STRATEGEN
WEBINARS

FREE WEBINAR

GREEN HYDROGEN TECHNOLOGY 101

AUGUST 11

10:00 AM (PT)

STRATEGEN

Moderator:
Melanie Davidson

Director of Marketing
Strategen

Today's agenda

- Housekeeping, Intros and Announcements
- Main Presentation:
  - Batteries Are Not Enough: Why We need Hydrogen to Power our Clean Future
  - Hydrogen Safety
  - Technology Overview
    - Electrolyzer
    - Fuel Cell
    - Hydrogen Gas Turbine
    - Bulk Hydrogen Storage (Underground)
    - Pipelines
  - Green Hydrogen System: Putting the Technologies Together at Intermountain Power Project (IPP)
- Q&A
- Visit www.ghcoalition.org

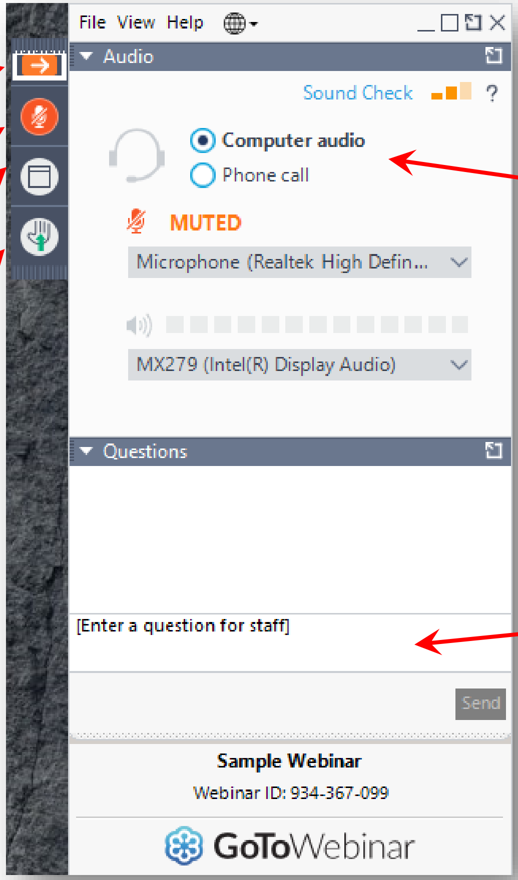
Using GoToWebinar

Minimize control panel

Mute microphone (all attendees are listen-only today)

Toggle full screen mode

Raise hand (not used today)



Audio options

Type you questions here – questions will be answered after all panelists have presented

Today's webinar is being recorded; the recording and slides will be available after the webinar

Strategen is a mission-driven professional services firm dedicated to decarbonizing energy systems

ASSOCIATIONS

Strategen co-founded and manages the California Energy Storage Alliance (CESA) , the Vehicle-Grid Integration Council, and the Green Hydrogen Coalition. Through these organizations, Strategen policy work has been pivotal in building the energy storage industry in California, the US, and around the world.

CONSULTING

Since 2005, Strategen Consulting provides analysis and insight to governments, utilities, NGO's, and industry to help them achieve leading-edge market development and transformational clean energy strategies.

CONVENINGS

Strategen excels in stakeholder engagement, via customized small and large events. Strategen founded Energy Storage North America (ESNA), the largest grid-connected storage conference in North America. ESNA 2021 is affiliated with Intersolar North America.

www.strategen.com

Today's Webinar

Green Hydrogen Technology 101	August 11, 2020

Past Webinars

Global Progress & Momentum for Green Hydrogen	May 12, 2020
Perfect 50-State Storm: COVID-19 and the Utility Crisis	April 2020
Re-Imagining the Energy Ecosystem with Green Hydrogen	April 2020
V-DER Tariffs: Encouraging Good Grid Citizenship	March 2020
Energy Storage on the Move	September 2019
Energy Storage in Emerging Markets	April 2019
Storage as a Peaker Replacement	October 2018

Recordings and slides available at https://www.strategen.com/webinars

Stay Tuned for More Webinars!

MISSION:

Facilitate policies and practices to advance the production and use of Green Hydrogen in all sectors where it will accelerate a carbon free energy future

GREEN HYDROGEN COALITION

APPROACH:

Prioritize Green Hydrogen project deployment at scale; leverage multi-sector opportunities to simultaneously scale supply and demand

www.ghcoalition.org

GHC Members

8MINUTE SOLAR ENERGY

Intersect Power

LA DWP Los Angeles Department of Water & Power

MHPS

MAGNUM Development

PHOTOSOL US

SoCalGas A Sempra Energy utility®

Bloomenergy®

HATCH

NEXCERIS where energy meets environment

MCE My community. My choice.

GREEN HYDROGEN COALITION

What is Green Hydrogen?

What is Green Hydrogen?

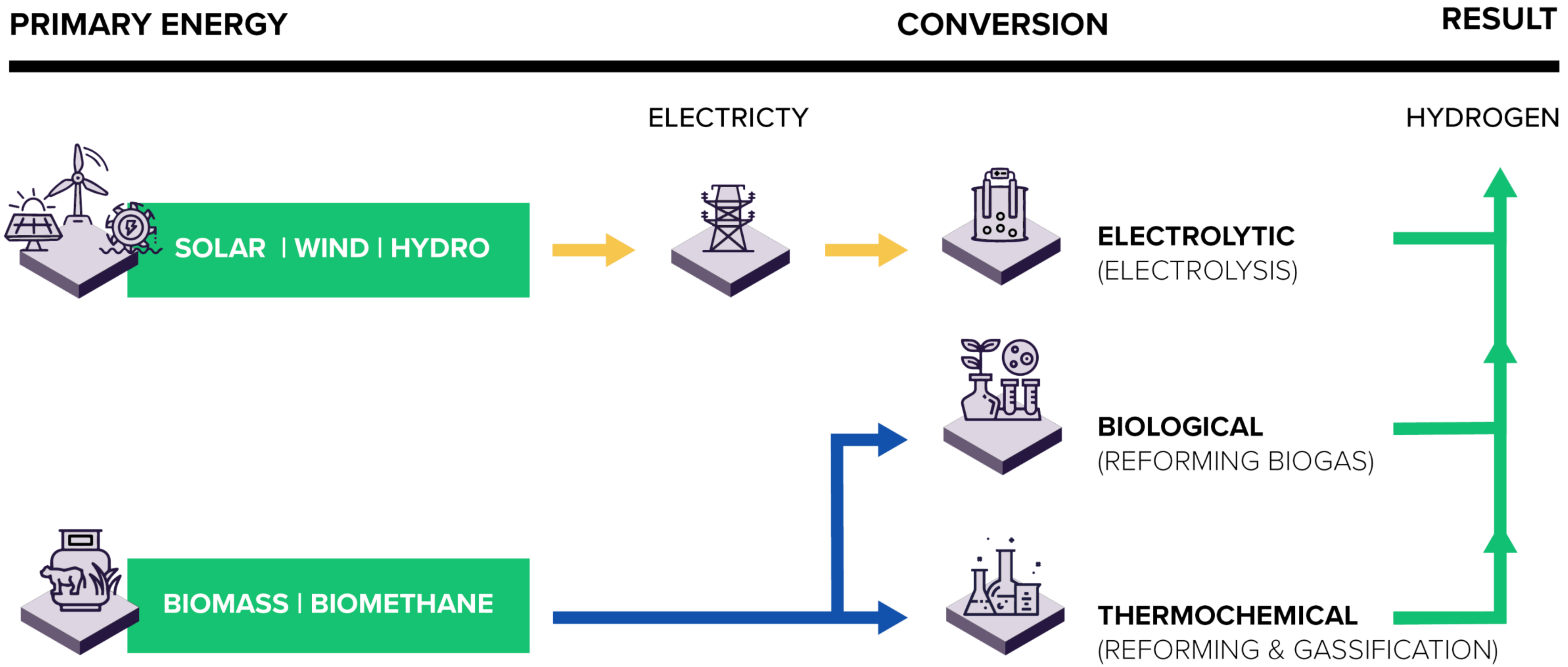
DEFIINITION Green hydrogen is hydrogen created from renewable energy sources such as solar, wind, hydro power, biomass, biogas and municipal waste.

Green hydrogen can be created by the following methods:

1. Electrolysis of water with renewable energy
2. Steam Methane Reformation (SMR) of biogas
3. Thermal conversion or gasification of organic matter and other waste streams

GREEN HYDROGEN COALITION

What is Green Hydrogen?



GREEN HYDROGEN COALITION

Green Hydrogen Guidebook

STRATEGEN

Dr. Jack Brouwer

Director of the National Fuel Cell Research Center (NFCRC)

Professor of Mechanical and Aerospace Engineering

University of California, Irvine

STRATEGEN CONSULTING

Dr. Vince McDonell

Director UCI Combustion Laboratory

University of California, Irvine

Why do we need green hydrogen?

Why Hydrogen?

Hydrogen offers 12 features that are required for 100% zero GHG & pollutant emissions

- Zero emissions (GHG & pollutant) conversio
- Naturally recycled (in short period of time)
- Massive energy storage potential
- Rapid vehicle fueling
- Long vehicle range
- Heavy vehicle/ship/train payload
- Seasonal (long duration) storage potentia
- Sufficient raw materials on earth
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g., a
- Pre-cursor for high energy density rene
- Re-use of existing infrastructure (lowe

Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Current Opinion in Electrochemistry

Review Article

Hydrogen is essential for sustainability

Alireza Saeedmanesh, Michael A. Mac Kinnon and Jack Brouwer*

Sustainable energy conversion requires zero emissions of greenhouse gases and criteria pollutants using primary energy sources that the earth naturally replenishes quickly, like renewable resources. Solar and wind power conversion technologies have become cost effective recently, but challenges remain to manage electrical grid dynamics and to meet end-use requirements for energy dense fuels and chemicals. Renewable hydrogen provides the best opportunity for a zero emissions fuel and is the best feedstock for production of zero emission liquid fuels and some chemical and heat end-uses. Renewable hydrogen can be made at very high efficiency using electrolysis systems that are dynamically operated to complement renewable wind and solar power dynamics. Hydrogen can be stored within the existing natural gas system to provide low cost massive storage capacity that (1) could be sufficient to enable a 100% zero emissions grid; (2) has sufficient energy density for end-uses including heavy duty transport; (3) is a building block for zero emissions fertilizer and chemicals; and (4) enables sustainable primary energy in all sectors of the economy.

Address
National Fuel Cell Research Center, University of California, Irvine, 92697-3550, United States

electricity generation, and industrial applications, will increase substantially over this century [7–14].

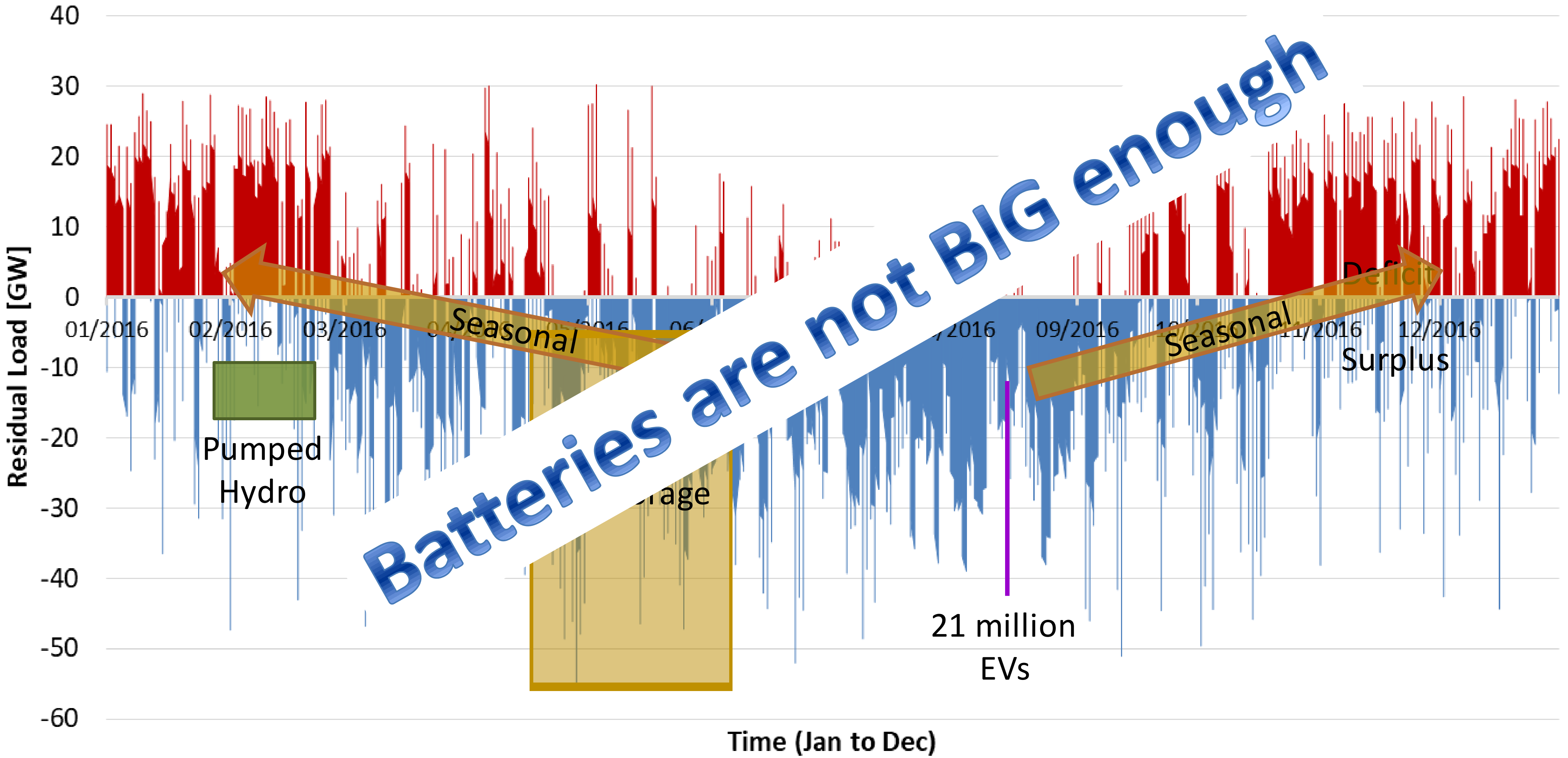
Since the Industrial Revolution, the vast majority of energy converted in society has been obtained from fossil fuels – coal, natural gas, and petroleum – which require tremendously long times for earth and the power of the sun to produce. This trend is widely expected to continue in coming decades [15–18]. Although the available global quantity of these fuels is extremely large, they are nevertheless finite and so will inevitably 'run out' at some near future time as we consume them much faster than the earth produces them [19]. A primary reason for their continued use is economics – energy from fossil fuels has been more cost effective than most other sustainable forms of energy, including renewable resources.

In addition, the continued use of fossil fuels is associated with increased criteria pollutant and greenhouse gas emissions [20]. Emissions from fossil fuel combustion degrade air quality, pose human health risks, and drive global climate change. In 2017, global energy-related CO_2 emissions reached an historic high of 32.5 Gt as a result of

Saeemanesh, A., Mac Kinnon, M., and Brouwer, J., *Hydro...*
for Sustainability, Current Opinion in Electrochemistry, 2019.

Why Hydrogen? Magnitude of Storage Required

- **Wind dominant case (37 GW solar capacity, 80 GW wind capacity)**



Why Hydrogen? Availability of Materials on Earth

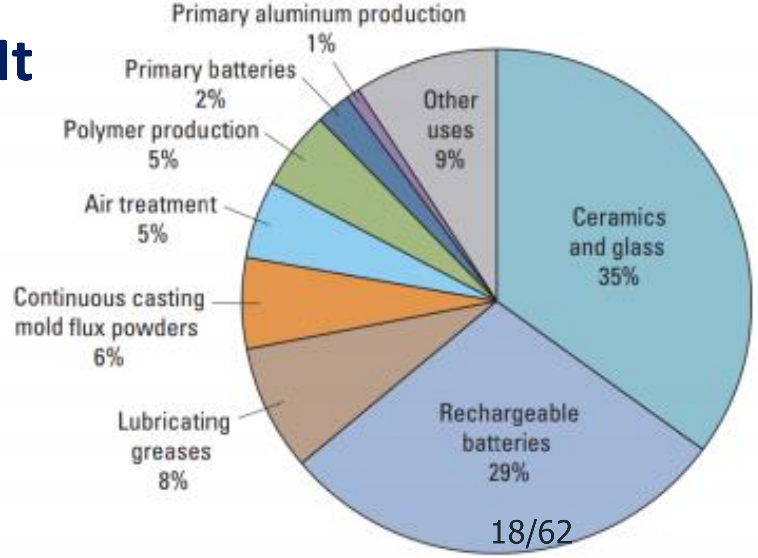
Simulate meeting of TOTAL world electricity demand w/ Solar & Wind

	Solar contribution	Wind contribution	Consumption and storage ratio	Consumption (TWh)	Storage (TWh)
Africa	0.70	0.30	8.39	9 [illegible]	1,088
America	0.45	0.55	7.83	[illegible]	4,919
Asia	0.50	0.50	7.95	[illegible]	10,178
Europe	0.30	0.70	7.50	[illegible]	3,592
Oceania	0.50	0.50	[illegible]	[illegible]	205
TOTAL					19,981 TWh

[... M.S. Thesis, 2018]

There is not enough lithium or cobalt in the world

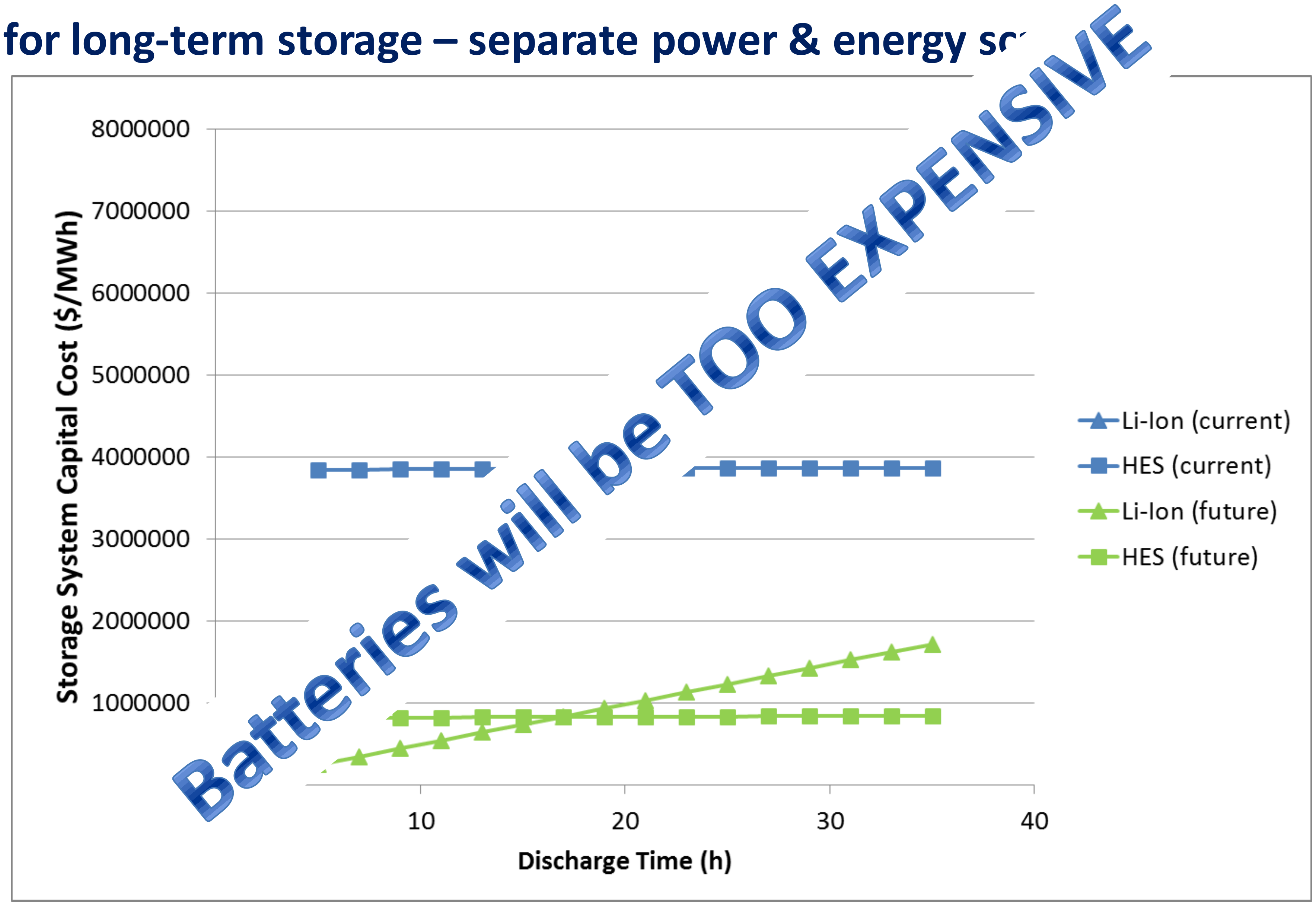
- To build one Li-ion batte[...] Co: 25,815 Mt
- World Li resources[...]
- World Co reso[...]al), 120 Mt (ocean floor)
- 40% of Co come[...]mocratic Republic of the Congo



Source: U.S. Geological Survey, 2018

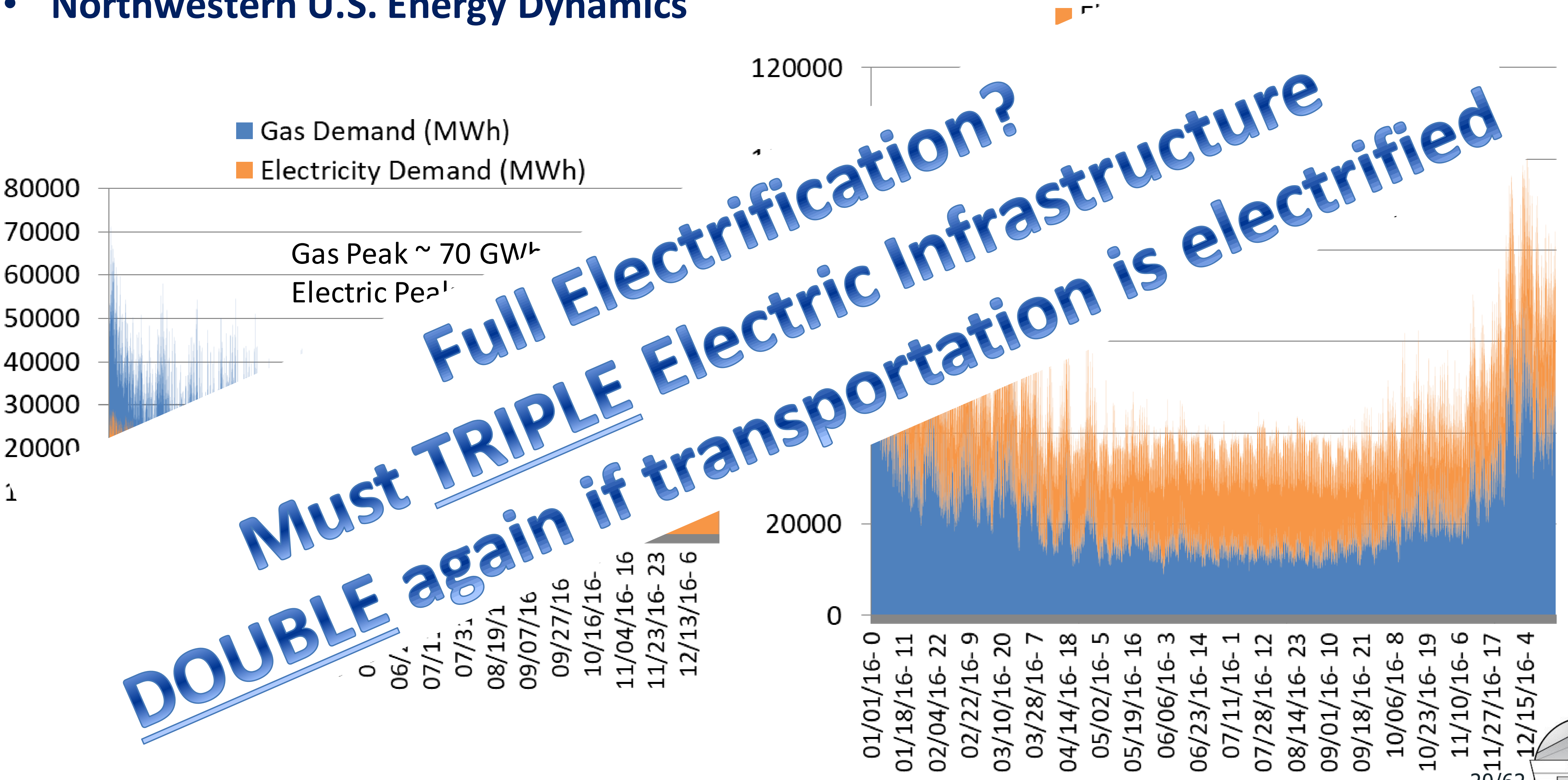
Why Hydrogen? Lower Cost Energy Storage

HES Better for long-term storage – separate power & energy sc



Why Hydrogen? Energy Demand Dynamics

- **Northwestern U.S. Energy Dynamics**



Full Electrification?

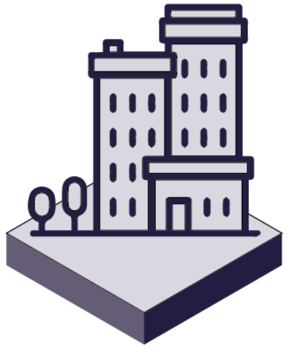
Must TRIPLE Electric Infrastructure

DOUBLE again if transportation is electrified

Green Hydrogen has versatile applications

TRANSPORT

POWER



INDUSTRY

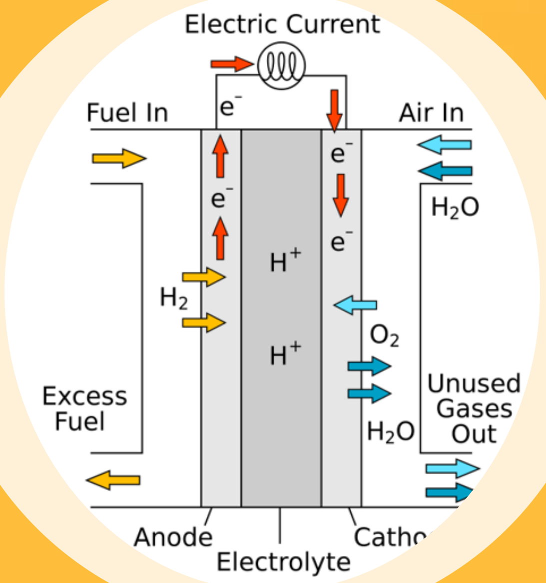
CHEMICAL

AGRICULTURE

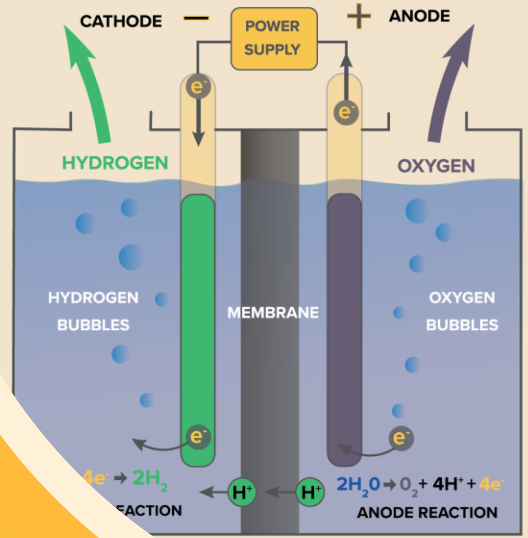
Hydrogen has the potential to reduce emissions across many sectors

Green Hydrogen Technologies

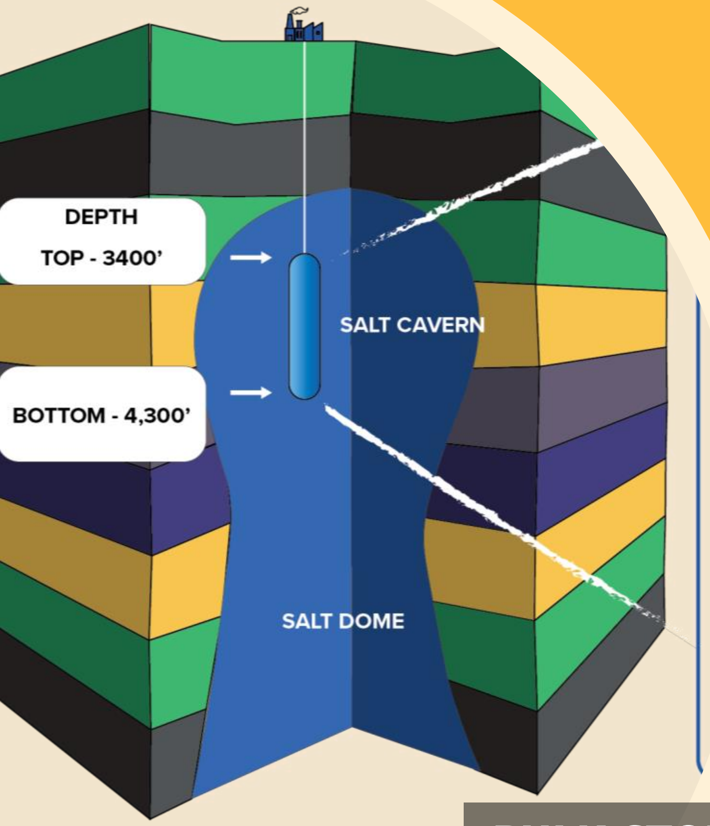
PIPELINE



FUEL CELL



ELECTROLYZE R



BULK STORAGE

HYDROGEN GAS TURBINE

Hydrogen Safety 101

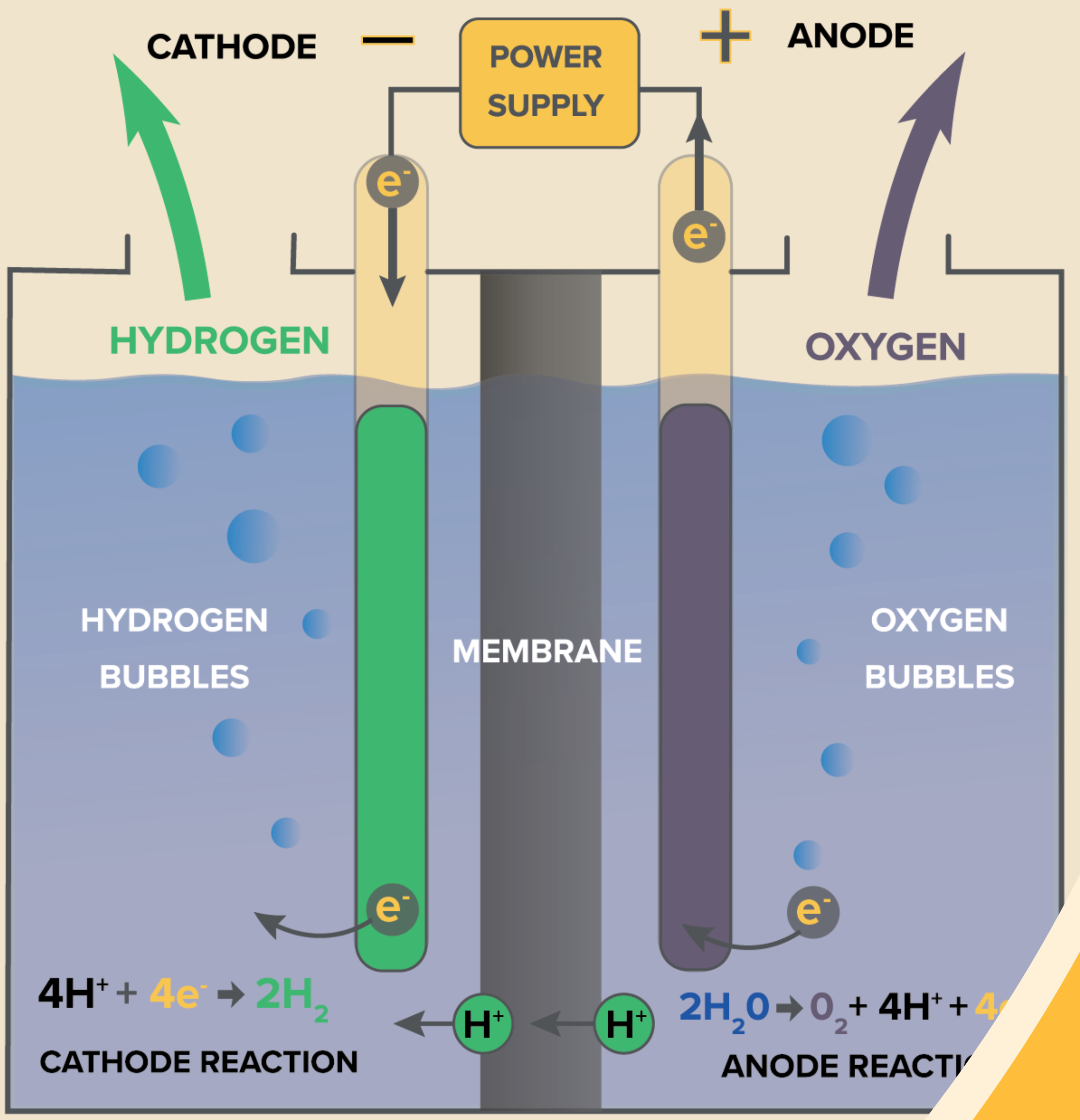
•Hydrogen is **non-toxic**, colorless, and odorless gas that does not threaten human or environmental health if released into the environment

•Hydrogen is much lighter than air (14x lighter) and about 57x lighter than gasoline vapor, so it **dissipates rapidly when it is released**. This allows for rapid dispersal of the fuel in the case of a leak.

•Hydrogen rises in surrounding air, so it is **unlikely to remain near the ground where people are in the case of a fire**.

•Hydrogen combustion is more rapid than combustion of other fuels. **A hydrogen cloud will burn within seconds, and all the energy of the cloud will be released.**

•Safety features are designed and engineered into hydrogen systems and managed by governments as well as regulated in accordance with expert third-party international hydrogen safety standards



Electrolyzer

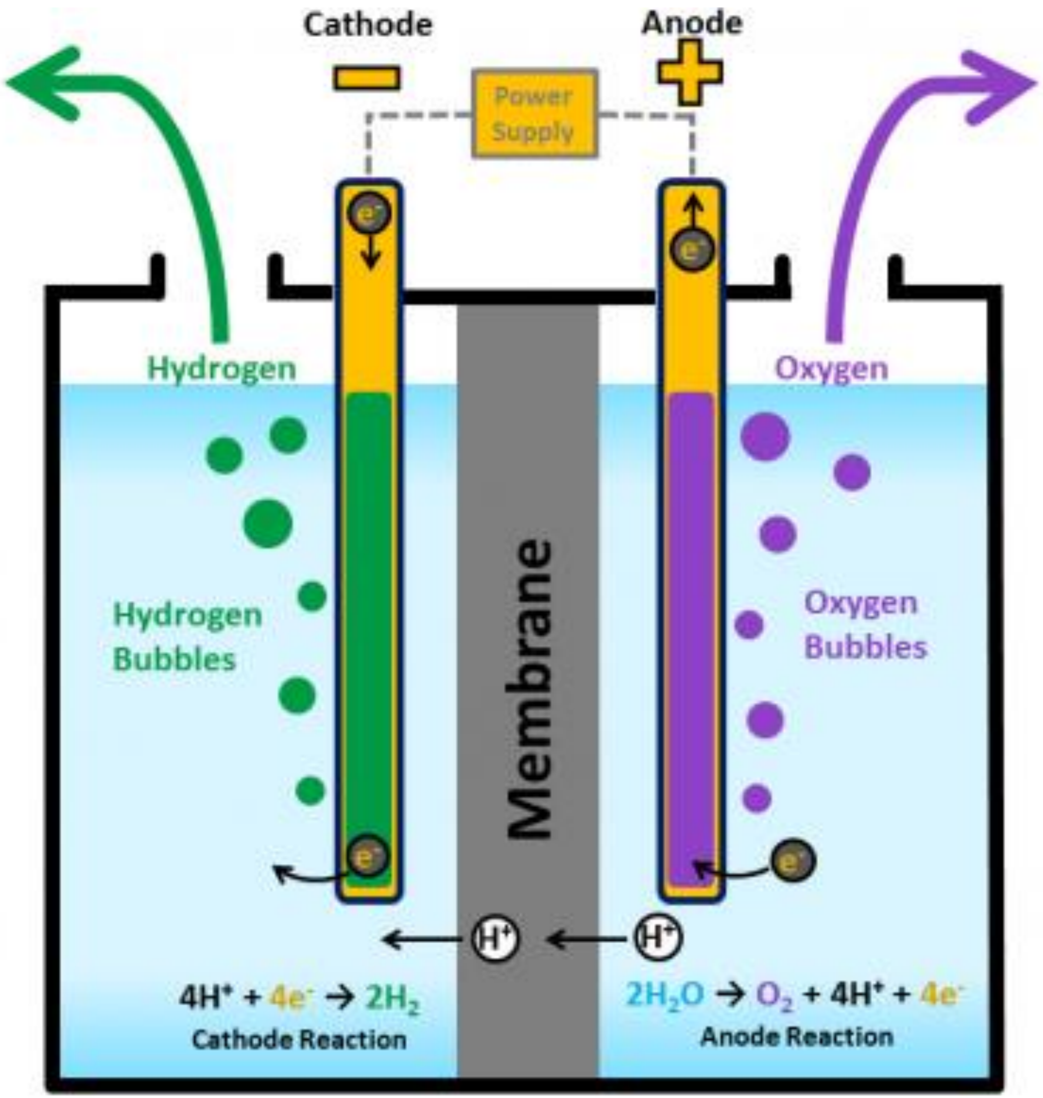
Electrolysis – like charging a battery

Electrolysis

- 2 H_2O + Electricity → 2 H_2 + 1 O_2
- 1 liter of Water yields ~ 1 Nm^3 H_2
- Typical efficiency: 45 – 78 kWh/kg (60 –

Various Types:

- Alkaline
  - Currently lowest cost, highest efficiency
- Proton Exchange Membrane (PEM)
  - Pressurized, dynamic operation capabilities
- Solid Oxide
  - Most efficient (can also use heat)

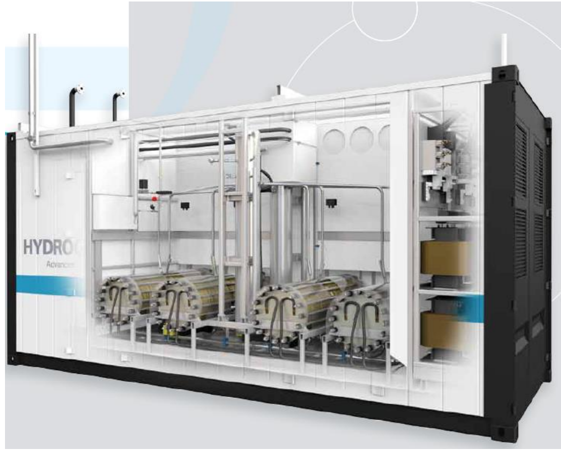


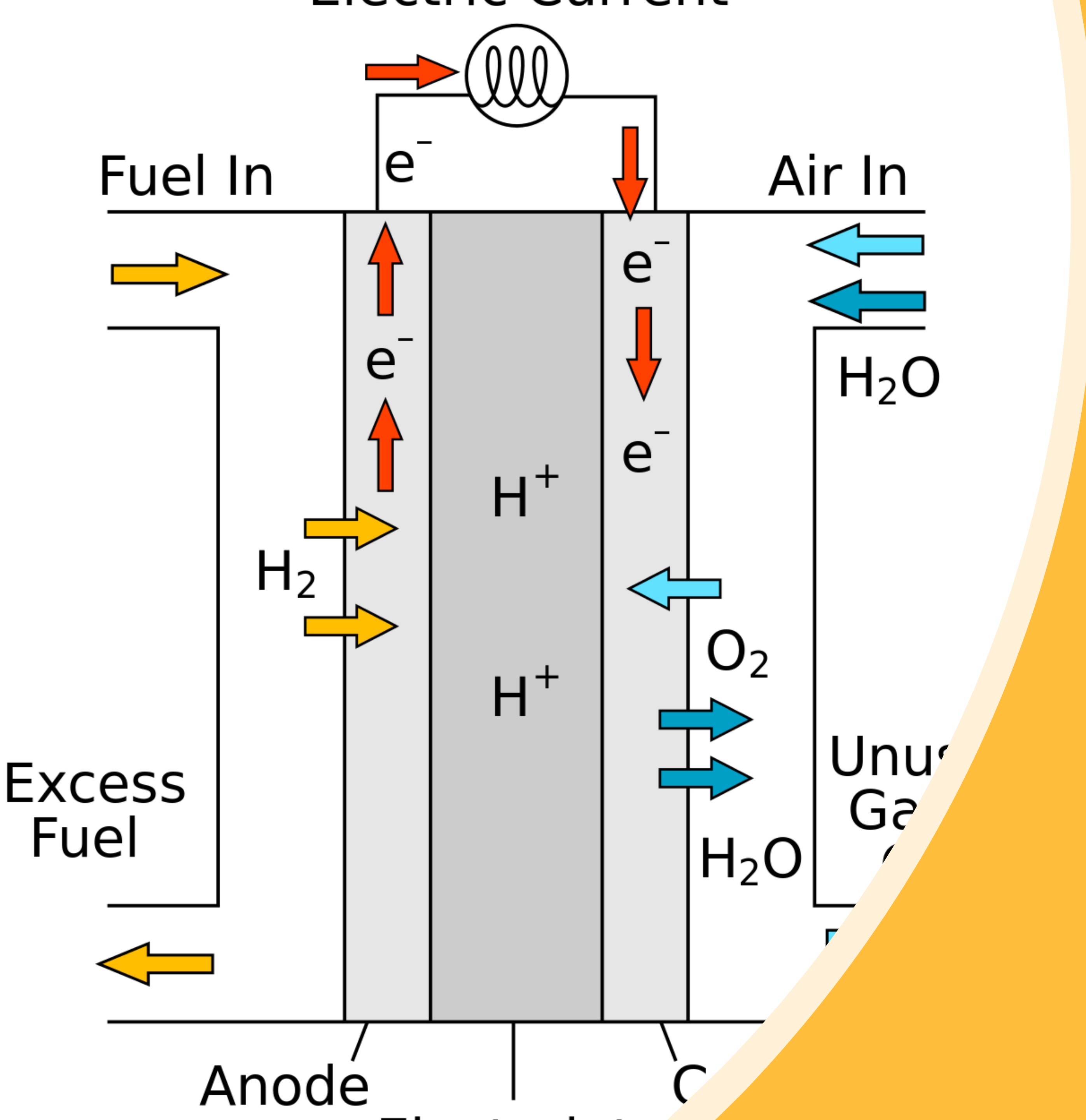
From: U.S. DOE, 2020

Electrolysis

<u>A Commercially Available & Widely Used Flexible Load</u>

- Electrolyzers (PEM, alkaline) interconnected with inverters
- Provide load when wind or solar would otherwise be curtailed or when cheaply available
- Fast response allows for use with variable input
- Fast response can provide other ancillary services (e.g., regulation, Volt/VAR support)
- Sizes range from 10's of KW to 10's MW (today)





Fuel Cell

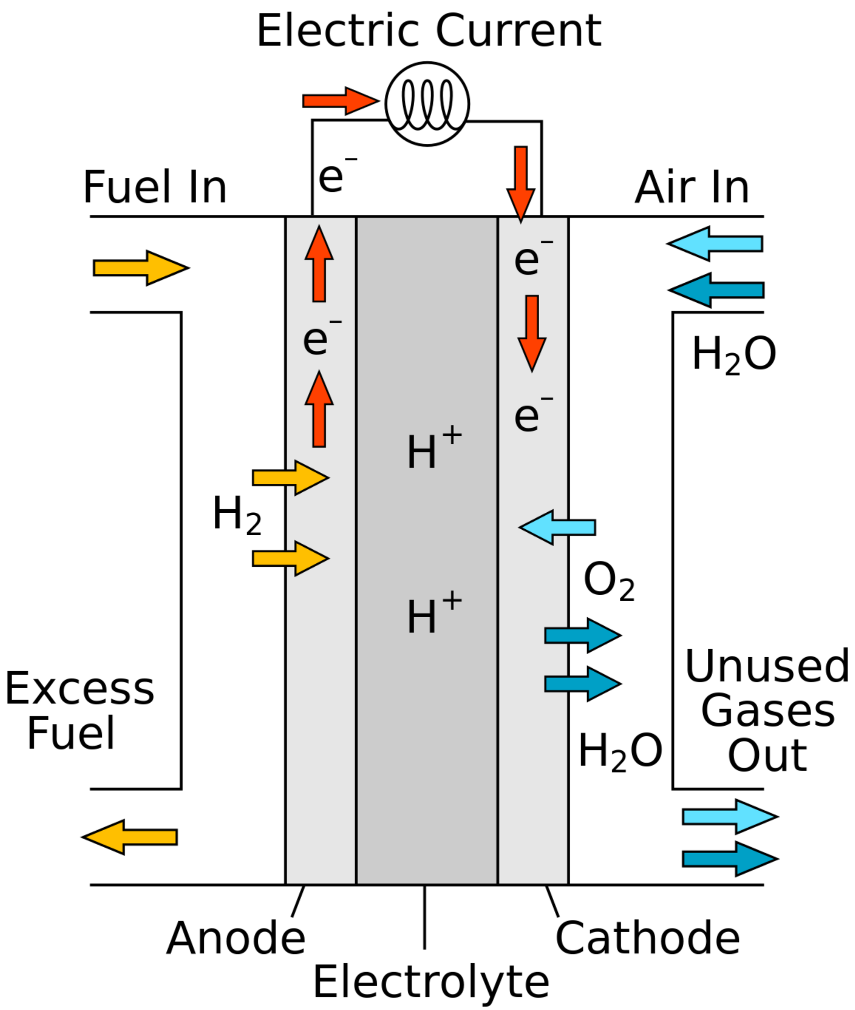
Fuel Cell – like discharging a battery

Fuel Cell

- $2\ H_2 + 1\ O_2 \rightarrow 2\ H_2O$ + Electricity
- Typical electrical efficiency: 45 – 65%
- Combined heat/cooling & power efficiency: >90%

Various Types:

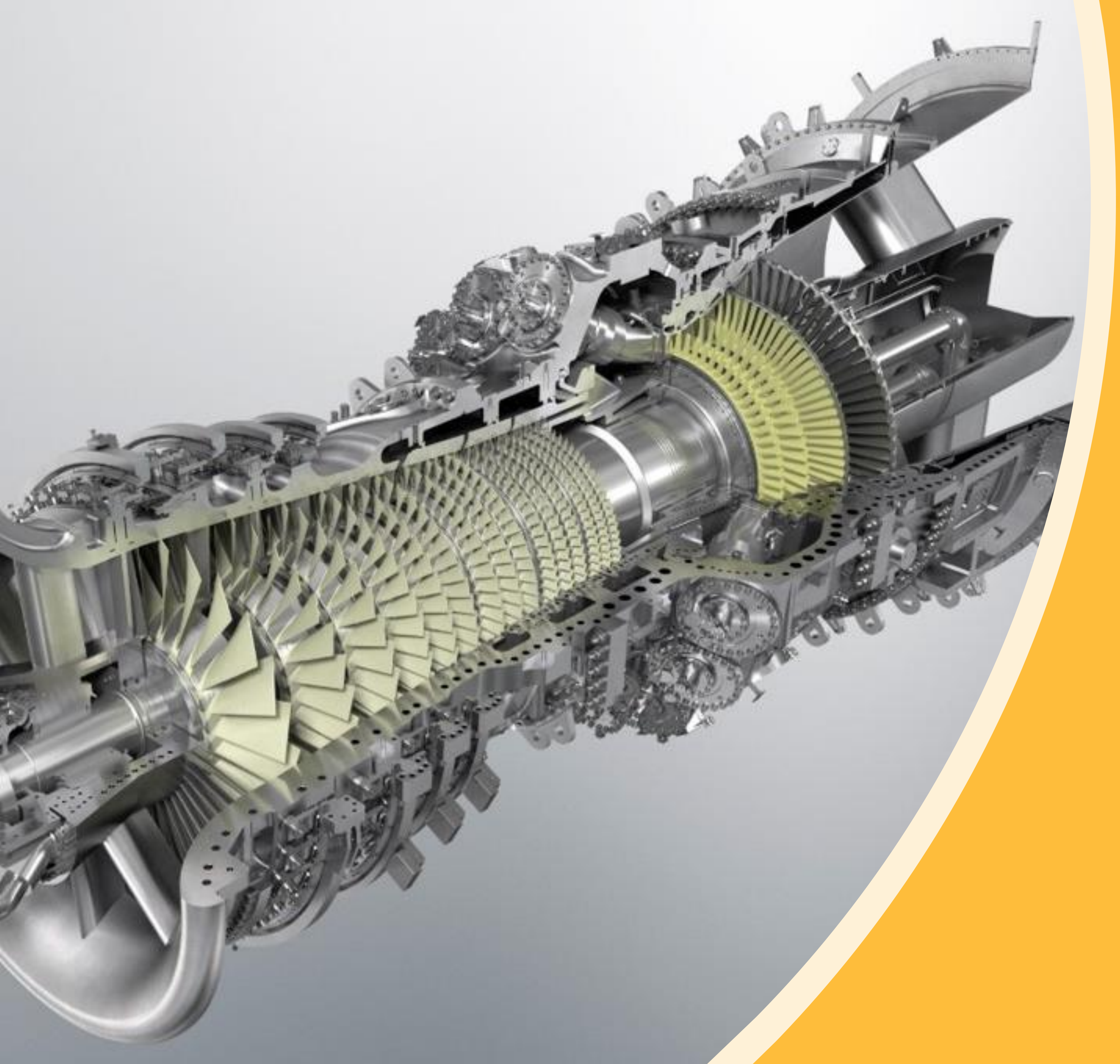
- Proton Exchange Membrane (PEM)
  - Pressurized, dynamic operation capabilities, direct H2
- Solid Oxide
  - Most efficient & fuel flexible
- Phosphoric Acid
  - Direct hydrogen use today
- Molten Carbonate
  - Carbon capture features



From: U.S. DOE, 2020

Fuel Cell

- **Highest efficiency of conversion, lowest GHG emissions of conversion, zero pollutants**



Hydrogen Gas Turbine

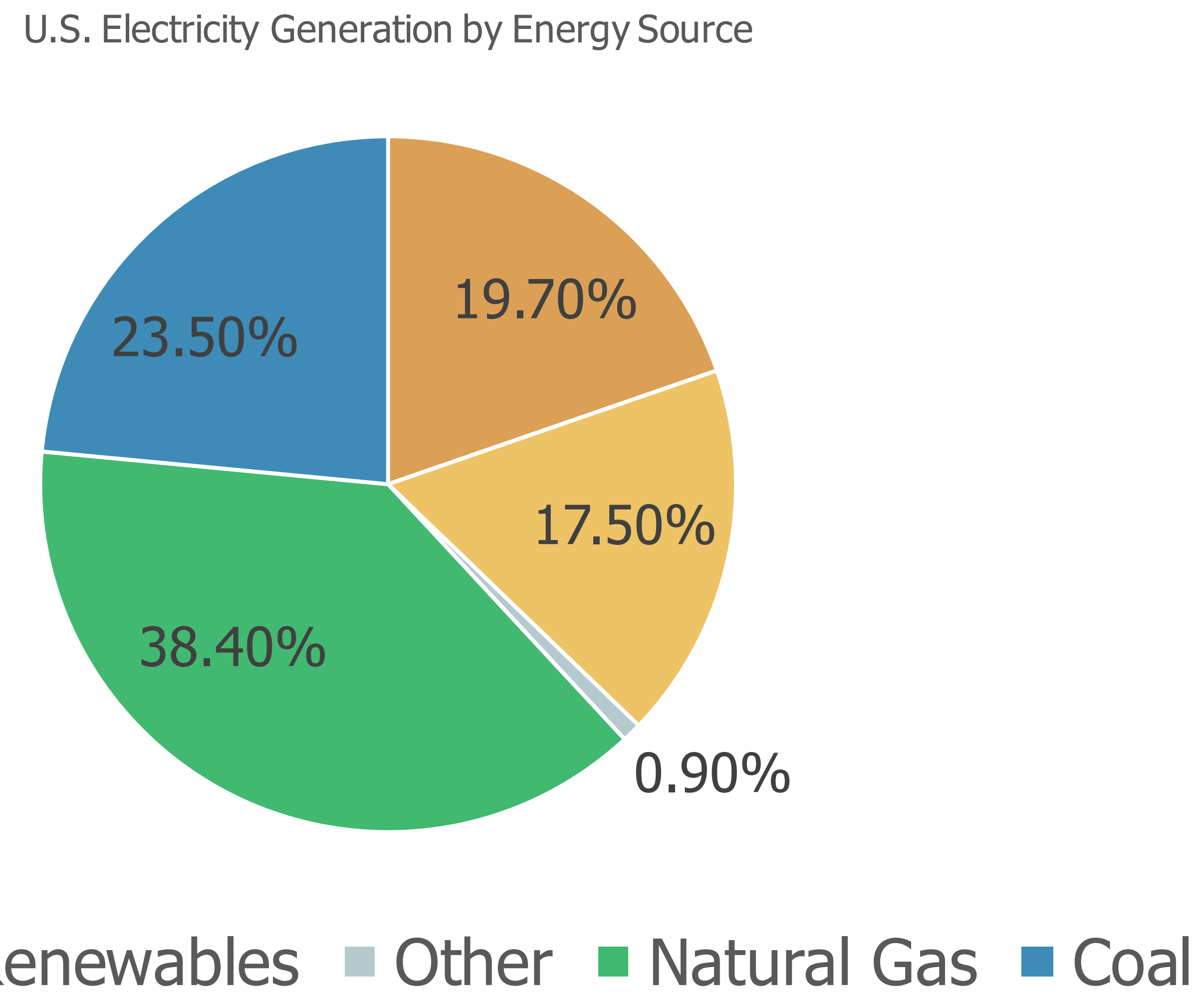
Background

- **Gas Turbines reflect state-of-the-art technology for *large scale power* generation**

800 MW
Power for ~650,000 households

The US is heavily dependent on Gas for its Electricity Needs

Total US Natural Gas Capacity: 546.5 GW



Source: US EIA

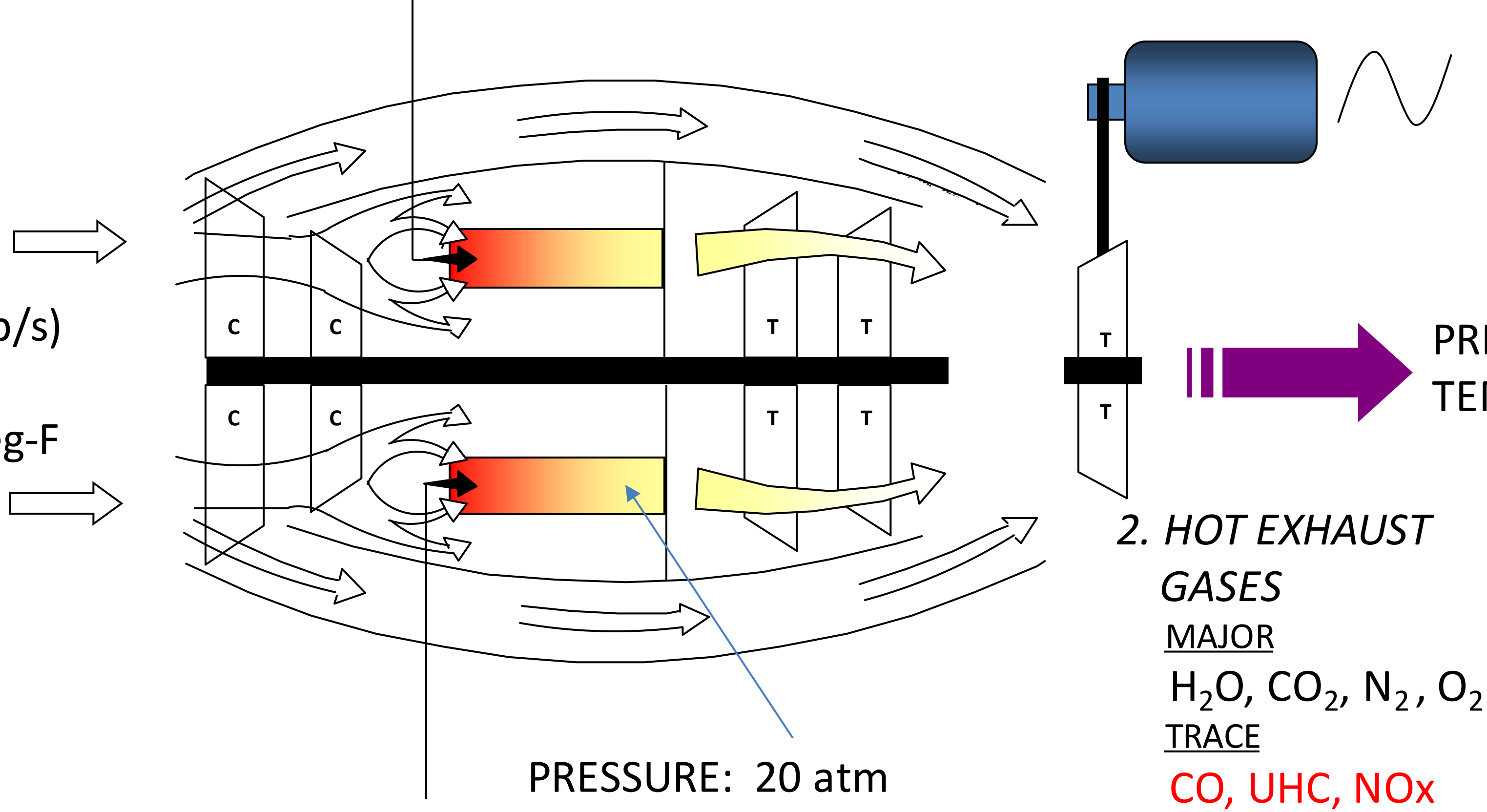
Background

"PRODUCTS"

FUEL* (~1 lb/sec)

1. ELECTRICITY

AMBIENT AIR* (~90 lb/s)
PRESSURE: 1 atm
TEMPERATURE: 70 deg-F



PRESSURE: 1 atm
TEMPERATURE: 1000 deg F

2. HOT EXHAUST GASES

MAJOR

H_2O, CO_2, N_2, O_2

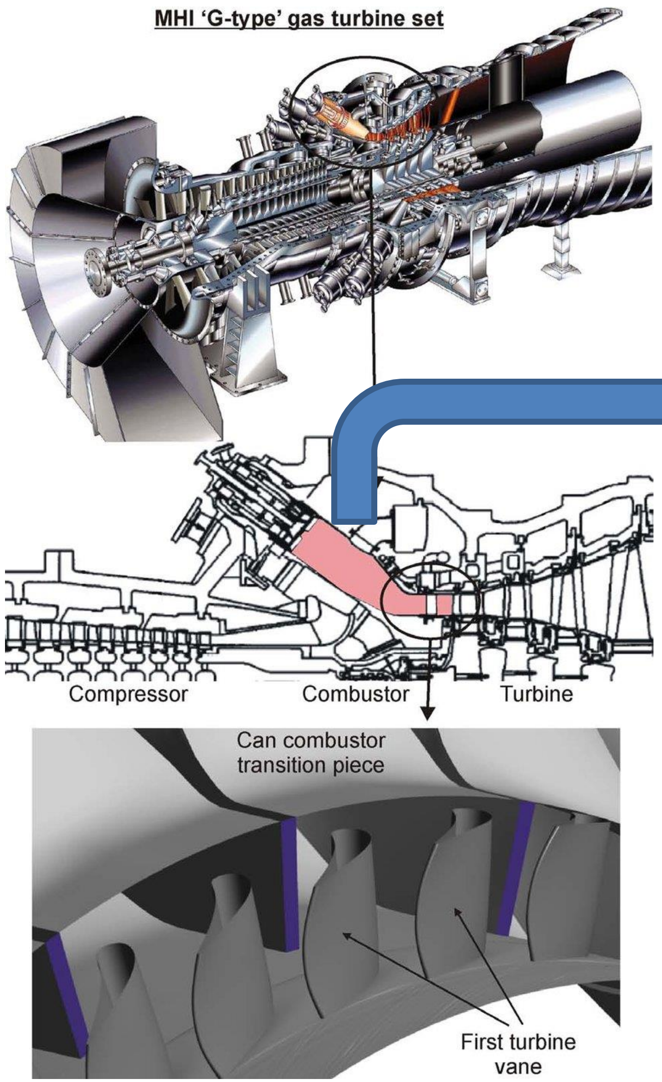
TRACE

CO, UHC, NOx

PRESSURE: 20 atm
TEMPERATURE: 2400 deg F

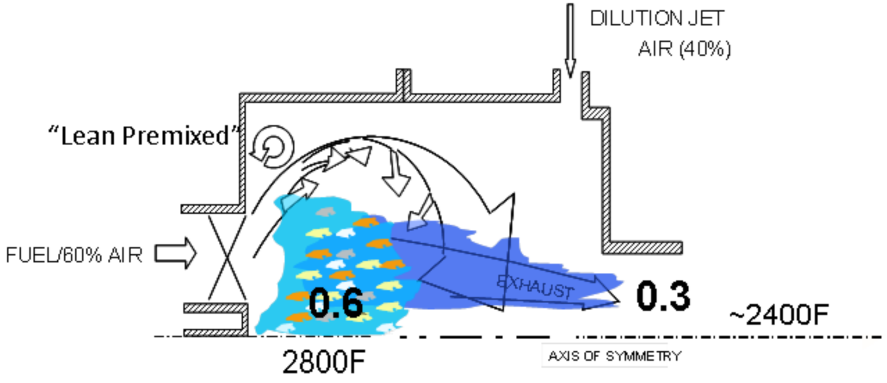
** ~10 MW STATIONARY GTE*

Background



Aslanidou, et al. (2012). J. Turbomachinery, Vol 135(2)

Representation of Low Emission Combustor



Turbine Inlet Temperature ~2400 F

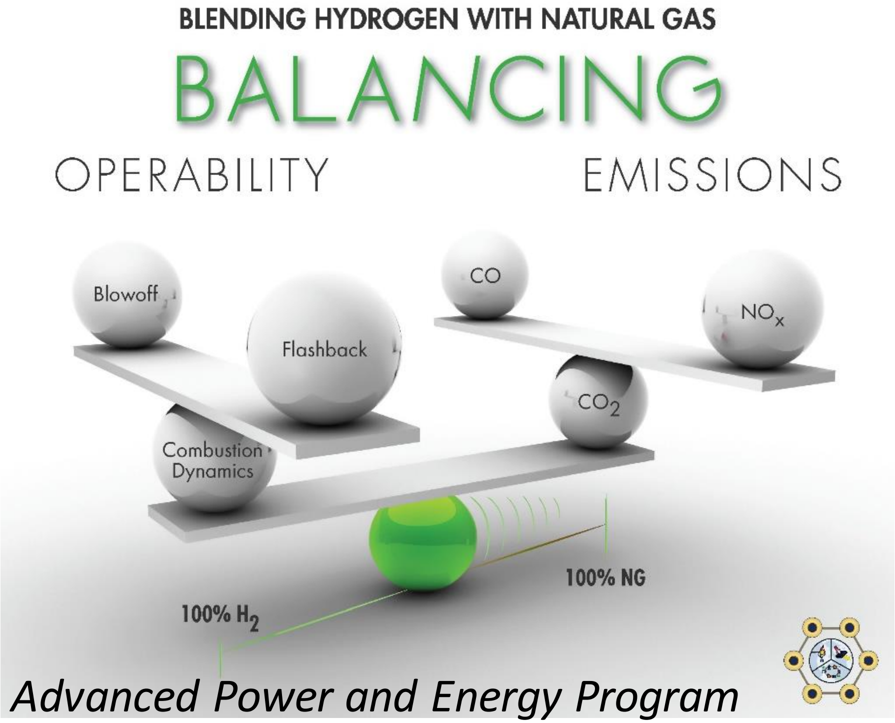
UCI Gas Turbine Combustion Short Course

Higher Turbine Inlet Temperature →Higher Efficiency

Brayton Cycle: Higher Turbine Inlet/Combustor Exit Temperature

Technical Questions w/Hydrogen or Hydrogen Addition to NG

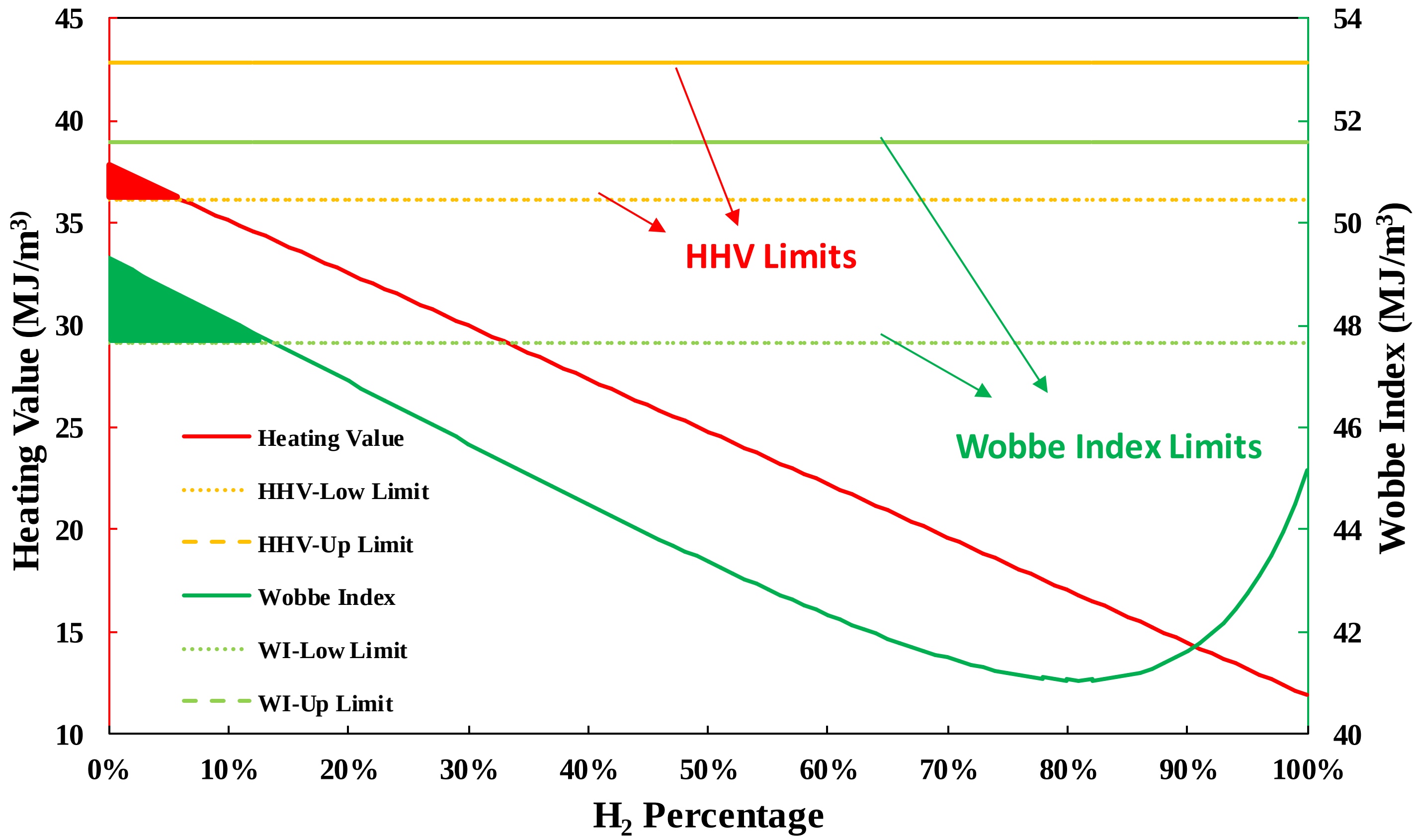
- **Interchangeability?**
- **What about concerns related considerations when using hydrogen with advanced low emission combustion?**
  - **Operability**
    - ✓ Wide flammability limits?
    - ✓ Autoignition?
    - ✓ Flashback?
  - **Emissions**
    - ✓ Criteria Pollutant Emissions?
    - ✓ Carbon Emissions?



Technical Questions

Hydrogen is relatively interchangeable with existing pipeline gas

- **Interchangeability**
  - **Context of SCG Rule 30**



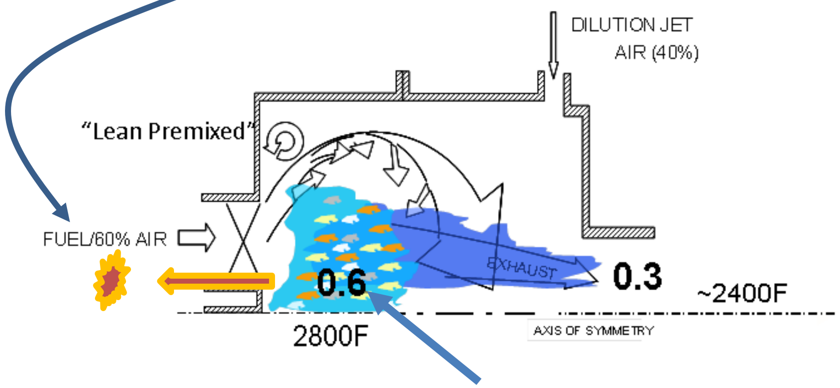
Heating Value Limit: 6.1% addition
Wobbe Index Limit: 13.8% addition

$$Wobbe\ Index = \frac{HHV}{\sqrt{Sg}}$$

Technical Questions

- **What about combustion related considerations?**
  - **Operability?**
    - ✓ **Wide flammability limits?**
      - – improved static stability limits improves operating range
    - ✓ **Autoignition?**
      - – Evaluated and is not an issue for well designed system
    - ✓ **Flashback/Flameholding?**
      - – Most difficult challenge: understood and designs to avoid have been developed and/or are under development by major engine manufacturers
  - **Emissions?**
    - ✓ Minimal NOx Emissions w/ advanced technology
      - – (CO and CO_2 inherently reduced as Green Hydrogen displaces fossil Carbon)
    - ✓ Carbon Emissions displaced as hydrogen is added
    - ✓ Considering replacement for COAL—major reduction in other pollutants such as sulfur compounds/particulate

Flammable Mixture
Pressure up to 50 atm
Temperature up to 1200 F

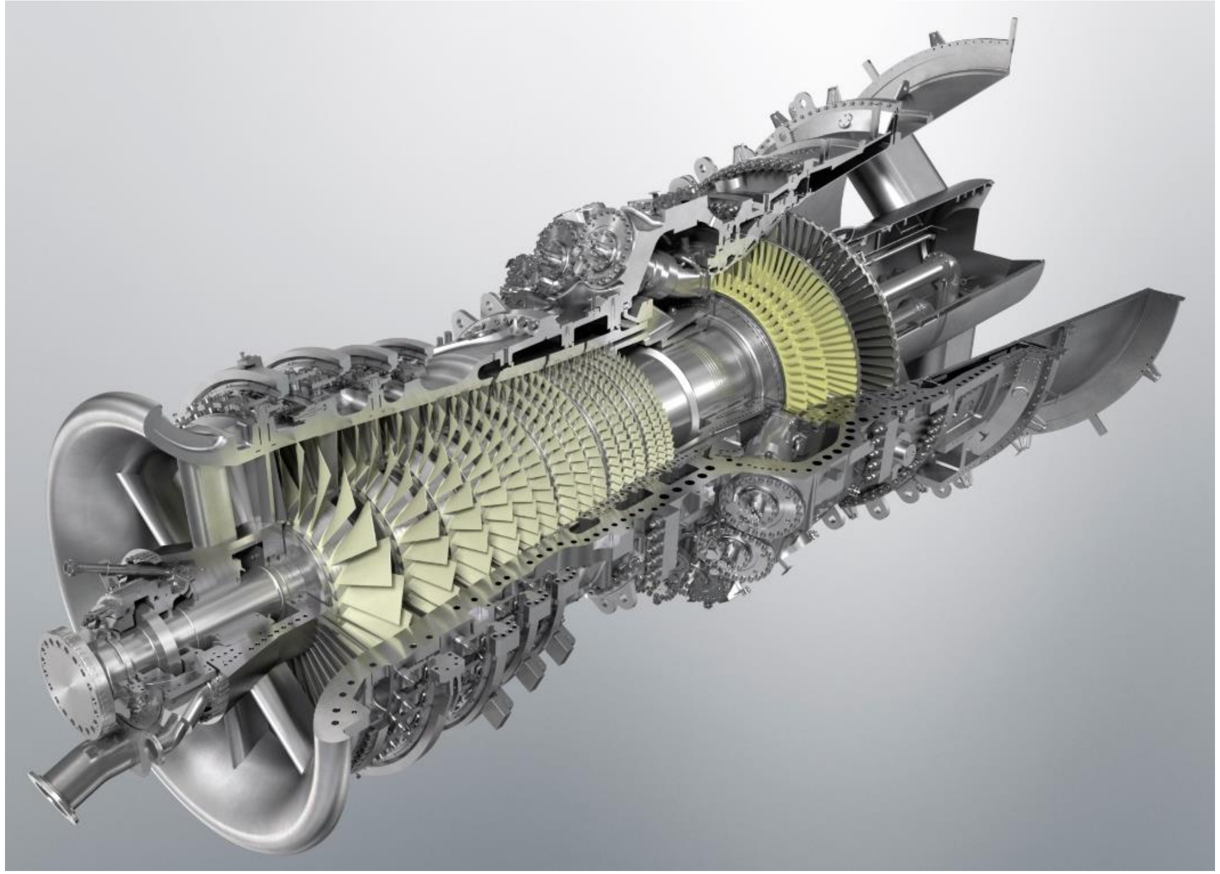


0.5, 0.4?
2500, 2600 F?

State of the Art: MHPS J-Series

Gas Turbines already operate on high levels of H_2

- **Advanced Technology—M501 JAC**



-- 425 MW
-- 44.0% Simple Cycle (SC) Efficiency
-- ~64% Combine Cycle (CC) Efficiency
-- 2 ppm NOx at the Stack
-- 50% turndown
-- 42 MW/min ramp rate
-- 30 min cold start
-- Air Cooled

---MHPS: (>1.0 million AOH* experience on the J Class equipment)
--MHPS: (>3.5 million AOH* of experience with hydrogen containing fuels)

* - AOH = Actual Operating Hours

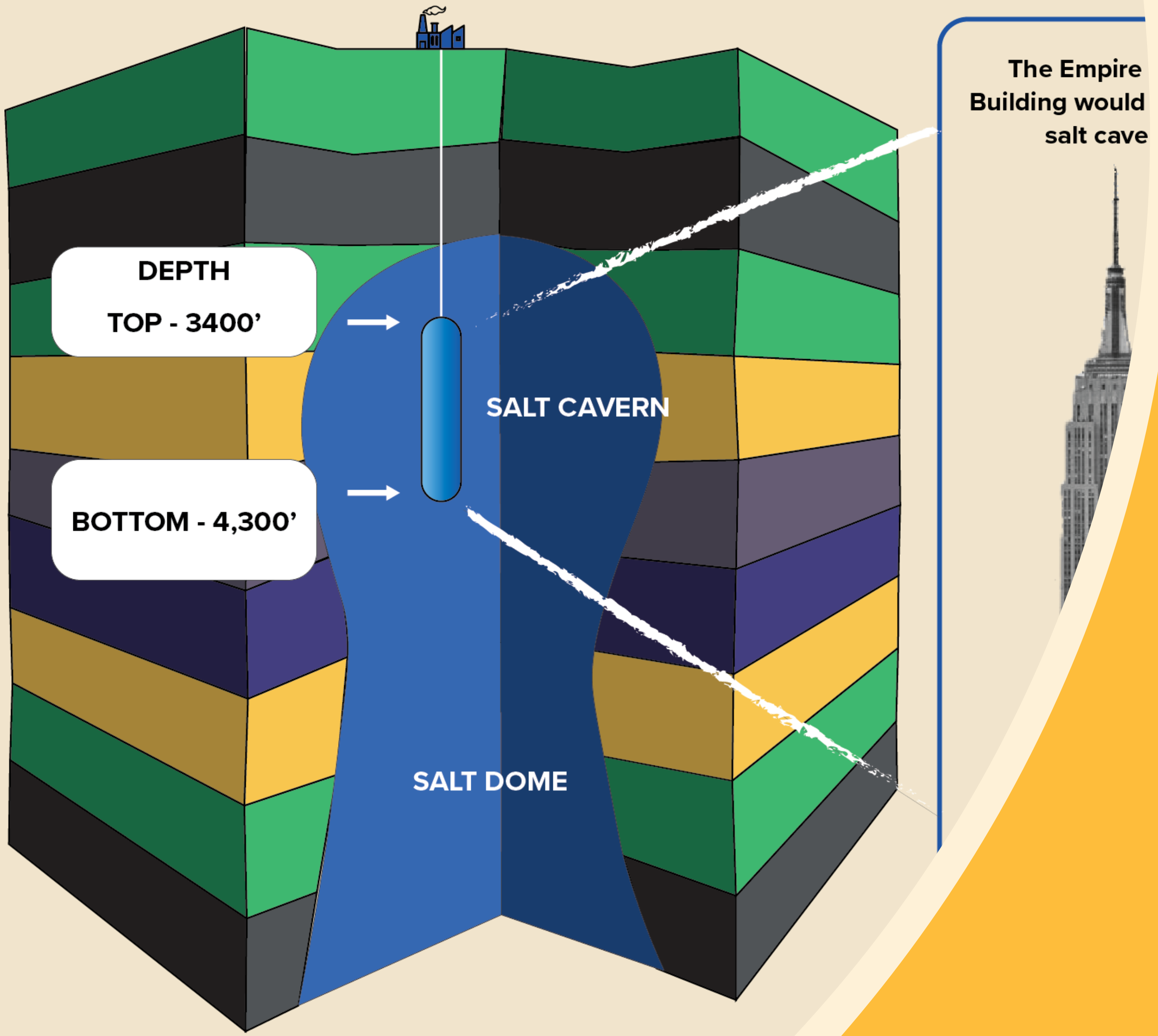
https://www.mhps.com/products/gasturbines/lineup/m501j/

Summary

- **Current *natural gas* combined cycle plants can achieve ~64% fuel to electricity efficiency**
  - Low Single digit NOx levels are achieved at the stack
  - Without water injection (Dry Low NOx (DLN) technology)
  - 64% efficiency compares to ~33% average for typical coal fired power plant

- **Hydrogen has been used in gas turbines and industry for many years**
  - Petrochemical industry has a long history utilizing hydrogen (not discussed here)
  - Water has been used as a diluent for NOx reduction in gas turbines

- ***DLN technology* developed for natural gas is evolving for use with hydrogen**
  - Autoignition, flashback issues—understood and mitigating design strategies are being developed
  - All OEMs developing DLN technologies for hydrogen
    - ✓ 30% hydrogen in natural gas already offered by several large turbine OEMs
    - ✓ MHPS has committed to low emissions performance on 100% hydrogen within next 5 years

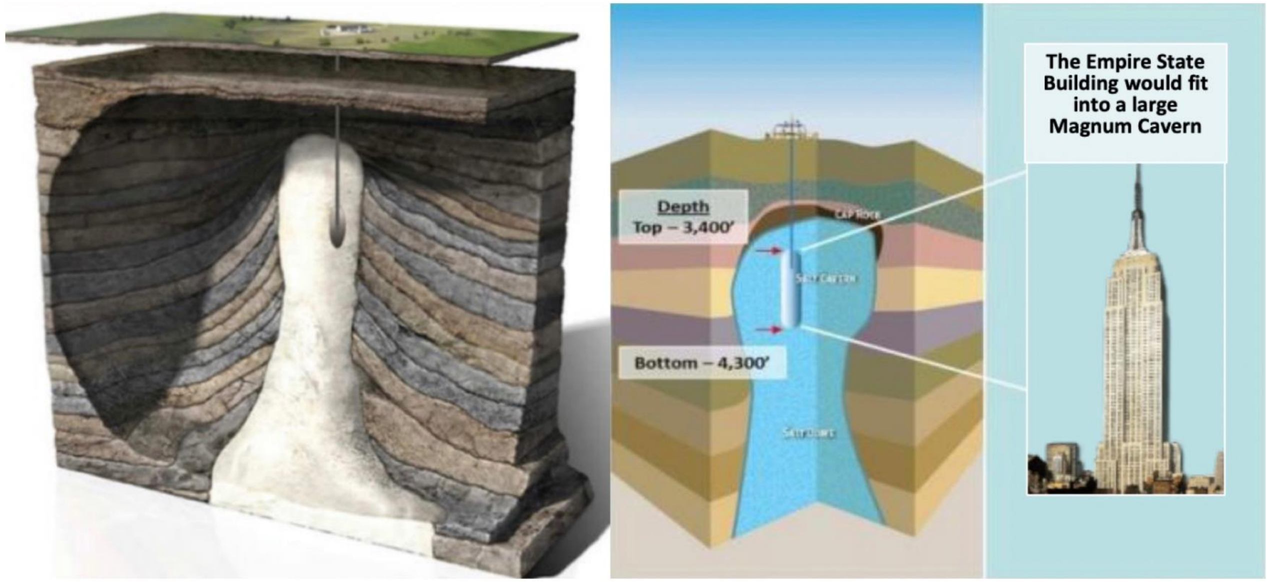


Bulk Storage

Bulk Storage Facilities

<u>Salt Caverns already widely used and proven</u>

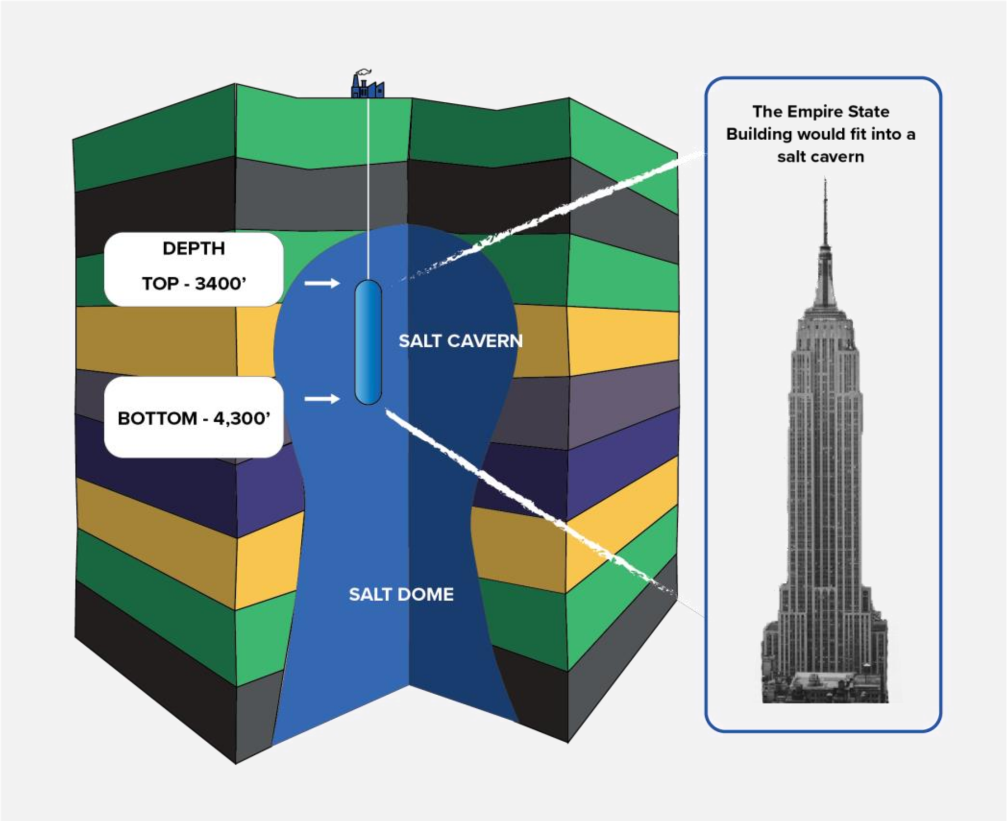
- **Air Liquide & Praxair operating H2 salt cavern storage in Texas since 2016**
  - Very low leakage rate
  - Massive energy storage
  - Safe & Low-cost storage
- **Similar success in Europe**
- **Magnum working with LADWP to adopt similar salt cavern H2 storage in Utah**



Plan for storing hydrogen in Utah salt caverns

Images: Los Angeles Department of Water and Power

Bulk Storage Facilities: An Example



INTERMOUNTAIN POWER PROJECT CONVERSION IN DELTA, UTAH

Hydrogen Storage in Underground Salt Caverns

- A typical cavern size at IPP = 4,000,000 barrels
- 1 cavern = 5,512 tons of H_2 (operational limit)
- This is equivalent to:
  - 200,000 hydrogen buses
  - 1,000,000 fuel cell cars
  - 14,000 tube trailers used for delivery
- Over 100 caverns can be constructed in the IPP salt dome
- Storing H_2 in salt caverns is already done commercially around the world

Bulk Storage Facilities: Areas of Research

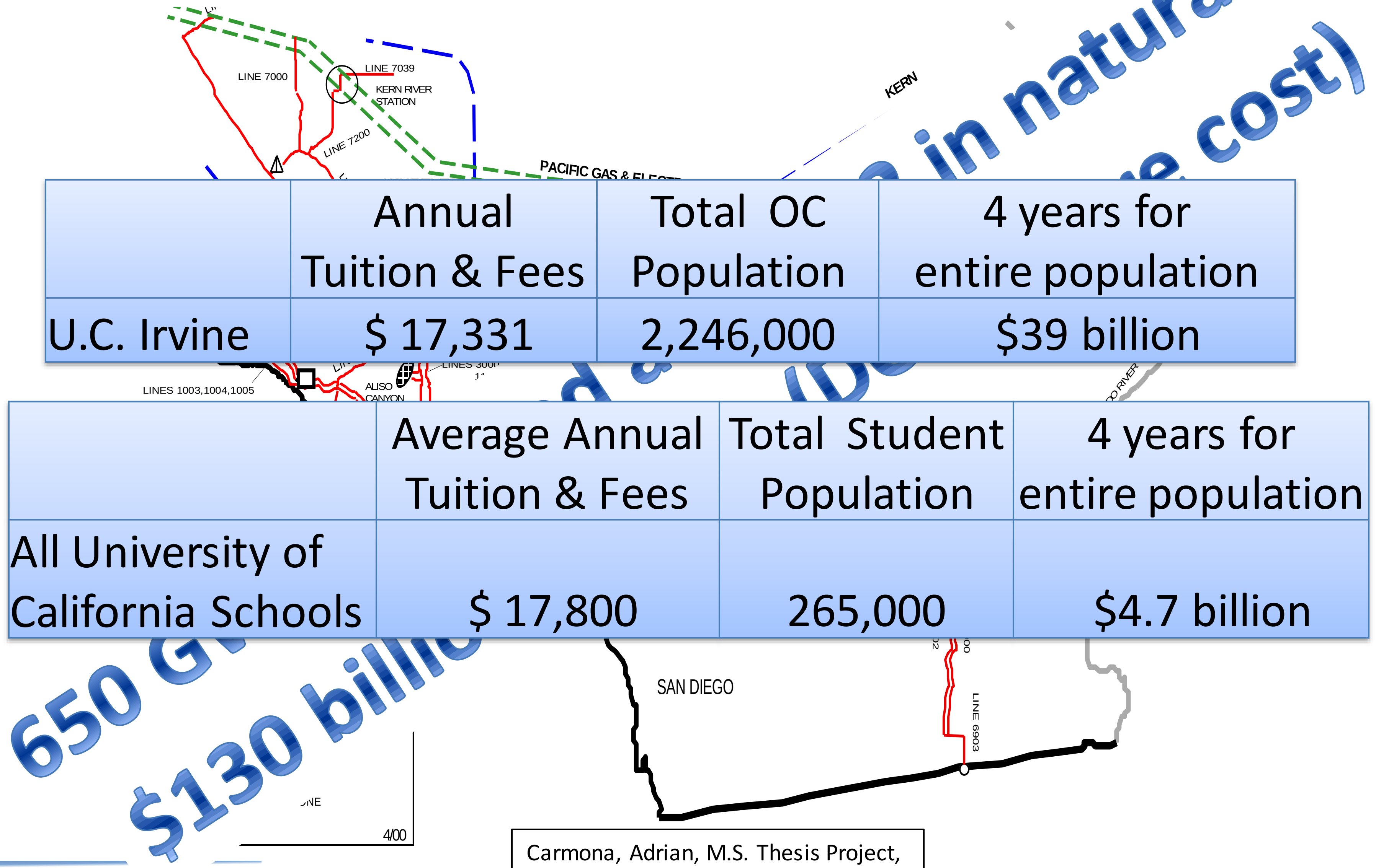
Current CA depleted oil and gas fields not yet used or proven for H_2 use

- **Several research and development needs**
  - H2 leakage
  - H2 reaction with petroleum remnants
  - H2 biological interactions
  - H2 storage capacity
  - H2 safety

Pipeline

Pipeline Storage & Transmission/Distribution Resource

- **Natural Gas Transmission, Distribution & Storage System**



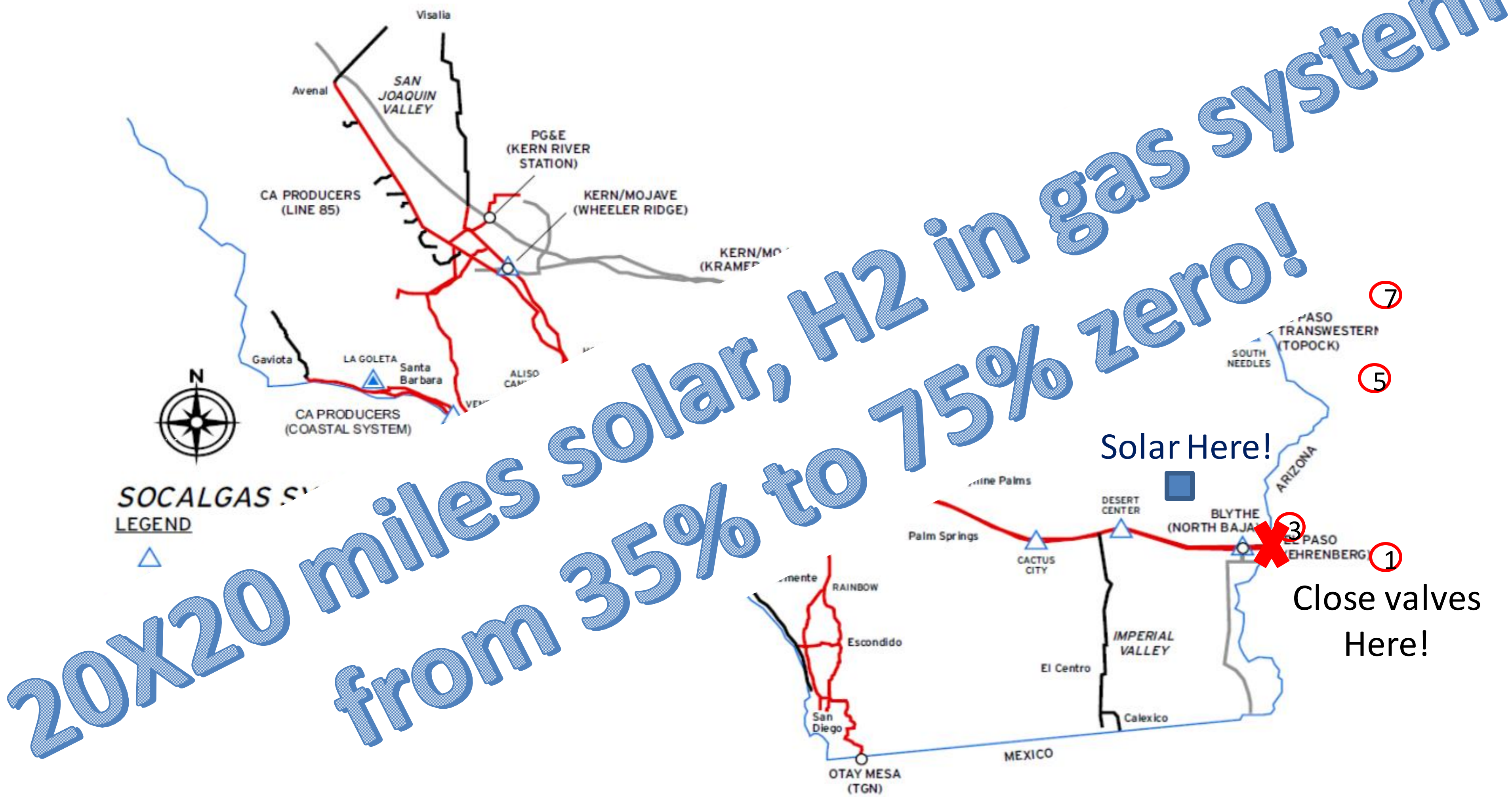
	Annual Tuition & Fees	Total OC Population	4 years for entire population
U.C. Irvine	$ 17,331	2,246,000	$39 billion

	Average Annual Tuition & Fees	Total Student Population	4 years for entire population
All University of California Schools	$ 17,800	265,000	$4.7 billion

Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.

Magnitude of Pipeline, Storage, and Power Plant Resources

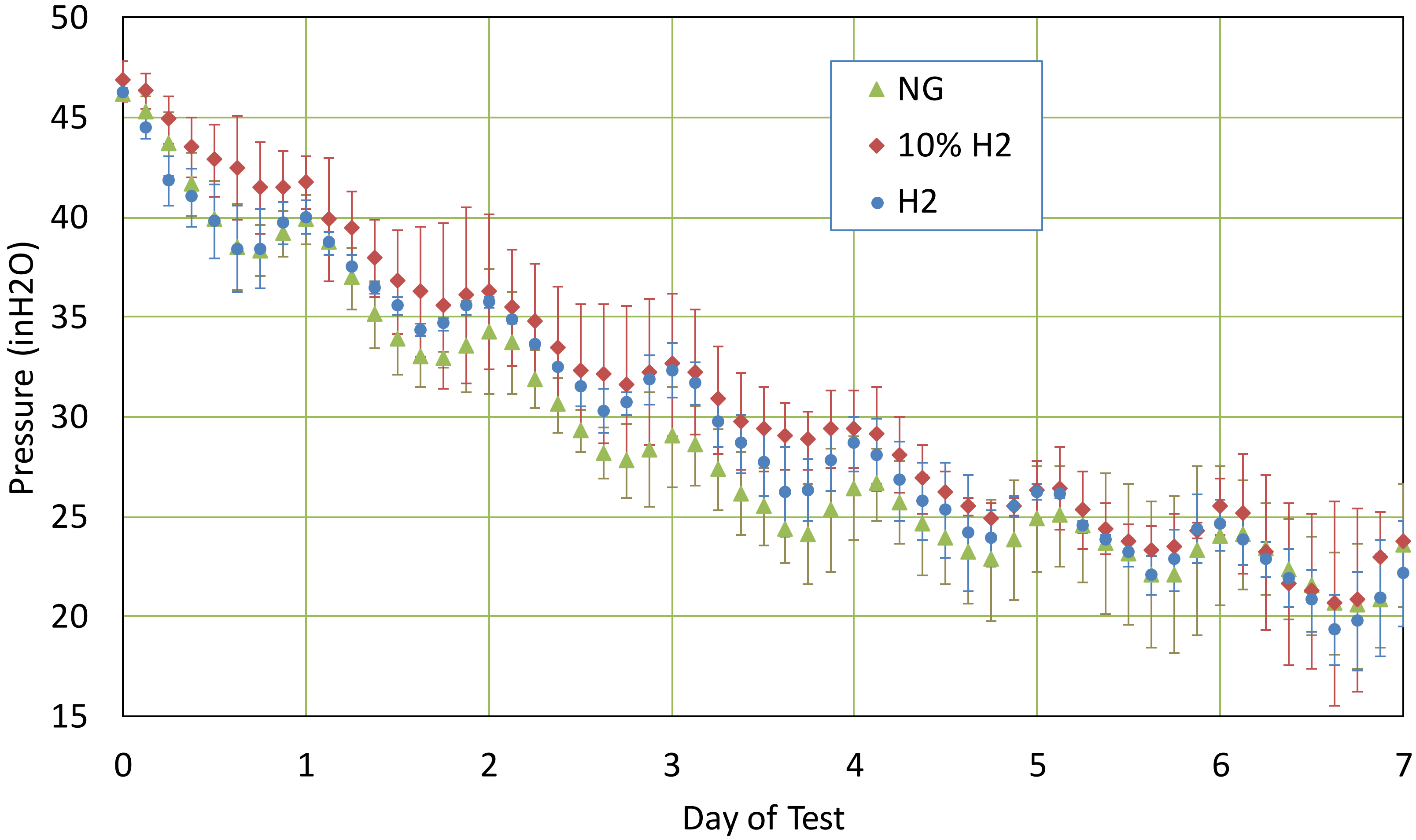
- **Note storage AND Transmission & Distribution functions**



Hydrogen Pipeline Injection & Leakage

H2 injection into existing natural gas infrastructure (low pressure)

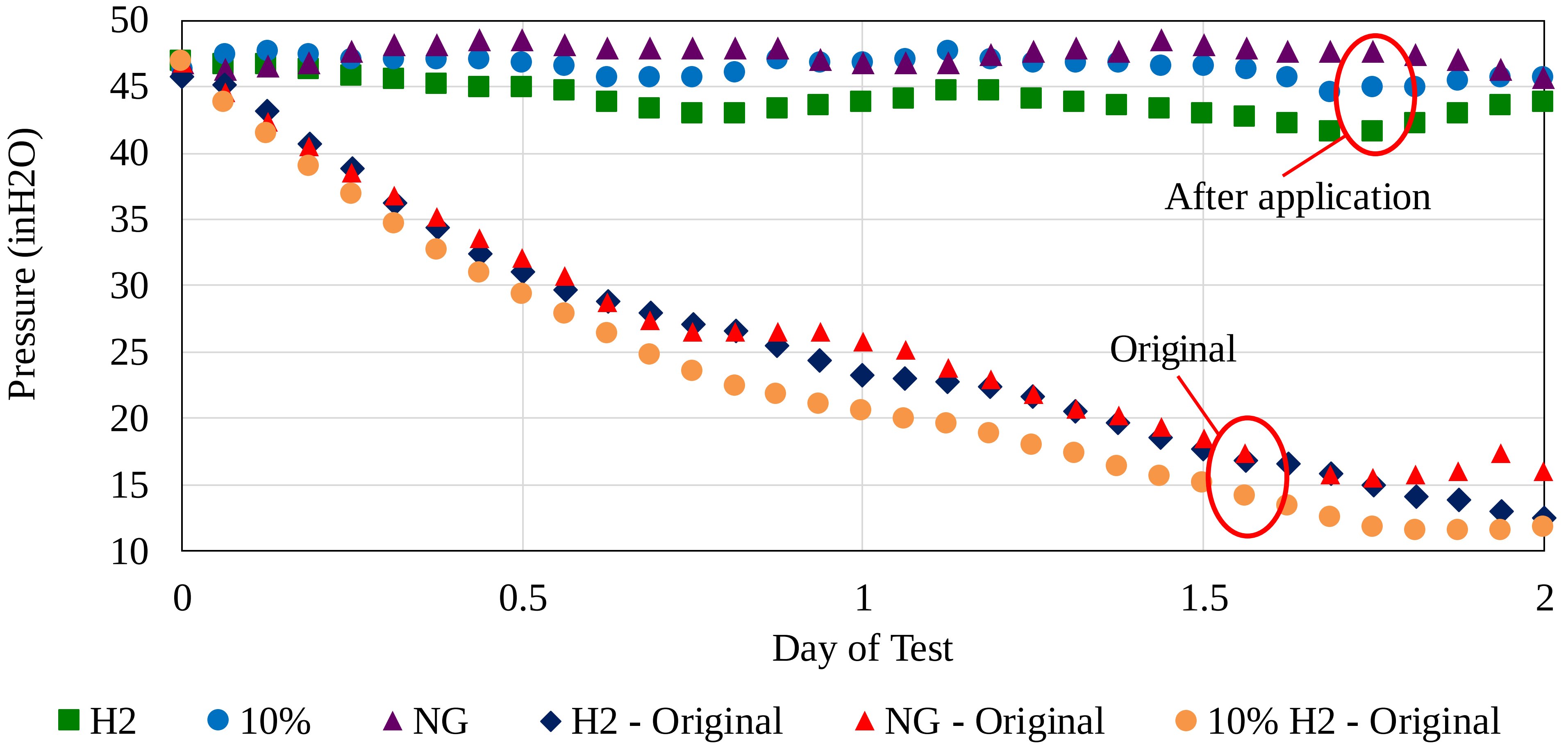
- NG, H_2/NG mixtures, H_2 leak at same rate



Pipeline Leak Mitigation Evaluation

H2 injection into existing natural gas infrastructure (low pressure)

- **Copper epoxy applied (Ace Duraflow®)**

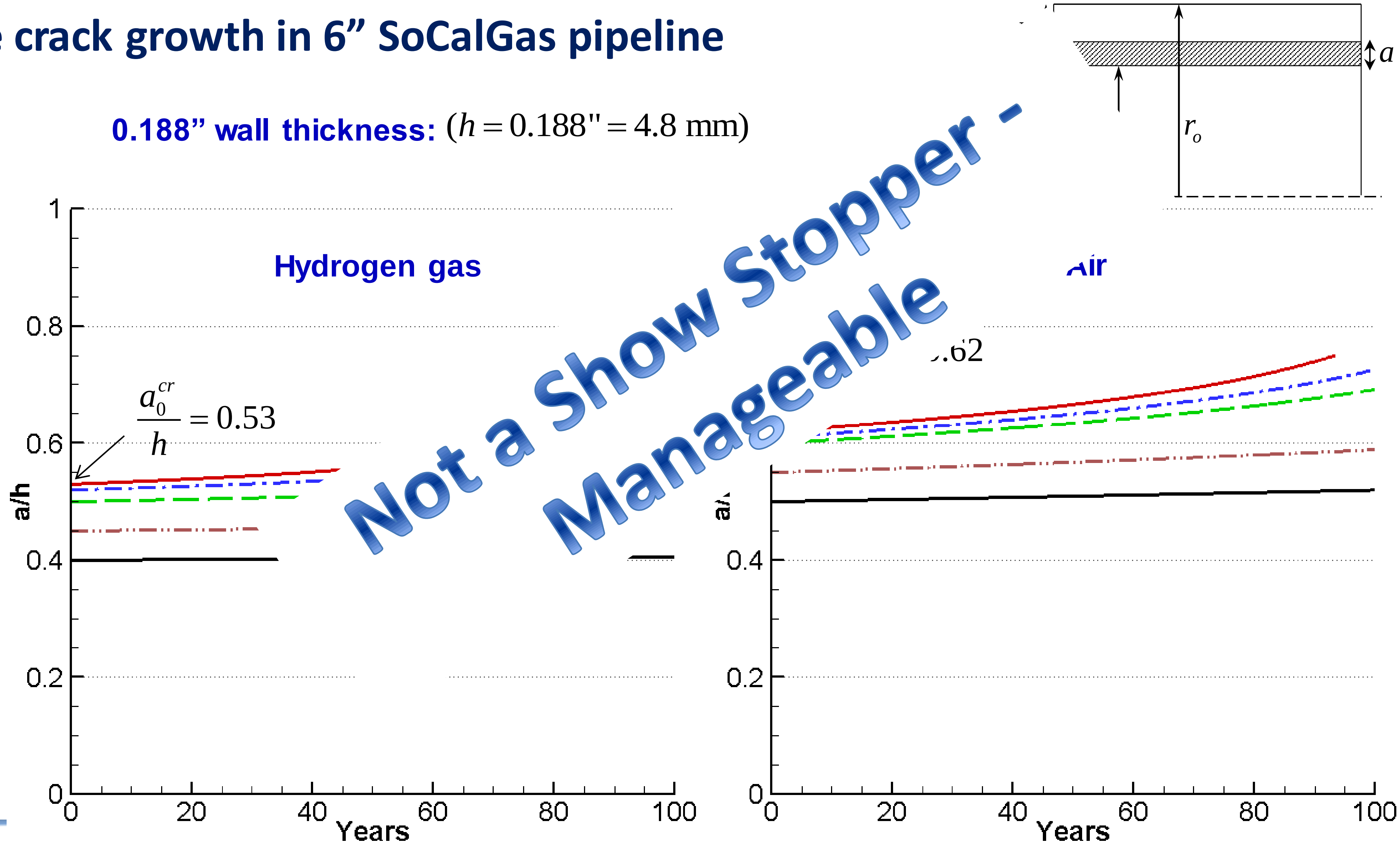


Pipeline Materials Impacts

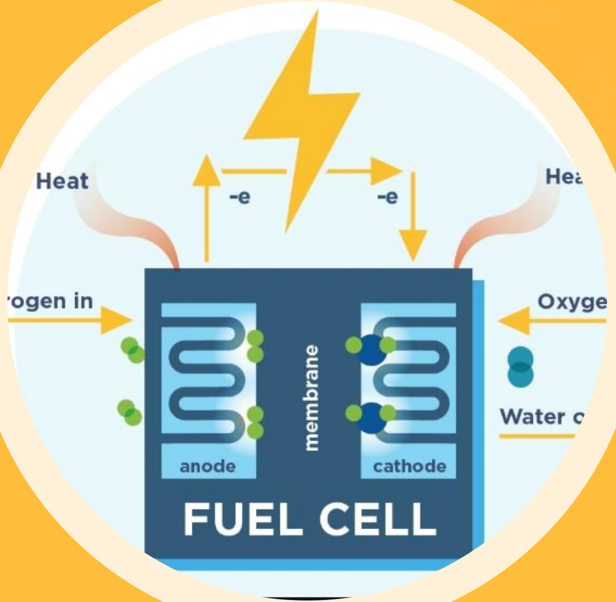
Simulation of H2 embrittlement and fatigue crack growth with UIUC

- **Fatigue crack growth in 6" SoCalGas pipeline**

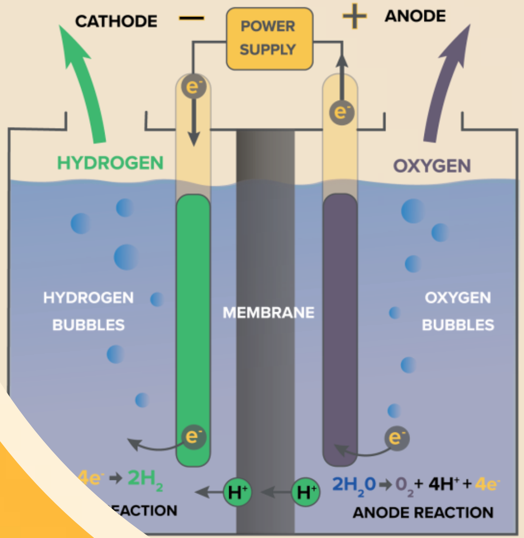
0.188" wall thickness: $(h = 0.188'' = 4.8\text{ mm})$



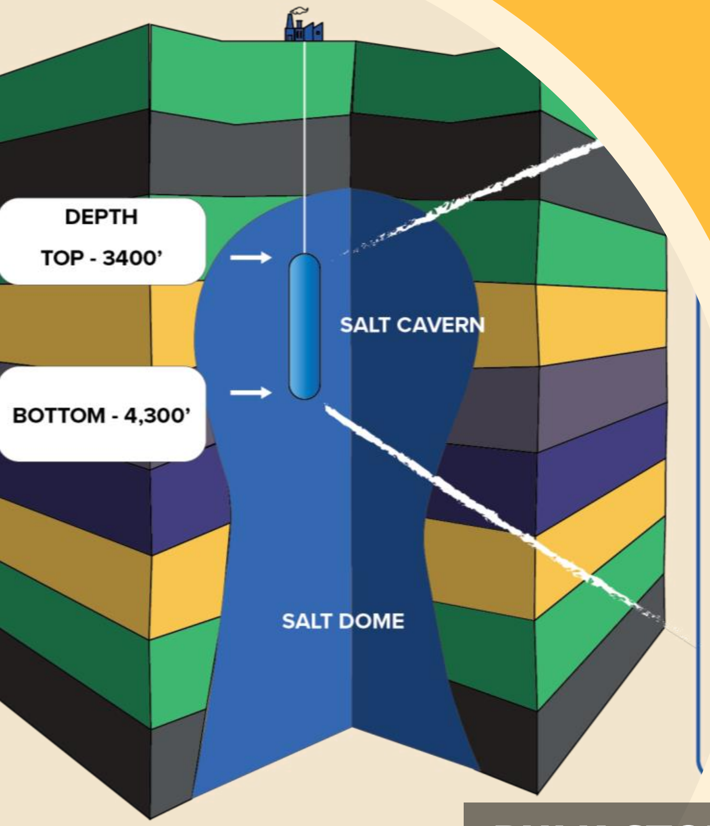
PIPELINE



FUEL CELL



ELECTROLYZER

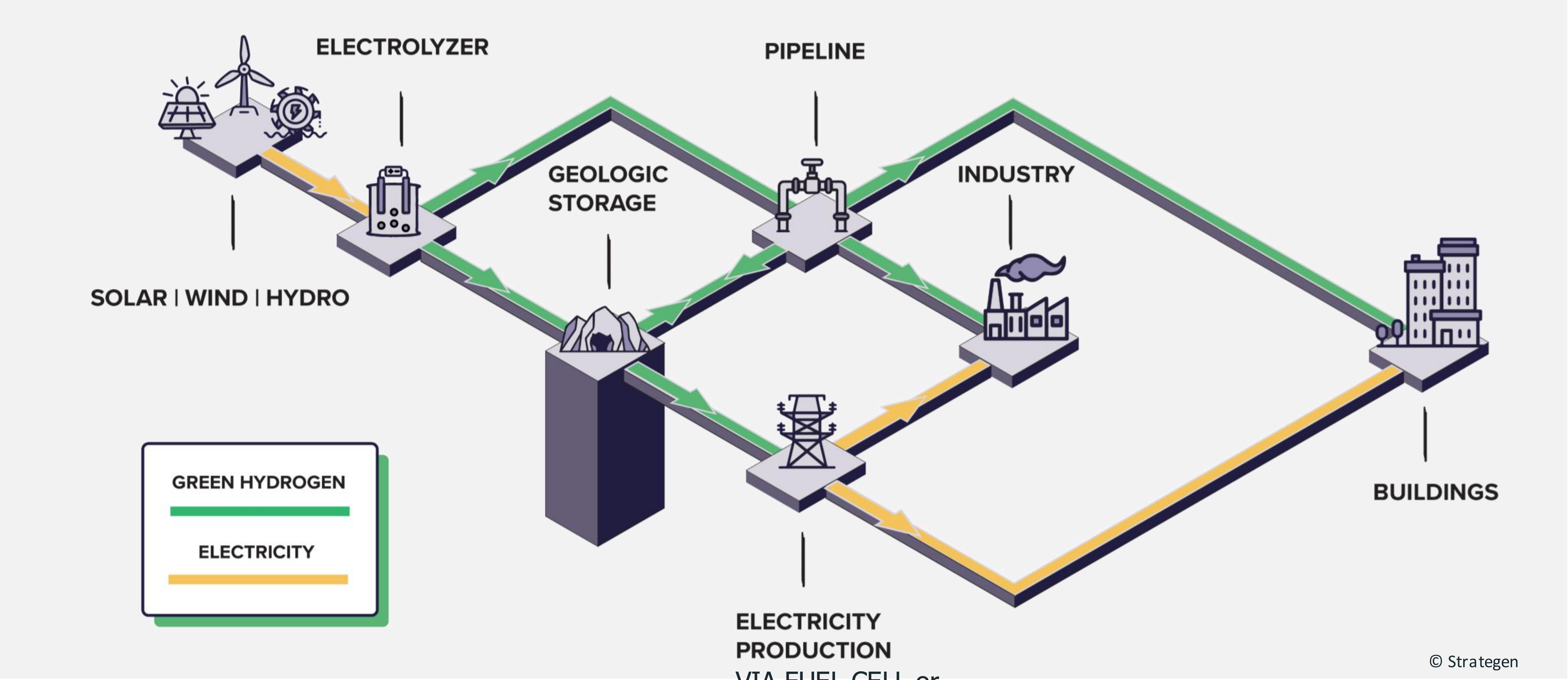


BULK STORAGE

Green Hydrogen Technologies

HYDROGEN GAS TURBINE

A Green Hydrogen Powered System



VIA FUEL CELL or
HYDROGEN GAS TURBINE

GREEN HYDROGEN COALITION

Green Hydrogen Repurposing Existing Infrastructure…..

…Enabling an affordable ar
responsible transition

IPP Overview: Convert Large-Scale Thermal Plant to 100% Green Hydrogen & Establish Regional Renewable Reliability Reserve

PROJECT OVERVIEW

Leverage curtailed and low-cost purpose-built wind and solar to produce Green Hydrogen at scale, displacing natural gas at IPP and providing renewable regional reliability (Green Hydrogen stored in purpose-built salt caverns on site)

PROJECT GOALS

1. Demonstrate large-scale thermal plant conversion to 100% Green Hydrogen by 2045
2. Leverage IPP project to develop market products & contracting mechanisms to establish a scalable regional renewable reliability reserve for Western US

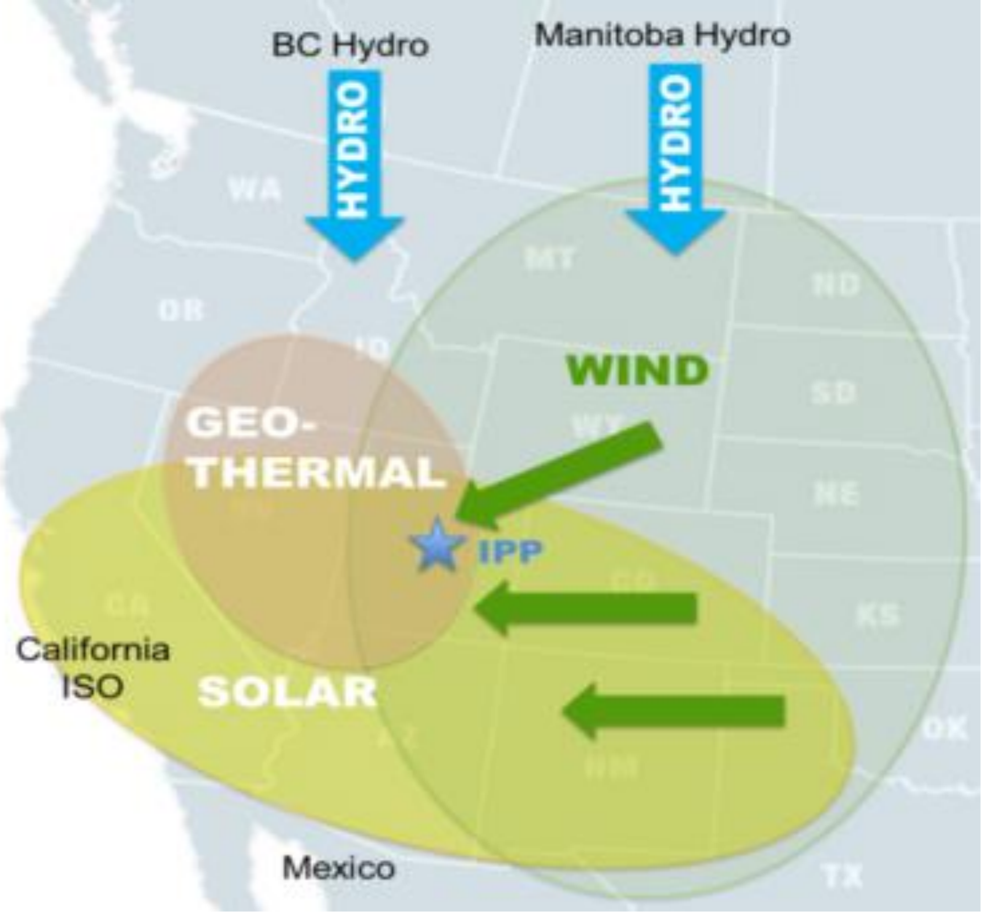
GREEN HYDROGEN COALITION

IPP History and Plan

- Located in Delta, Utah
- Two coal-fired units operating since 1986 with 1,800 MW net capacity
- Two Transmission Systems :
  - STS To Southern California 2400 MW HVDC System
  - NTS To Utah & Nevada
  - Interconnected to 370MW of Wind Generation
- 35 Project Participants, 6 from Southern California
- Coal Units to be retired by 2025; IPP conversion to 840 MW natural gas combined cycle gas facility
- Day 1: run on 30% blend of green hydrogen ramping up to 100% over time

Utah's Renewable Hub

- IPP sits in a confluence of renewable resources
- Currently interconnected to 370 MW of wind generation
- Secondary Path for existing Geothermal Projects and potential for additional geothermal in the area
- 2,300 MW of current solar interconnection requests in queue
- 1,500 MW of Wyoming wind interconnects currently being discussed



GREEN HYDROGEN COALITION

“*We spend* ***1000x*** *more on global* ***fossil fuel*** *subsidies than on* ***natural-based solutions****.”*
-Greta Thunberg

Why Fund the GHC?

Funding matters in the fight for our climate and a clean energy future.

Visit ghcoalition.org/fund

GREEN HYDROGEN COALITION

GHC Members

"Climate change is the defining issue of our time – and we are at a defining moment."

-Antonio Guterres
Secretary General
United Nations

Green Hydrogen

is the gamechanger to fight climate change and provide a clean energy economy for everyone

Q & A

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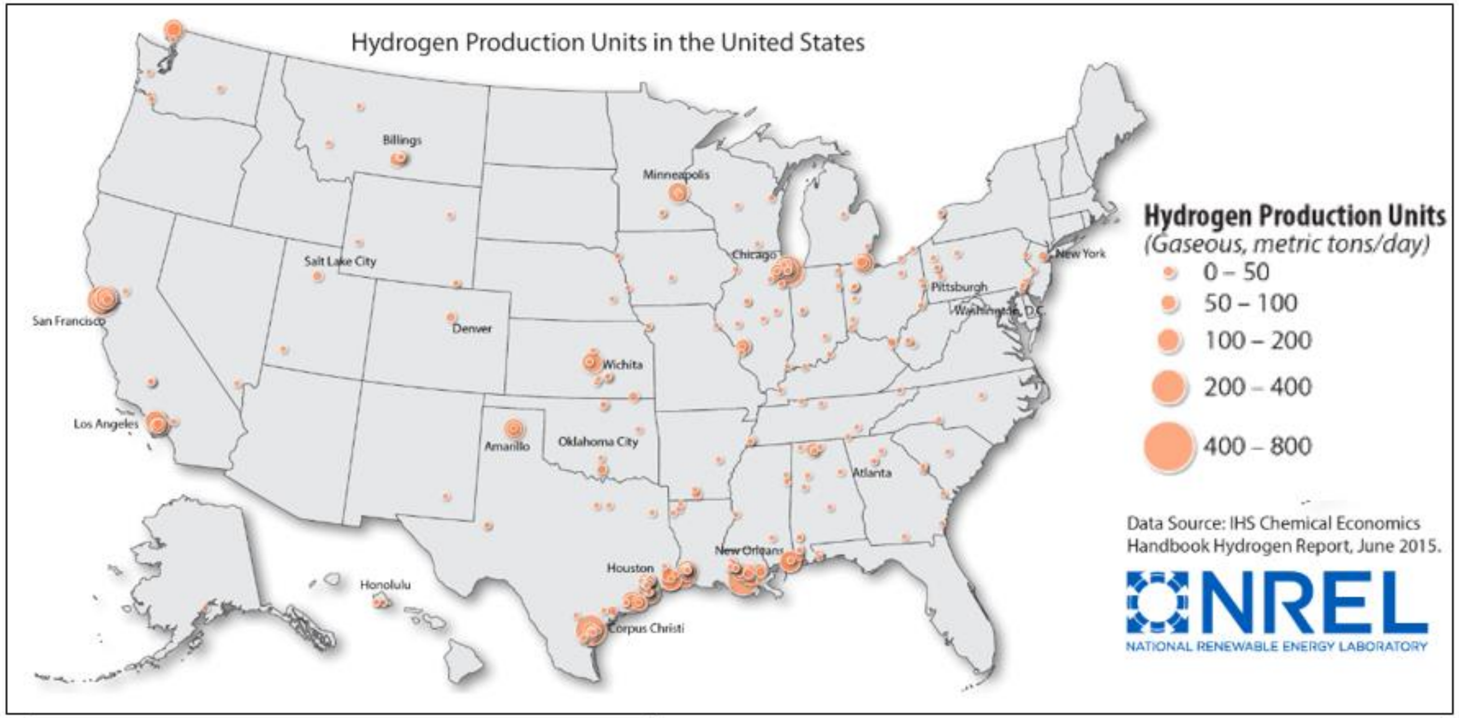


U.S. annual hydrogen production
10 million metric tons

Largest Users in the U.S.			
Petroleum Processing	68%	Fertilizer Production	21%

Hydrogen Pipeline Injection & Leakage

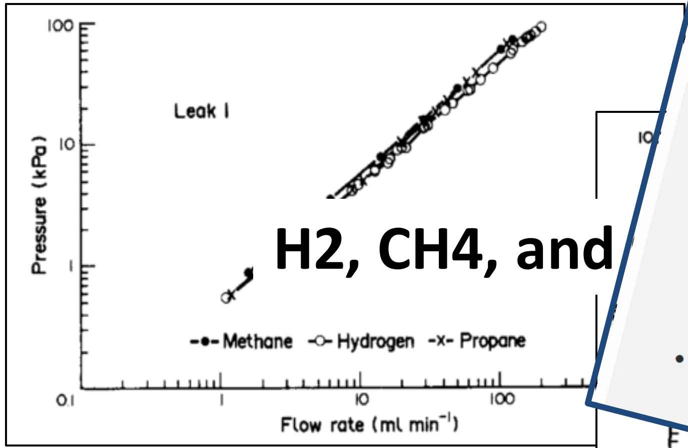
- Results from a previous study (1992) su… rt our recent findings!

Lea…	…	CH4
~~Diffusi…~~		
~~La…~~		
~~Tu…~~		

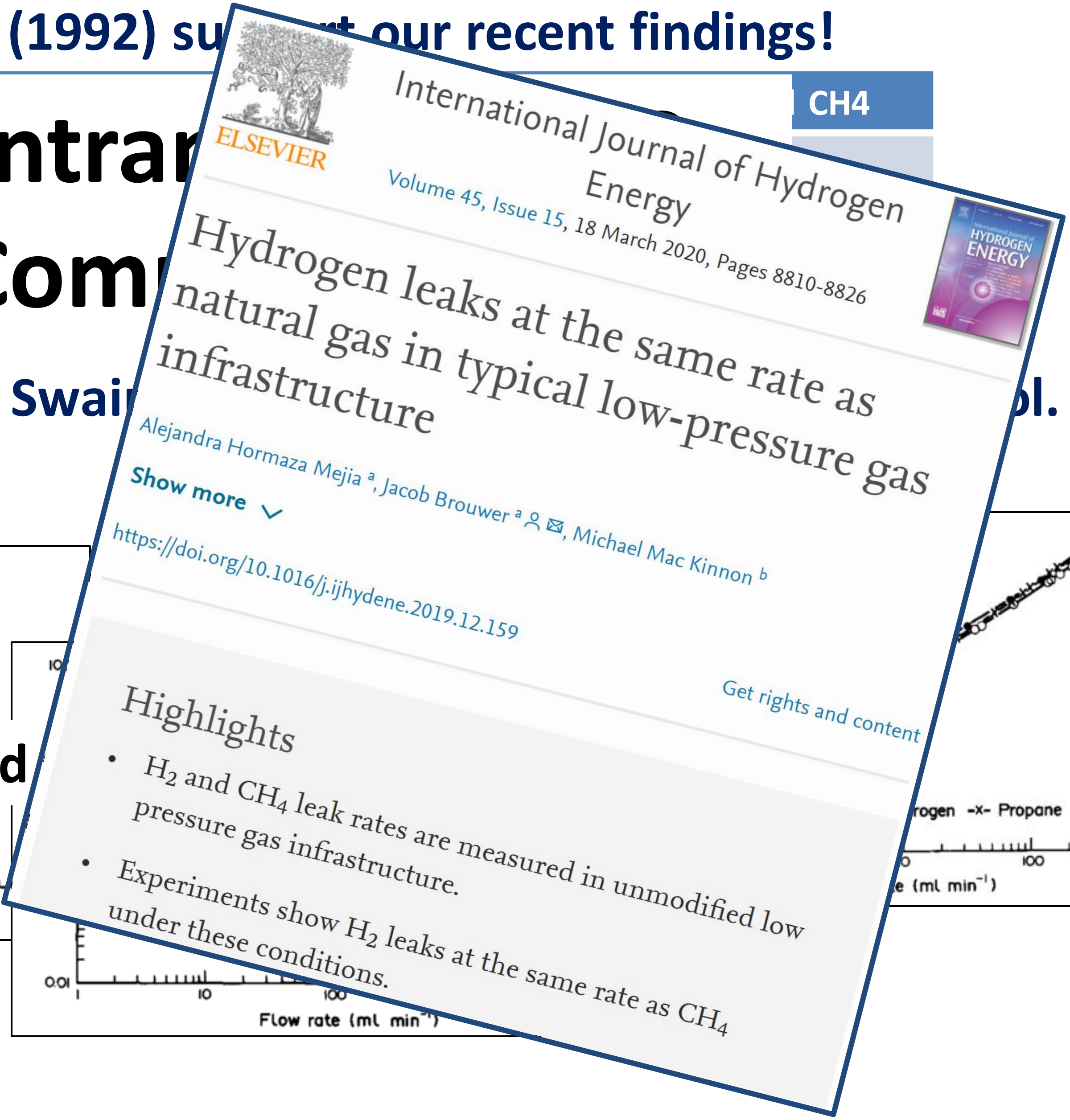
Entran…

Com…

- First publication on this topic: Swai… …ol. 17, pp. 807-815, 1992.



H2, CH4, and…


ELSEVIER

International Journal of Hydrogen Energy

Volume 45, Issue 15, 18 March 2020, Pages 8810-8826

Hydrogen leaks at the same rate as natural gas in typical low-pressure gas infrastructure

Alejandra Hormaza Mejia [a], Jacob Brouwer [a], Michael Mac Kinnon [b]

Show more

https://doi.org/10.1016/j.ijhydene.2019.12.159

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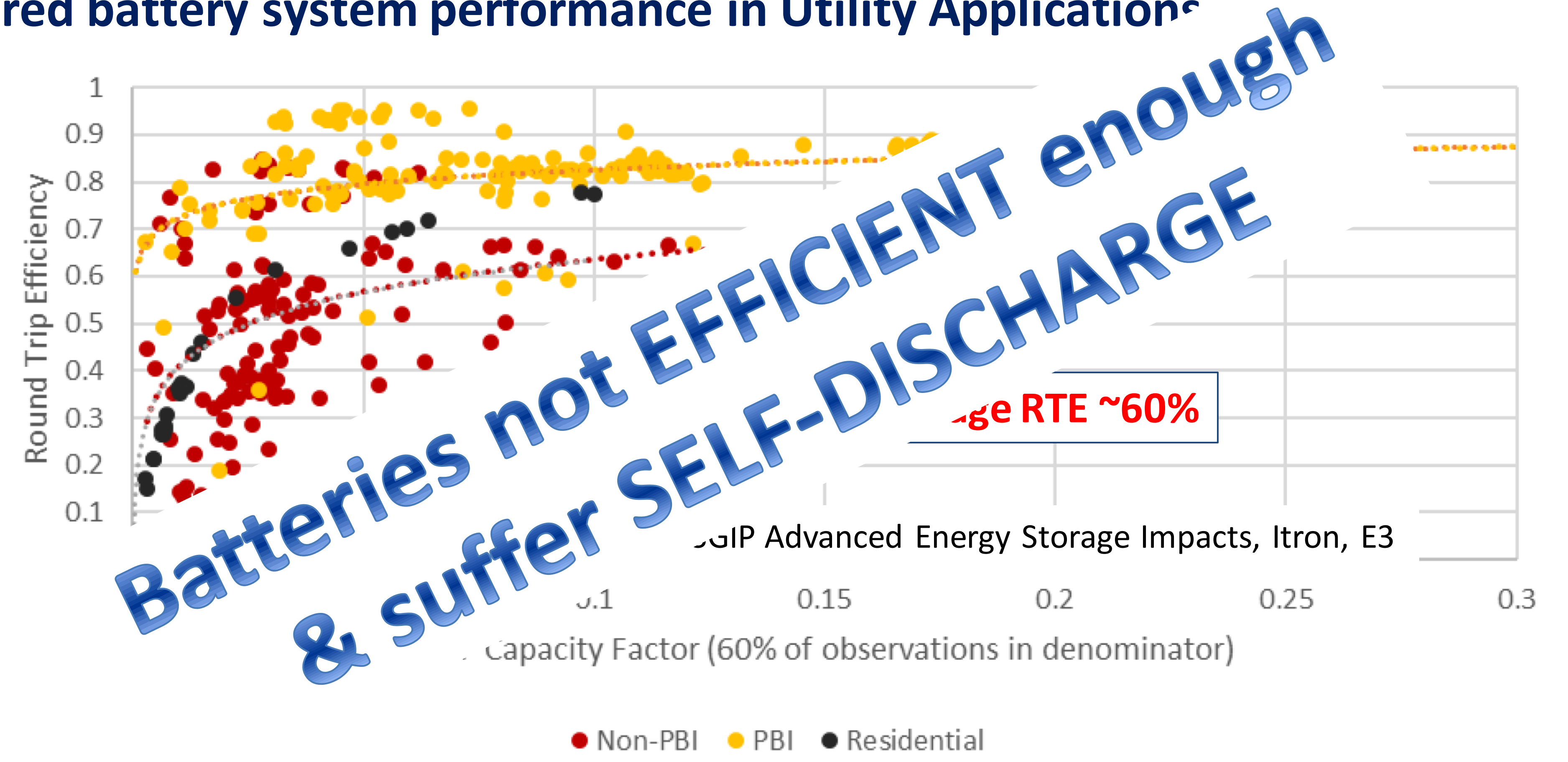
Highlights

- H_2 and CH_4 leak rates are measured in unmodified low pressure gas infrastructure.
- Experiments show H_2 leaks at the same rate as CH_4 under these conditions.

Why Hydrogen? Long Duration Storage

Round-Trip Efficiency (>90% in Laboratory Testing)

- Measured battery system performance in Utility Applications



- Self-Discharge (the main culprit), plus cooling, transforming, inverting/converting, and other balance of plant