3 million to 3.4 million kg/day H2 production capacity
- 1.8 million to 4.5 million FCEVs
- $3.0 billion to $9.2 billion in revenues Assuming average hydrogen prices of $8–$10 per kg
- The largest and most robust station networks would initially be a select number of major urban areas

Source: https://www.nrel.gov/docs/fy18osti/71083.pdf

Curtailed Wind and Solar Electricity

2020 Jan-Sept Curtailments: 1.3 TWh

CAISO



Updated as of 10/12/2020

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

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Green Hydrogen Challenges

- Energy density
  - H2 = NG/3
- Compatibility with existing systems
- Cost
  - \$3/MMBtu = 1¢/kWh
  - Dependence on low-cost electricity
  - Intermittency of renewable power
  - Antiquated dispatch systems
  - Low duty cycle of renewable electrolysis systems

1
H
Hydrogen
1.008

Water Electrolysis

Blue Hydrogen Strategies

- Low-cost, modular, point of use, electric SMR
- Co-production of H2 & C
- Monetizing carbon
- Methanation

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Hydrogen
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STARS Compact SMR

Originally developed to operate on concentrated solar thermal energy

Demonstrated a SDSU Brawley

> 70% Solar to chemical energy conversion.

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STARS Compact SMR

SoCalGas is working to install and operate the "STARS," a 3D printed, microchannel hydrogen production system here in Southern California.

The reactor can operate using either concentrated solar thermal energy or electric induction heating, or both.

A single compact (12" x 1") reactor can produce more than 30 kg/d hydrogen (20 barg) at the point-of-use with production costs below $3/kg (assuming $3/MMBtu NG).

Low-cost hydrogen is essential.

This microchannel chemical process "chip" and heat exchanger is a technology platform that can be used for many reactions such as CO2 reduction.

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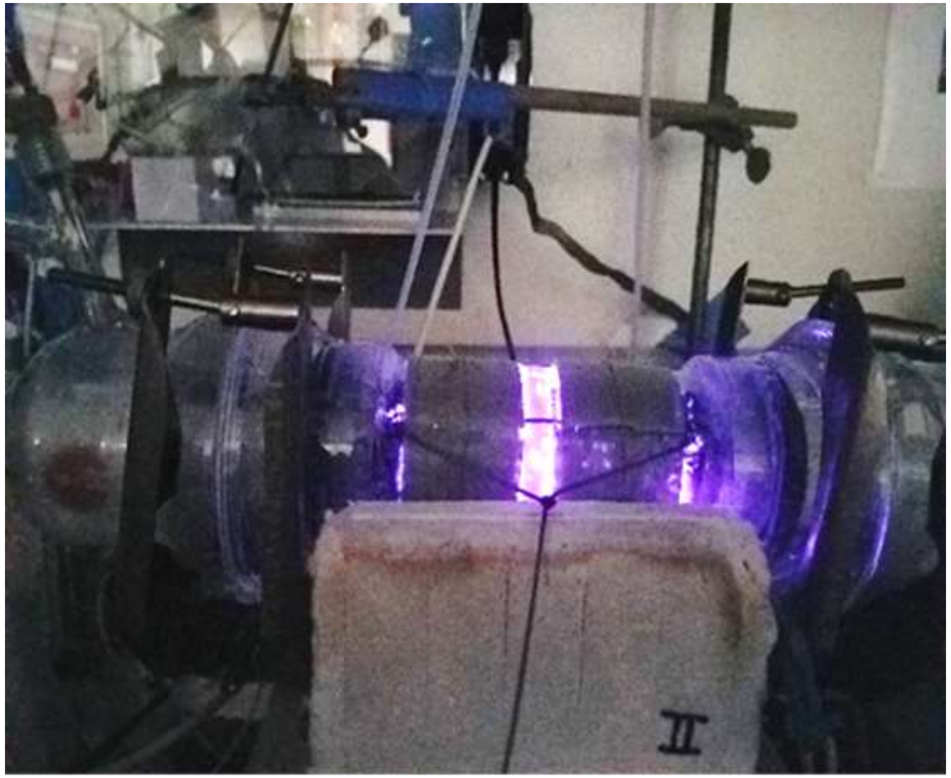
Catalytic Non-Thermal Plasma SMR

JPL and SoCalGas have developed a very compact device that uses low-temperature plasma to catalyze the SMR reaction

We are now in the process of developing an scaled-up system that, if successful, may make point-of-use hydrogen production a reality.

- Conversion energy efficiency: > 75%
- Startup time: < 30 minutes;
- Low-temperature operation
- Subscale unit production capacity: ~ 1Kg H_2/d
- Full-scale production capacity: 5kg/d
- Production Cost: \$ 2 - \$4 /kg H_2



CNTP SMR Reactor

- Dielectric barrier discharge (DBD) or catalytic non thermal plasma (CNTP) technology can be used for many reactions such as CO2 reduction.

Monetizing Carbon

CCS / CCUS Federal Support

- Since FY2010, Congress has provided more than **$5 billion** total in appropriations for DOE CCS-related activities. The annual DOE budget for CCS in 2019 was **$727 million**.

- The Bipartisan Budget Act of 2018 amended **Section 45Q,** increasing the tax credit from $20 to **$50 per ton of CO_2**

  - For permanent sequestration, the tax credit was increased from $10 to **$35 for EOR purposes**

  - Removed the 75-million-ton cap on the total amount of CO_2 injected underground, among other changes.

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SoCalGas CCS / CCU RD&D

CO2 Capture and Use Pathways

Pathway[a]	Removal and/or capture[b]	Utilization product	Storage[c,d] and likelihood of release (high/low)	Emission on use[f] or release during storage[g]
(1) Chemicals from CO_2	Catalytic chemical conversion of CO_2 from flue gas or other sources into chemical products	CO_2-derived platform chemicals such as methanol, urea and plastics	Various chemicals (days/decades) – high	Hydrolysis or decomposition
(2) Fuels from CO_2	Catalytic hydrogenation processes to convert CO_2 from flue gas or other sources into fuels	CO_2-derived fuels such as methanol, methane and Fischer–Tropsch-derived fuels	Various fuels (weeks/months) – high	Combustion
(3) Products from microalgae	Uptake of CO_2 from the atmosphere or other sources by microalgae biomass	Biofuels, biomass, or bioproducts such as aquaculture feed	Various products (weeks/months) – high	Combustion (fuel) or consumption (bioproduct)
(4) Concrete building materials	Mineralization of CO_2 from flue gas or other sources into industrial waste materials, and CO_2 curing of concrete	Carbonated aggregates or concrete products	Carbonates (centuries) – low	Extreme acid conditions
(5) CO_2-EOR	Injection of CO_2 from flue gas or other sources into oil reservoirs	Oil	Geological sequestration (millennia) – low[e]	n.a.
(6) Bioenergy with carbon capture and storage (BECCS)	Growth of plant biomass	Bioenergy crop biomass	Geological sequestration (millennia) – low[e]	n.a.
(7) Enhanced weathering	Mineralization of atmospheric CO_2 via the application of pulverized silicate rock to cropland, grassland and forests	Agricultural crop biomass	Aqueous carbonate (centuries) – low	Extreme acidic conditions
(8) Forestry techniques	Growth of woody biomass via afforestation, reforestation or sustainable forest management	Standing biomass, wood products	Standing forests and long-lived wood products (decades to centuries) – high	Disturbance, combustion or decomposition
(9) Soil carbon sequestration techniques	Increase in soil organic carbon content via various land management practices	Agricultural crop biomass	Soil organic carbon (years to decades) – high	Disturbance or decomposition
(10) Biochar	Growth of plant biomass for pyrolysis and application of char to soils	Agricultural or bioenergy crop biomass	Black carbon (years to decades) – high	Decomposition

n.a., not applicable.
[a]The ten pathways are depicted in Fig. 1 and are represented as a combination of steps in Fig. 2.
[b]Removal and/or capture corresponds to steps A, B and/or C in Fig. 2.
[c]Storage corresponds to steps D, E or F in Fig. 2.
[d]Storage durations represent best-case scenarios. For instance, in CO_2-EOR, if the well is operated with complete recycle, the CO_2 is trapped and can be stored or more[22]. This is also relevant only for conventional operations.
[e]Release during geological storage is usually a consequence of engineering implementation error.
[f]Emission on use corresponds to step G in Fig. 2.
[g]Release during storage corresponds to steps H, I or J in Fig. 2.
[h]The letters stated are the steps from Fig. 2 that comprise the example cycle.

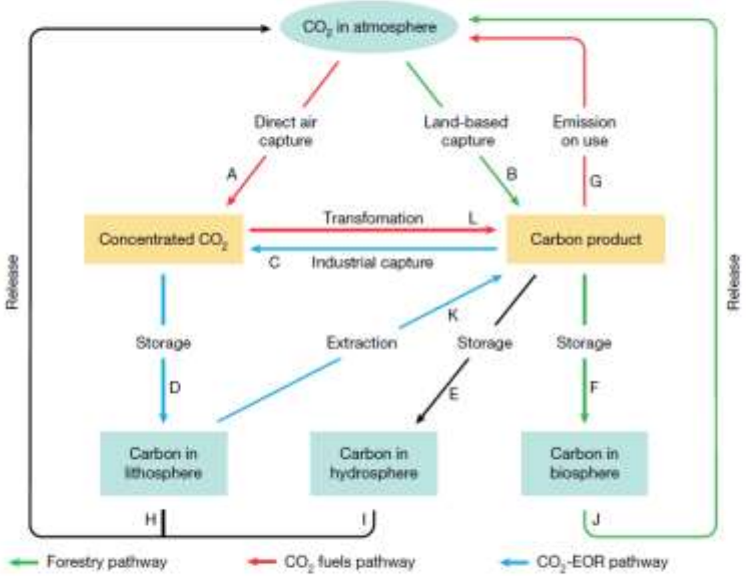

Fig.2 Carbon dioxide utilization and removal cycle.

Source: Hepburn, C., Adlen, E., Beddington, J. et al. The technological and economic prospects for CO2 utilization and removal. Nature 575, 87–97 (2019). https://doi.org/10.1038/s41586-019-1681-6

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RD&D Program CCUS

20 Projects

"Flooding the zone!"

General	Team	Technology	Principal Investigator	TRL	Years to Commercial Pilot
Methane Pyrolysis	PNNL, WVU, SCG DOE	Fluidized bed, microwave	John Hu Rob Dagle	4	4
	Stanford, SCG DOE	Thermocatalyic	Arun Majumdar	2	8
	Xerox, Parc, SCG DOE	Metal Fog	Jessy Rivest	3	5
	C-ZERO, SCG, SDG&E, Shell, DOE	Molten Salt	Zach Jones	5	6
	Monolith Materials (SCG Monitoring)	Fluidized bed, high temperature electic furnace	Pete Johnson	9	0
Electrochemical	Caltech, JCAP, SCG DOE	BPM Electrodialysis seawater CO_2 recovery	Chengxiang Xiang	3	6
	Opus 12, SCG DOE	Converting CO_2 to CH4, and plastics	Etosha Cave	7	4
	JPL, Susteon, Newcastle U, SCG DOE/NETL	Catalytic Non-Thermal Plasma (CNTP) assisted conversion of CO_2 and alkane to alkene and CO	S. James Zhou Raghubir Gupta	4	5
Sorbent-based Point-source CO_2 Separation	LLNL, Xebec, SCG DOE/BETO	Low-cost composite sorbents	Sarah Baker	7	2
	Susteon, Svante, LADWP, SCG DOE/ARPA-E	Rapid temperature swing adsorption carbon capture technology for optimal operation of fossil power plants	S. James Zhou Raghubir Gupta	8	3
Reactive CO_2 Capture	PNNL, WVU, SCG DOE	Integrated capture and conversion of CO_2 to methanol (ICCCM) process technology	David Hilibrandt Rob Dagle	3	5
	LLNL, Stanford, SCG DOE/BETO	Electromethanogenesis	Sarah Baker Alfred Spormann	5	6
	NREL, SCG, Electrochaea DOE/BETO	Water electrolysis with biomethanation	Kevin Harrison Nancy Dowe	9	2
	UCSD/Scripps IO, SCG	Capture and reuse of CO_2 and NO_x from stationary engine flue-gas for algae production	Dominick Mendola	8	5
	Susteon, Polytechnique Montreal, PNNL, Johnson Matthey (DOE Proposal)	Converting methane and CO_2 into methanol and DME using a microchannel reactor system	Raghubir Gupta	3	5
	Brimstone Energy, PG&E, Breakthrough Energy Ventures, Chevron	Electrolysis of SO_2 and water for the efficient co-production of sulfuric acid and hydrogen. Integration of sulfuric acid by-product for minerals leaching and CO_2 emissions mitigation in cement production	Cody Finke	3	5
Direct Air Capture	Electricore, Inc., Climeworks, Svante, Wintec, SCG, DOE	Sorption media	Deborah Jelen	7	3
	IWVC, PNNL, SCG DOE	Combined water and CO2 direct air capture system	Jamie Holladay	5	5
	Susteon, U of Wyoming SCG DOE	Low regeneration temperature amine doped solid sorbents catalyzed by ionic liquid	S. James Zhou Raghubir Gupta	3	7
Geological CO2 Sequestration	Clean Energy Systems, Schlumberger, SCG	GTI oxygen-blown biomass gasification, oxyfuel CO combustion, geological CO_2 injection	Keith Pronske	8	3

Methanation

NREL, SCG Integrating Water Electrolysis with Biomethanation

- Using the renewable H_2 and CO_2 in a downstream methanation process to produce renewable methane and water.

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

- Methanation is important because it
  - Enables higher penetration of renewables by provides long-duration energy storage using the NG network
  - Synthetic methane meets pipeline quality standards and has **3x more energy** than H_2 by volume
  - Recycles CO_2 from waste streams from ethanol refineries, dairies, wastewater, breweries
  - Scalable, non-toxic, self-replicating biocatalyst, low temperature systems
  - 200 MW of electrolysis per typical ethanol plant could recycle all of the CO_2 emissions into CH_4

700 Liter Vertical Stirred Biomethanation reactor at NREL

200 Ethanol Plants in the U.S. -- Each plant produces an average of 50 M gallons/y and 150,000 metric tons of CO_2

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LLNL, Stanford SCG Microbial Electro-methanogenesis

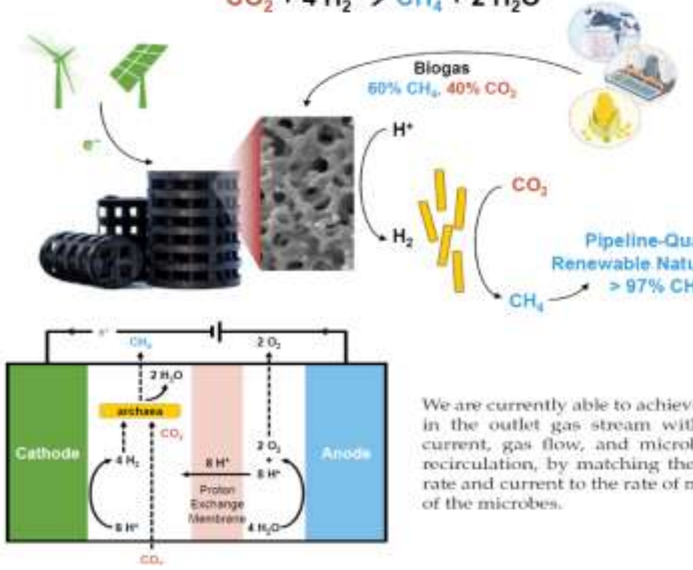
- It was recently discovered that certain microbes are capable of directly converting electrical current, water and carbon dioxide into methane, a process known as microbial electromethanogenesis, or ME.
- This process enables single-unit conversion of CO2 and electricity to methane, a much simpler process than the current approach.
- ME is important because it offers the potential to reduce CAPEX and OPEX costs associated with biogas upgrading.
- Rule of Thumb: 10MWe feeding a biomethanation reactor can recycle 7500 tons of CO2 per year

Keys to Success
- Well grounded science & engineering
- Strong team
- Commercialization partners in place
- TRL: 5; Years to commercial pilot: 6

In-Situ Microbial Electromethanogenesis

By producing hydrogen in the same reactor where the microbes utilize it to convert CO_2 into CH_4, we can overcome productivity limitations associated with poor solubility and mass transfer of hydrogen in water. By eliminating the need for a separate electrolyzer, the process can be made modular and the scale can be tuned to the size of the biogas source.

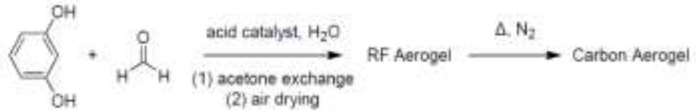
$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

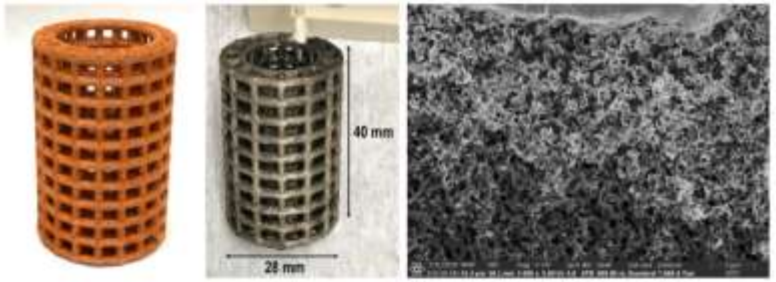


We are currently able to achieve 90% CH_4 in the outlet gas stream with constant current, gas flow, and microbial media recirculation, by matching the CO_2 flow rate and current to the rate of metabolism of the microbes.

Advanced Manufacturing of Electrodes

We can manufacture high surface area electrodes in any geometry for various applications. Cylindrical electrodes are electroplated with a NiMo catalyst for performing hydrogen evolution at neutral pH in a tubular bubble column flow reactor.



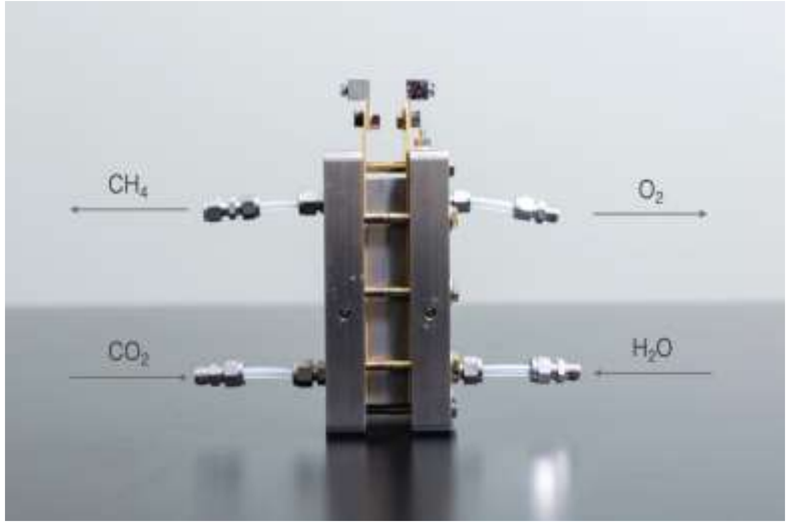


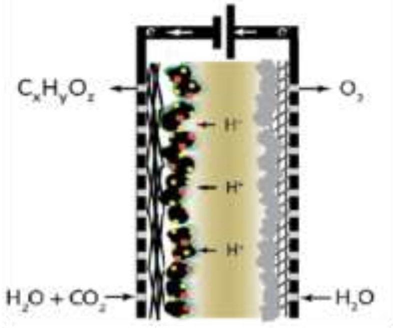
Opus 12, SCG, DOE Electrochemcial CO2 Reduction & Conversion System

- Opus 12 is developing an efficient polymer-electrolyte membrane (PEM) CO_2 electrolyzer that can couple to sources of renewable electricity and recycle carbon dioxide emissions into useful chemicals and fuels.

- Numbering-up to future CO_2 conversion plant, 10-100 modules would be capable 50 tons per day of total CO_2 conversion at Opus 12's current electrode performance, and over three times this amount at future performance targets.

- This technology is important because it has the potential to significantly improve the energy efficiency of CO_2 utilization and sequestration while reducing process costs.





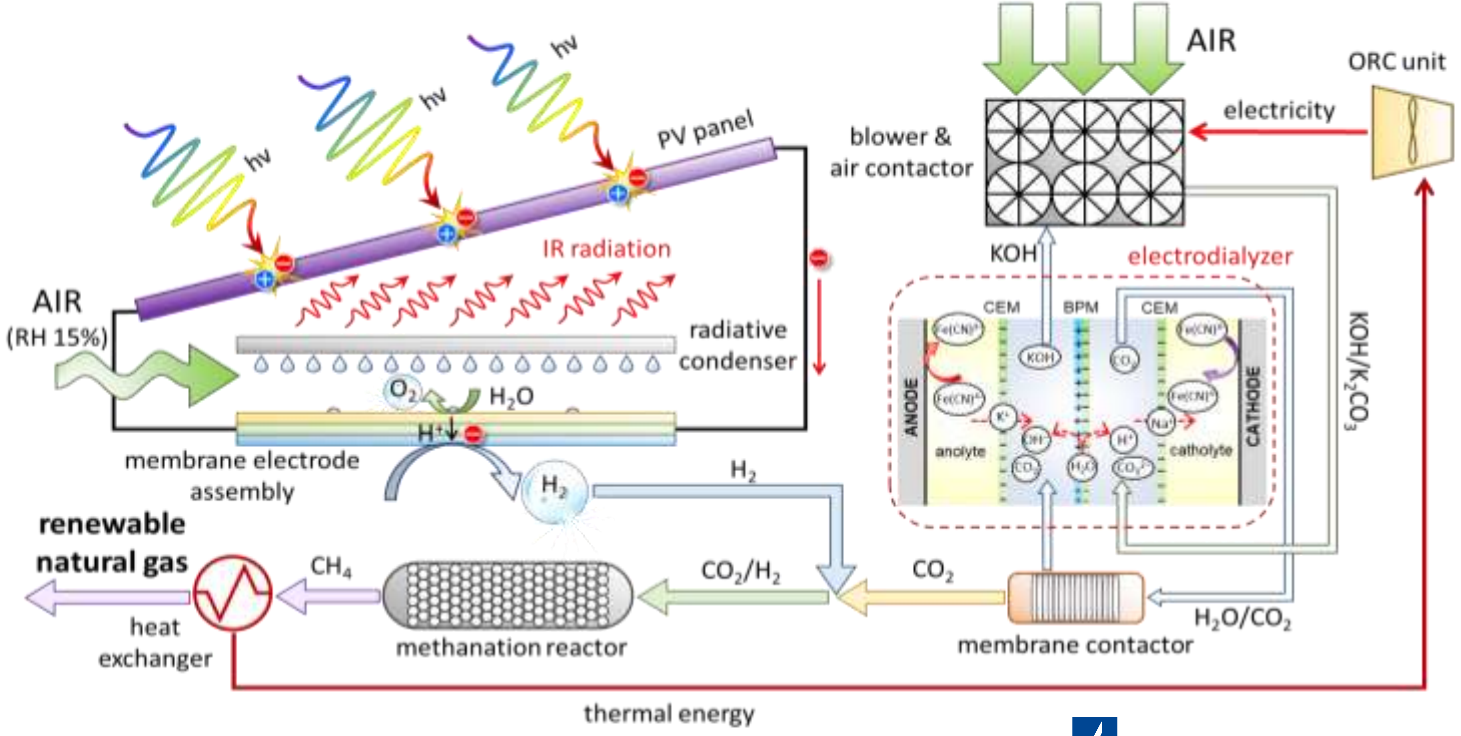
Opus 12 Electromethanogenesis –
metal nanoparticle catalyst/polymer membrane

Caltech, JCAP SCG Electrochemical Extraction and Conversion of CO_2 from Seawater

We have envisioned:

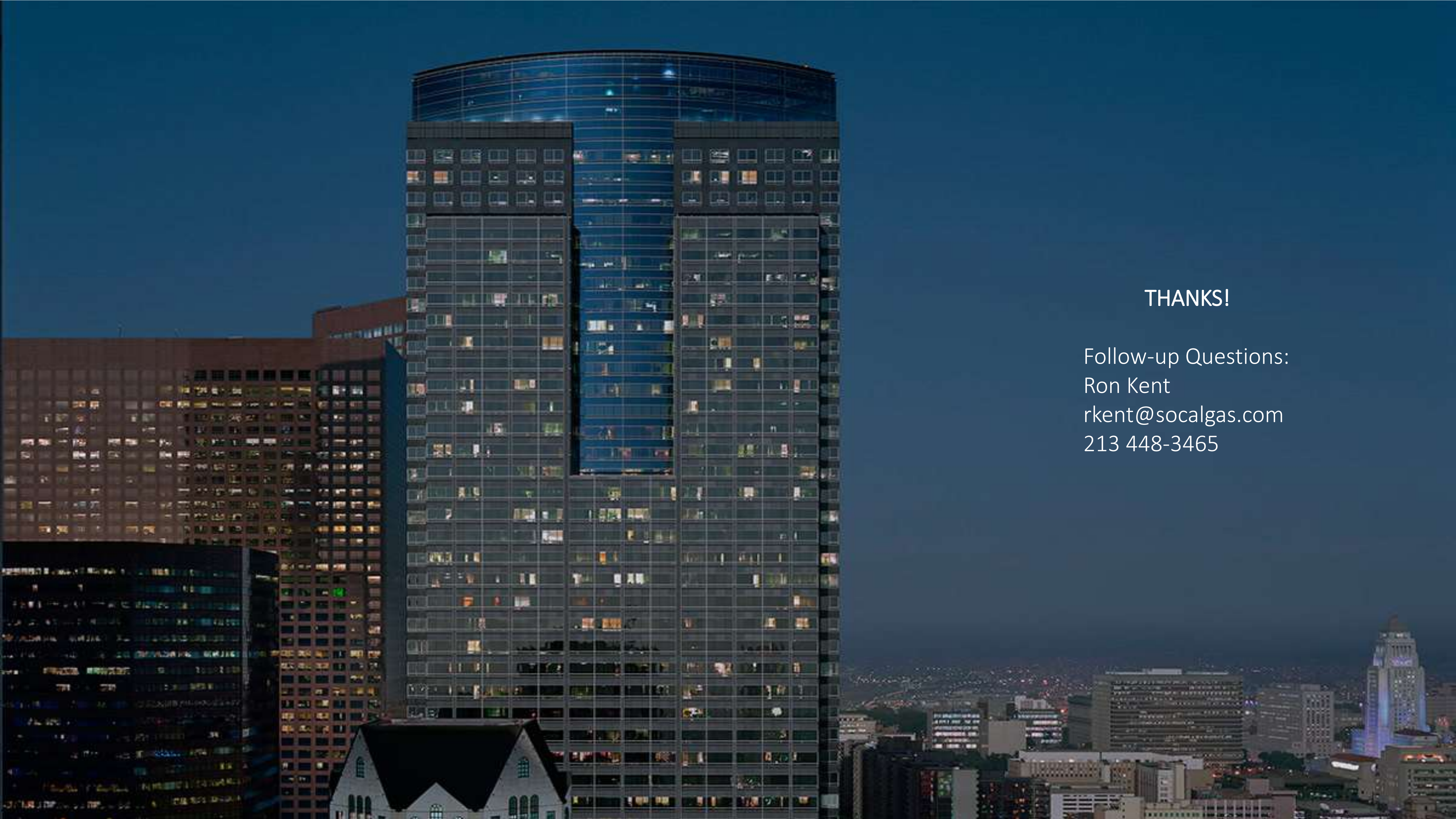
- A floating CH_4 farm powered by PV
- Direct CO_2 capture from oceanwater
- Modular Sabatier reactor

- CO_2 in the atmosphere is in constant equilibrium with the ocean.
- World's ocean represents a natural carbon sink that absorbs 25% of CO_2 entering the atmosphere.
- The effective concentration of CO_2 in seawater is a factor of 128 times larger than in the air.
- Direct coupling of electrochemical CO_2 extraction and conversion to nongaseous chemicals by using a bipolar membrane electrodialysis (BPMED) cell and a vapor-fed CO_2 reduction cell is an important advancement:
  - Record low electrochemical energy consumption of 0.98 kWh kg−1 CO_2 or 155.4 kJ mol−1 CO_2 from seawater
  - Record high CO_2 extraction efficiency of 71%
  - Highly selective conversion of CO_2 >80% into fuels and chemicals in the vapor-fed device



Bench-scale (10 cf^3/day), sunlight driven, CH_4 generator

SoCalGas A Sempra Energy utility



THANKS!

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SAND2020-12130 PE

Hydrogen in Natural Gas Infrastructure: Materials Compatibility

Chris San Marchi, Sandia National Laboratories

Joe Ronevich, Sandia National Laboratories

Kevin Simmons, Pacific Northwest National Laboratory

NARUC Annual Meeting

November 5, 2020

Supported by DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) in the Office of Energy Efficiency and Renewable Energy (EERE)

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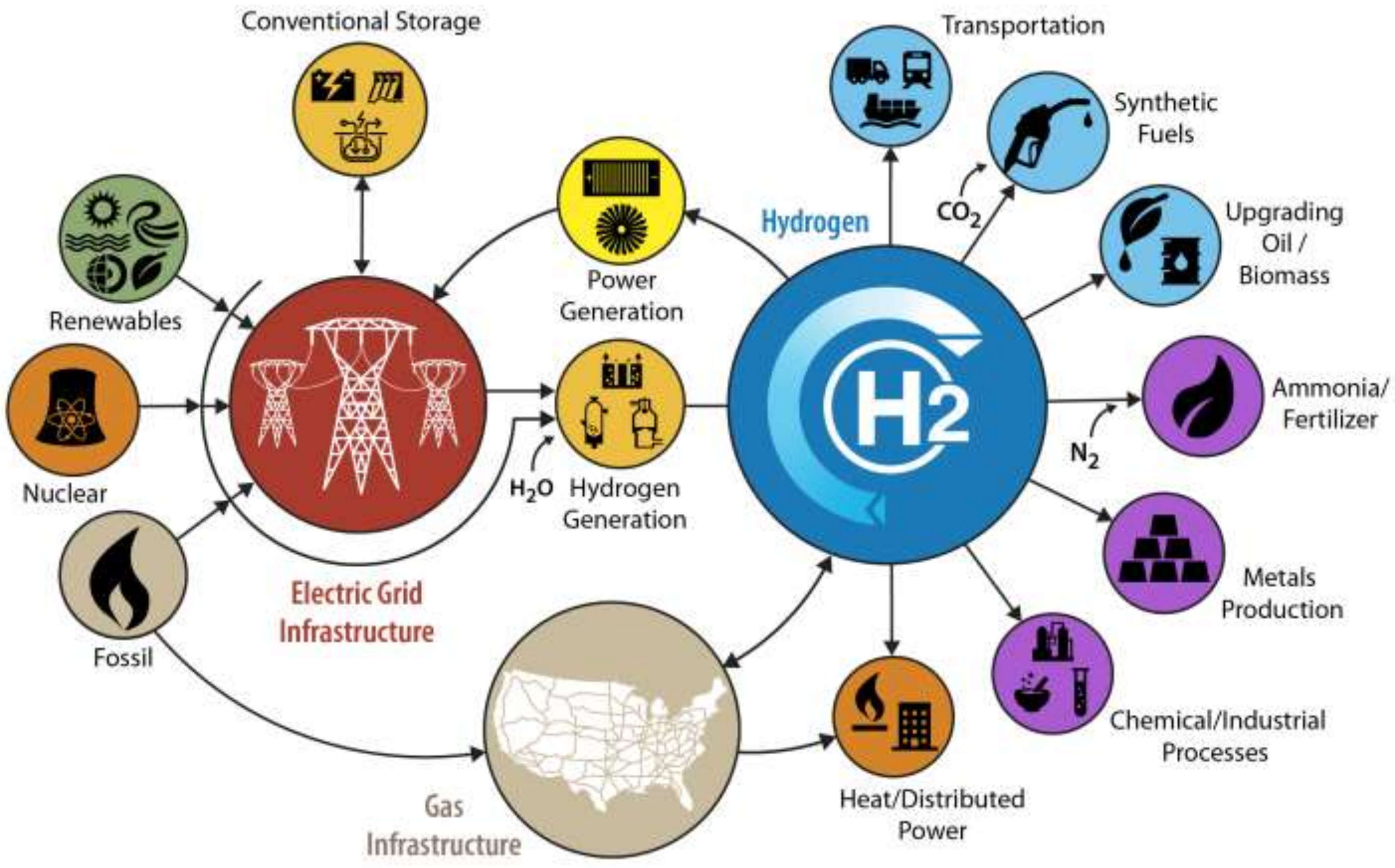
Why hydrogen in natural gas infrastructure?

Hydrogen is a convenient energy carrier for the storage and conveyance of energy to serve a range of industrial and transportation applications



- Hydrogen is already used extensively in industry – about 10 MT annually
- Large quantities are distributed in pipelines in the US

However, gaseous hydrogen is known to embrittle most metals

Motivation and Outline

- What is hydrogen embrittlement and when is it important?
- How does gaseous hydrogen affect fatigue and fracture of pipeline steels?
- Is there a threshold below which hydrogen effects can be ignored?
- Can the effects of hydrogen be masked by other physics?
- Where are the gaps in understanding structural integrity of hydrogen pipelines and piping?
- What is the implication of hydrogen on life of pipelines and piping?

Motivation and Outline

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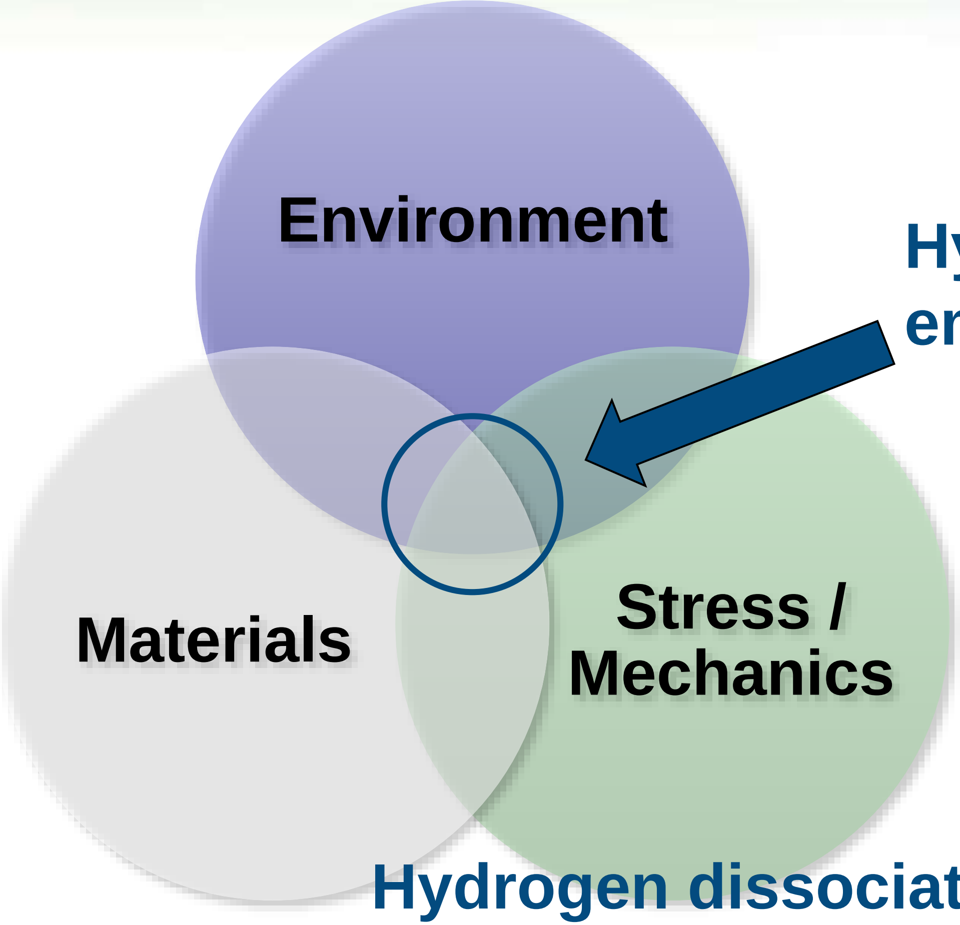
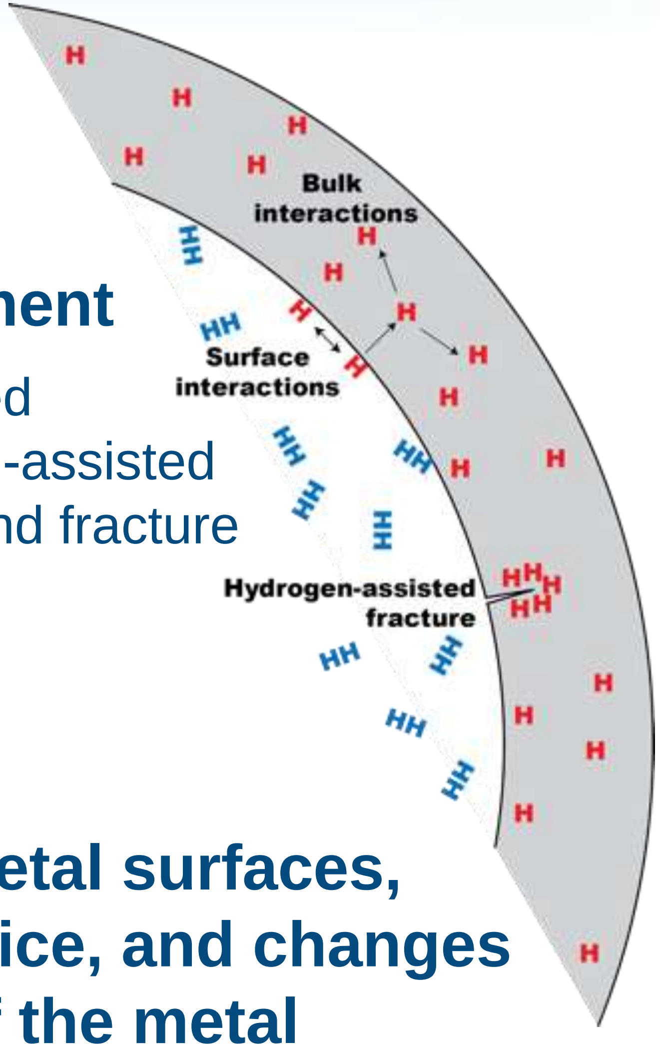
Hydrogen embrittlement occurs in metals under the influence of stress in hydrogen environments



Hydrogen embrittlement

also called hydrogen-assisted fatigue and fracture



Hydrogen dissociates on metal surfaces, dissolves into the metal lattice, and changes the mechanical response of the metal

Hydrogen-induced damage also occurs in polymer materials

- **Polymers are used extensively in hydrogen infrastructure**
  - Low-pressure piping and pipelines
  - Liners of composite structures
  - Seals
  - Potting and other pressure boundaries (e.g., feed-thrus)

Examples of damage in elastomers

Thermoplastics
HDPE, Nylon, PEEK, PEKK, PET, PEI, PVDF, Teflon, PCTFE, POM

Elastomers
EPDM, NBR/HNBR Silicone, Viton, Neoprene, polyurethanes

Thermosetting polymers
Epoxy, PI, Polyurethane

Motivation and Outline

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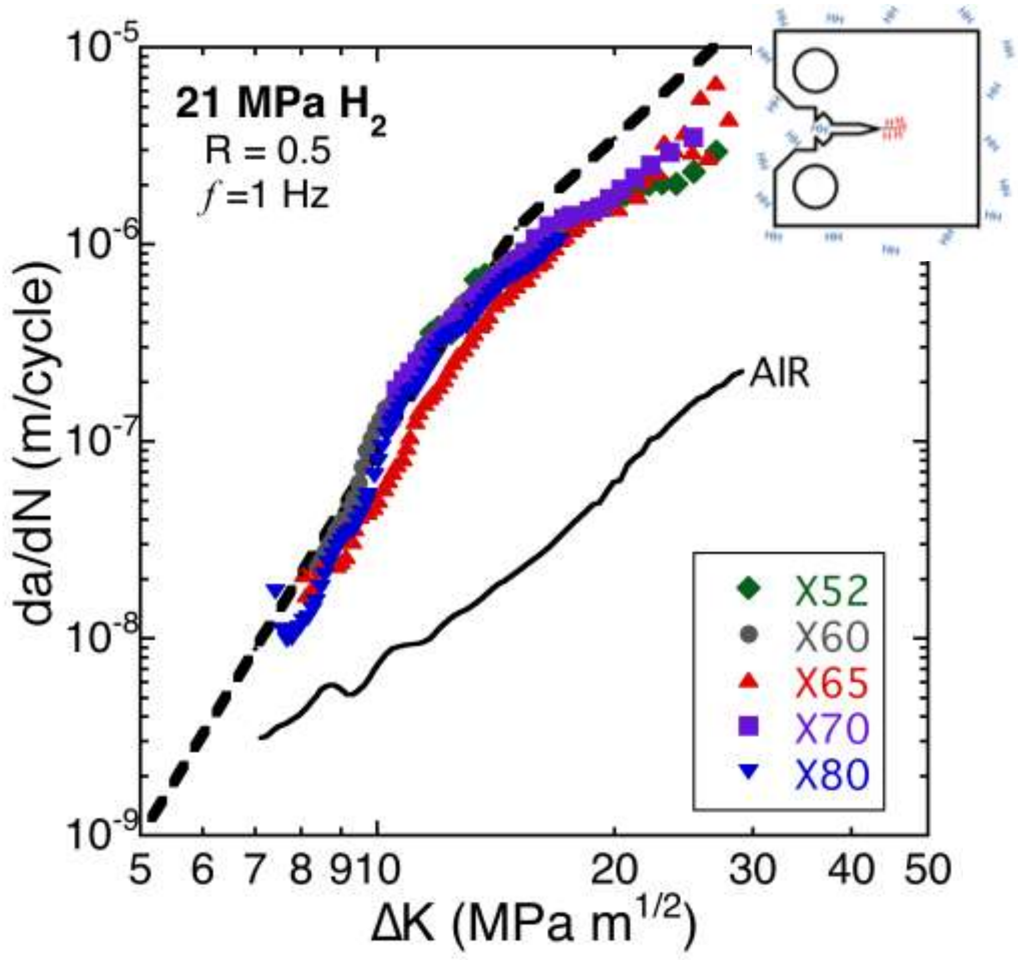
Pipeline steels tend to show very similar fatigue crack growth rates in gaseous hydrogen



- **A wide variety of pipeline steels display similar fatigue response in high-pressure gaseous hydrogen**
- **Fatigue crack growth rates in hydrogen scale approximately with square root of pressure (not shown)**
  - **Upper ‘plateau’ is independent of pressure**

Motivation and Outline

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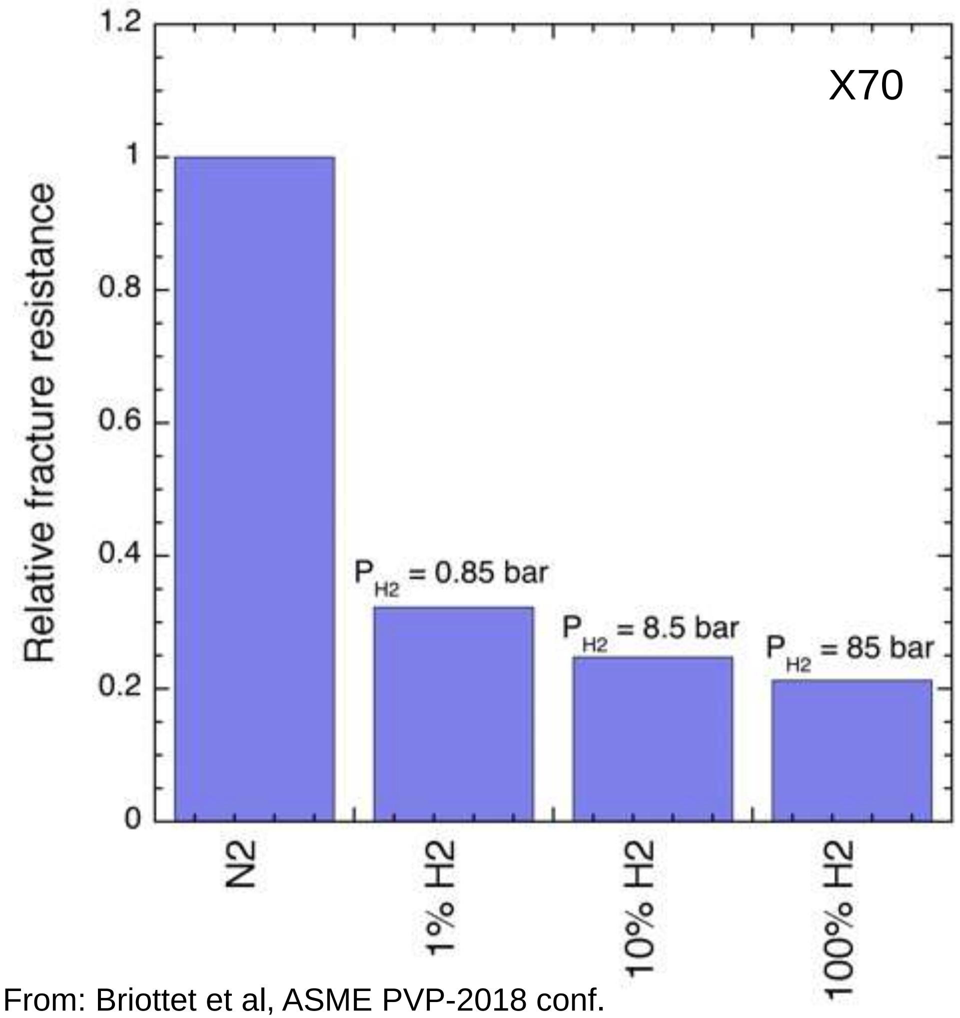
Low pressure hydrogen has substantial effect on fracture resistance of pipeline steels

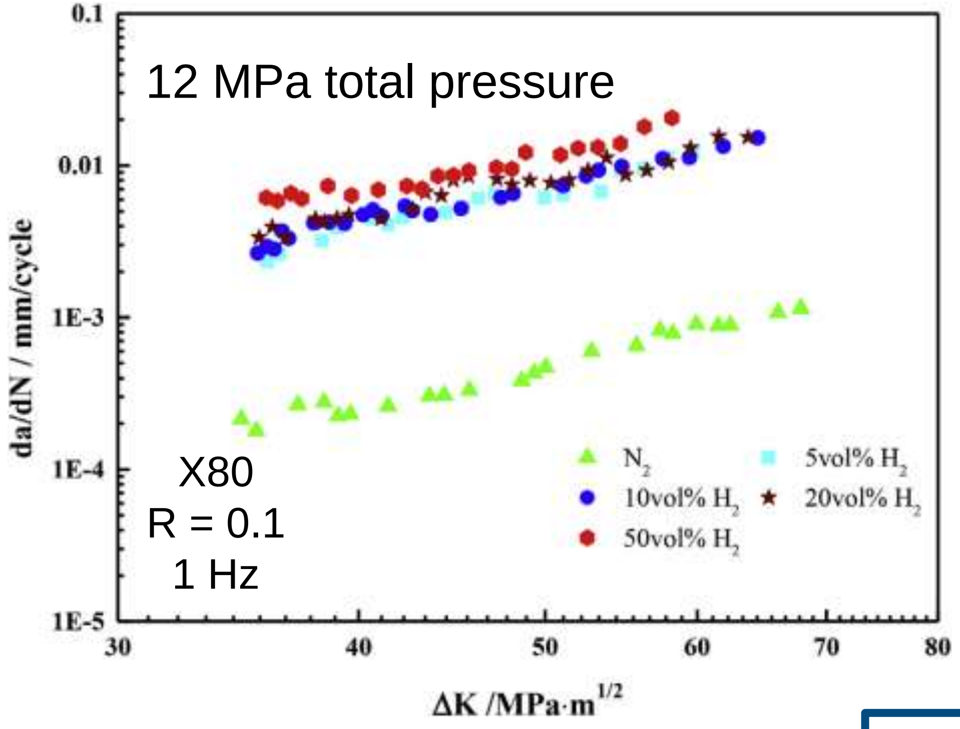


- **Measurements of fracture resistance in gaseous mixtures of H_2 and N_2 show substantial effects of H_2**
- **1% H_2 is only modestly different than 100% H_2**

<1 bar of H_2 reduces fracture resistance

From: Briottet et al, ASME PVP-2018 conf.

Low pressure hydrogen has substantial effect on fatigue crack growth of pipeline steels



From: Meng et al, *IJ Hydrogen Energy* **42** (2017) 7404.

- **Measurements in gaseous mixtures of H_2 and N_2 show acceleration of fatigue crack growth rate with 5% H_2**
  - **But little additional acceleration with higher H_2 content**

Small amounts of hydrogen can have substantial effect on fatigue and fracture

Motivation and Outline

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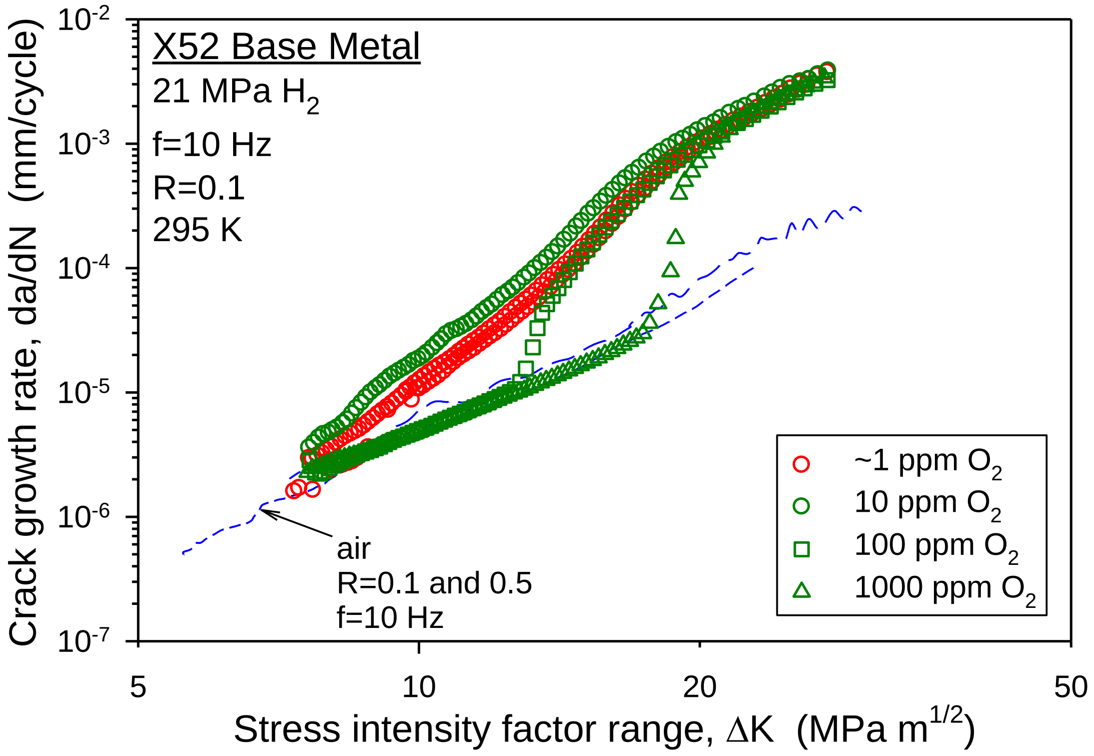
- Is there a threshold below which hydrogen effects can be ignored?
- **Can the effects of hydrogen be masked by other physics?**
- Where are the gaps in understanding structural integrity of hydrogen pipelines and piping?
- What is the implication of hydrogen on life of pipelines and piping?

Impurities can influence measurements, but can also provide pathways to mitigate the effects of hydrogen



- **Passivating chemical species can mitigate H_2-accelerated fatigue crack growth rates at low ΔK**
- **Attributed to diffusion to new crack surfaces**

From: Somerday et al, *Acta Mater* **61** (2013) 6153.

Impurity content in H_2 can have substantial effect on both measurements and in-service performance

Note: These oxygen contents are well below the flammability limit.

The role of mixed hydrogen gas environments and impurities should be considered carefully

- Small partial pressure of gaseous H_2 can have substantial effect on fracture and fatigue of steels
- Oxygen can mitigate effects of H_2 in ferritic steels
  - Sensitive to mechanical and environmental variables
  - Other passivating species can have similar effects
- Structural integrity of pipelines carrying mixed gases will depend sensitively on the details
  - NG has many impurities, which can mitigate H_2 effects
  - Pure methane is inert and even small additions of H_2 can be significant

Materials compatibility for hydrogen containment structures depends on the application and the design

Motivation and Outline

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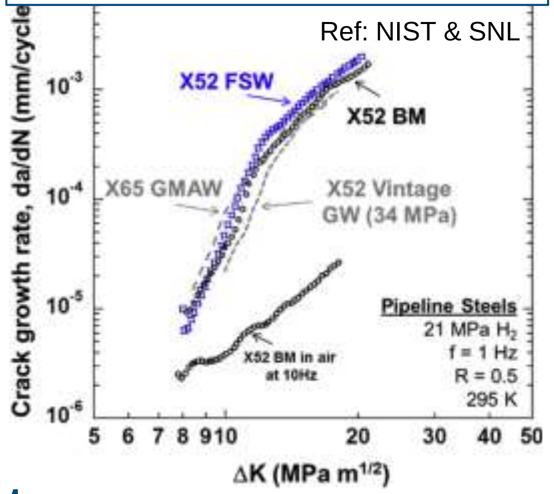
- What is the implication of hydrogen on life of pipelines and piping?

Materials data suggest no 'showstoppers' to integration of hydrogen in existing infrastructure

- **Transmission pipelines**
  - ***API steel grades*** **(including welds): wealth of data exists for fatigue & fracture properties measured in gaseous H_2**
- **Distribution piping and components**
  - **Includes a diverse range of materials, many of which have not been evaluated**
  - ***PE pipe*****: Hydrogen effects on fatigue and fracture of polyethylene (PE) pipe have not been systematically studied**
    - **Pressure and resulting stresses are generally low, suggesting cautious optimism (PE also used in FCEV fuel tanks)**
- **Blended gas environments**
  - **Role of gas impurities is not well understood, especially in dynamic environment (may not need to consider blended gas environments if systems are designed for pure hydrogen)**

Example data for welds

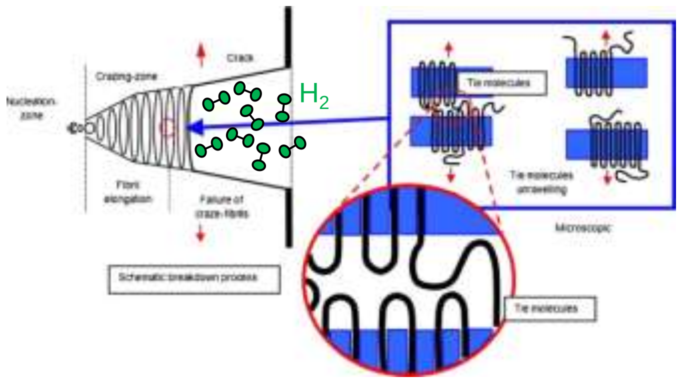


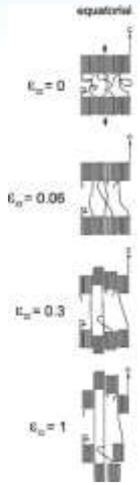
Evaluation of hydrogen-assisted fracture of PE pipe may require innovative test configurations…

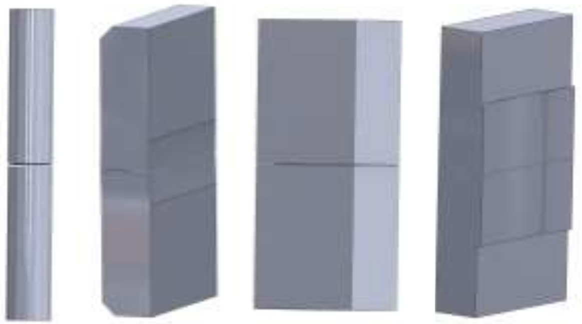
Testing methods for environmental-assisted fracture:

- Slow crack growth (SCG)
- Creep crack growth
- Fatigue resistance
- Effects of weld microstructure

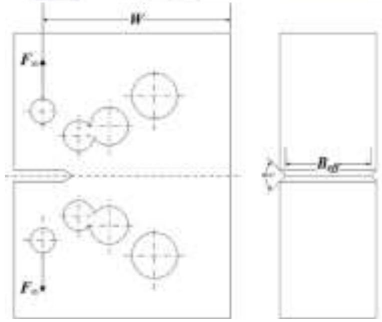
Engineering Fracture Mechanics 101 (2013) 2–9

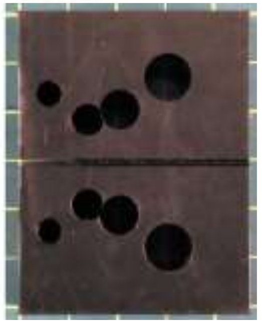


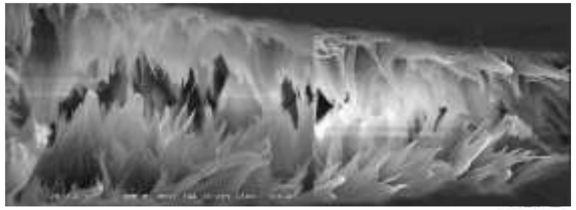




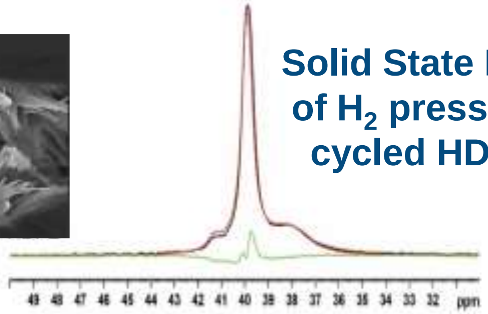
… which address characteristic fracture phenomena and unique damage associated with H_2 and H_2-pressure cycling







A. Chudnovsky et al. / International Journal of Engineering Science 59 (2012) 108–139

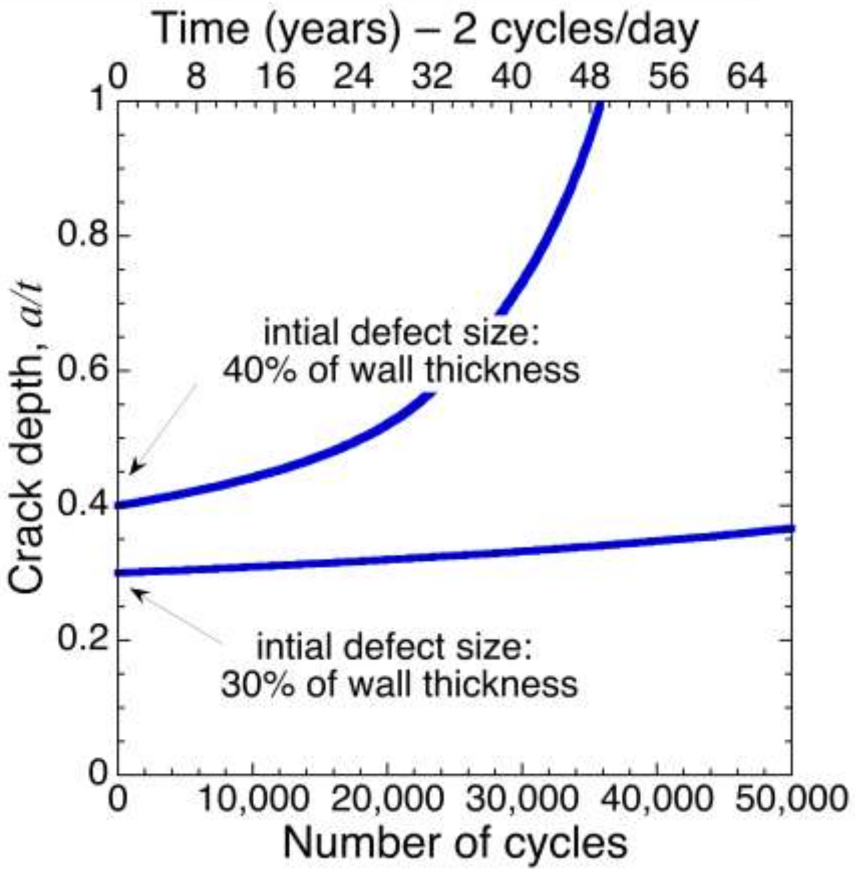


Solid State NMR of H_2 pressure-cycled HDPE

Motivation and Outline

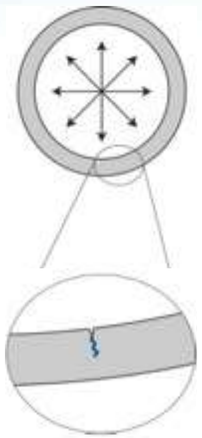
- What is hydrogen embrittlement and when is it important?
- How does gaseous hydrogen affect fatigue and fracture of pipeline steels?
- Is there a threshold below which hydrogen effects can be ignored?
- Can the effects of hydrogen be masked by other physics?
- Where are the gaps in understanding structural integrity of hydrogen pipelines and piping?
- **What is the implication of hydrogen on life of pipelines and piping?**

Example of predicted lifetime of steel pipeline with growing fatigue crack in H_2



<u>Assuming</u>

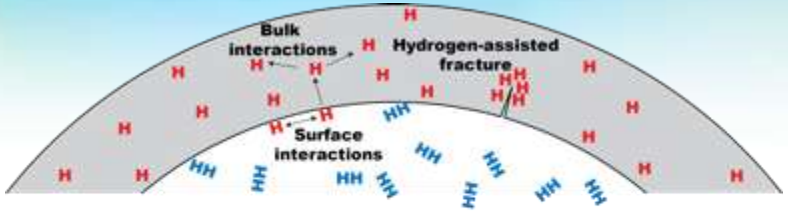
- OD = 762 mm, t = 15.9 mm
- Pressure cycles between 4 and 7 MPa
- Constant crack shape ($a/2c$)
- Large initial defects
- Fatigue crack growth rates in pure H_2 (at higher pressure)



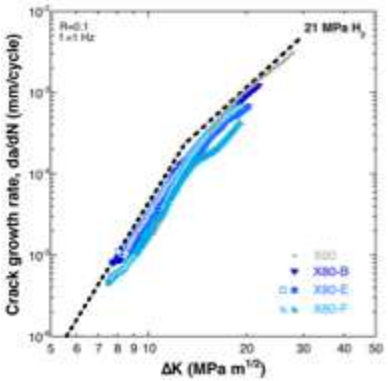
- **10,000s of cycles are needed to extend the crack**
- **At 2 cycles per day, decades are needed to advance the crack**

Available data is insufficient for similar assessment of PE pipe

Summary

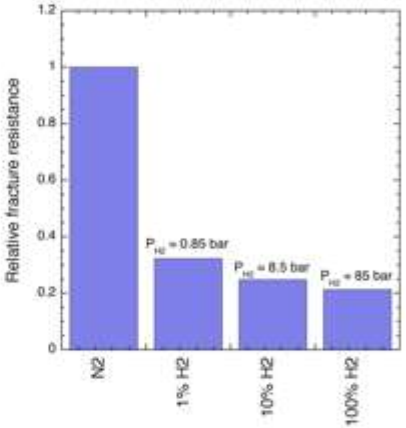


- **What is hydrogen embrittlement and when is it important?**
  - *Hydrogen degrades mechanical properties of most materials*
  - *Hydrogen gas interactions in polymers are not well understood chemically or physically*



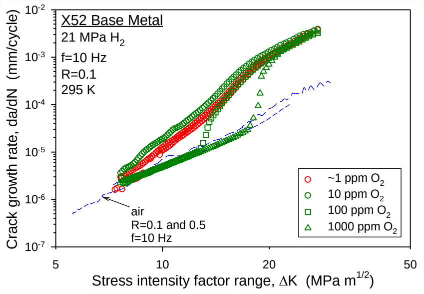
- **How does gaseous hydrogen affect fatigue and fracture of pipeline steels?**
  - *Fatigue is accelerated by >10x and fracture resistance is reduced by >50%*

- **Is there a threshold below which hydrogen effects can be ignored?**
  - ***NO**, even small amounts of hydrogen have large effects*



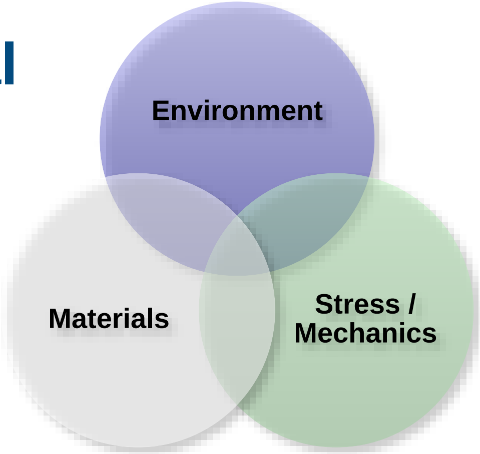
Summary

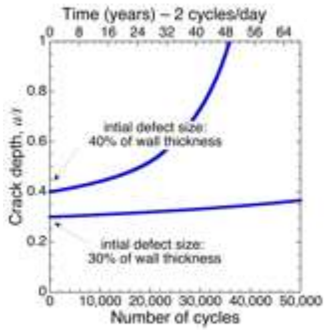
- **Can the effects of hydrogen be masked by other physics?**



  - *Oxygen and other passivating chemical species can mitigate the effects of hydrogen in some cases, which perhaps can be exploited*

- **Where are the gaps in understanding structural integrity of hydrogen pipelines and piping?**
  - *Materials on the distribution side have not been thoroughly evaluated – but operate at low pressure and low stress*





- **What is the implication of hydrogen on life of pipelines and piping?**
  - *In most cases, hydrogen does not threaten the structural integrity of pipelines and piping*

Thank you for your attention

Contacts:

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– Joe Ronevich jaronev@sandia.gov
– Kevin Simmons kl.simmons@pnnl.gov

Additional resources:

- Technical Reference for Hydrogen Compatibility of Materials: https://www.sandia.gov/matlsTechRef/
- Hydrogen-Materials Database: https://granta-mi.sandia.gov
- H-Mat: https://h-mat.org (coming soon)
- Center for Hydrogen Safety: https://h2tools.org/
- H2@Scale concept: https://www.energy.gov/eere/fuelcells/h2scale

Supported by DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) in the Office of Energy Efficiency and Renewable Energy (EERE)

2020 NARUC Annual Meeting
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Bridging the Divide

Thank you for attending

Interested in more hydrogen talk?

Tune into "**Electrification, Hydrogen and the Role of Gas**" Wednesday, 11/11 2:15 – 3:00 pm ET