Do We Really Need Hydrogen Infrastructure?

California Air Resources Board

July 15, 2020

NFCRC
National Fuel Cell Research Center
UCIrvine | University of California

Jack Brouwer, Ph.D.
Director

Hydrogen is Essential for Sustainability

Hydrogen offers 11 features that are required for 100% zero carbon & pollutant emissions

- 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
- Water naturally recycled in short time on
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g., a
- Pre-cursor for high energy density rene
- Re-use of existing infrastructure (lower

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Current Opinion in Electrochemistry

Review Article

Hydrogen is essential for sustainability

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

CrossMark

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.

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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 Brou... *for Sustainability*, Current Opinion in Electrochemistry, 2019.

Green Hydrogen Required for Zero

- Renewable energy carriers & chemicals are required to achieve zero emissions
- Hydrogen most important/ubiquitous

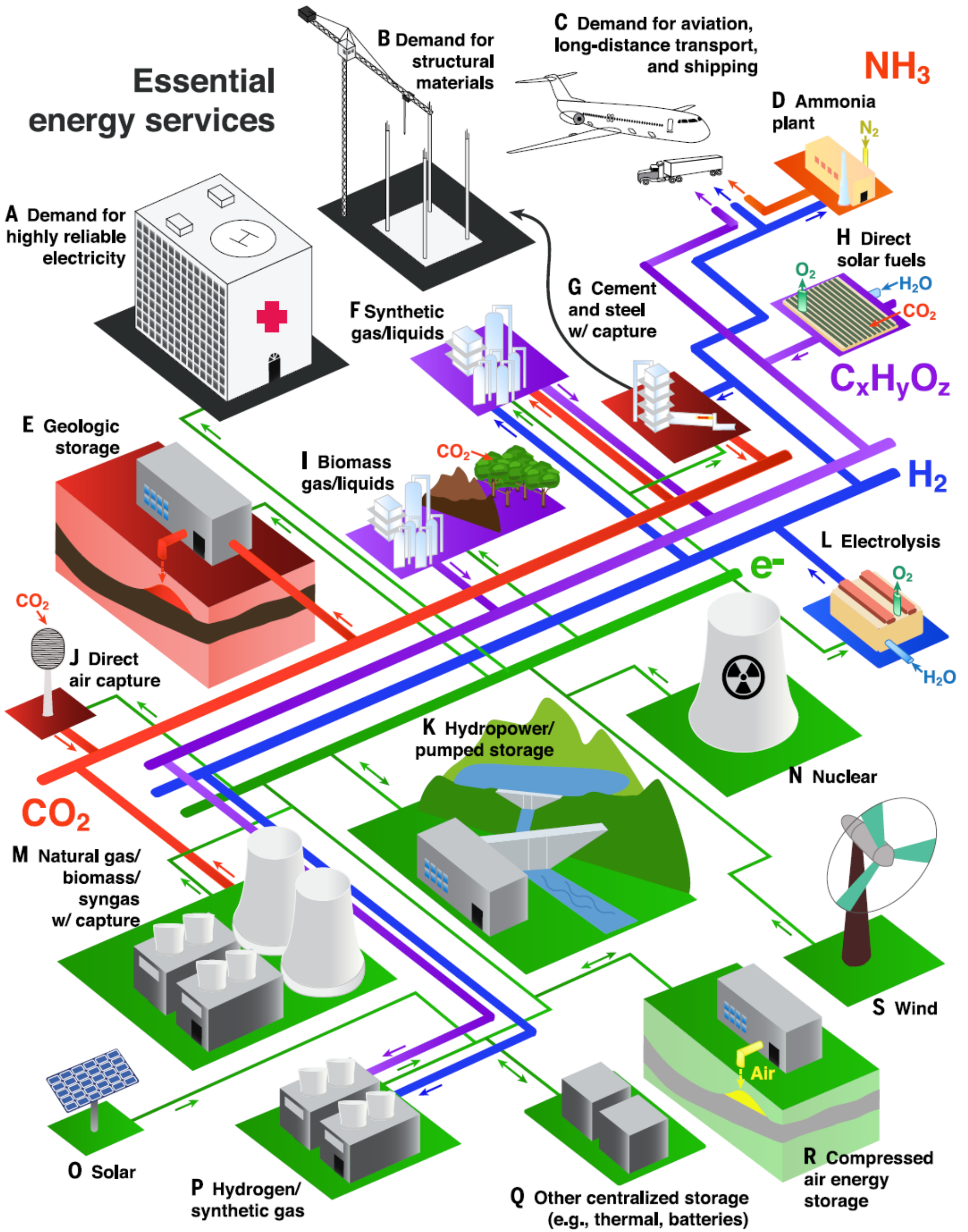
REVIEW SUMMARY

ENERGY

Net-zero emissions energy systems

Steven J. Davis*, Nathan S. Lewis*, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin I. Hoffert, Eric Ingersoll, Paulina Jaramillo, Klaus S. Lackner, Katharine J. Mach, Michael Mastrandrea, Joan Ogden, Per F. Peterson, Daniel L. Sanchez, Daniel Sperling, Joseph Stagner, Jessika E. Trancik, Chi-Jen Yang, Ken Caldeira*

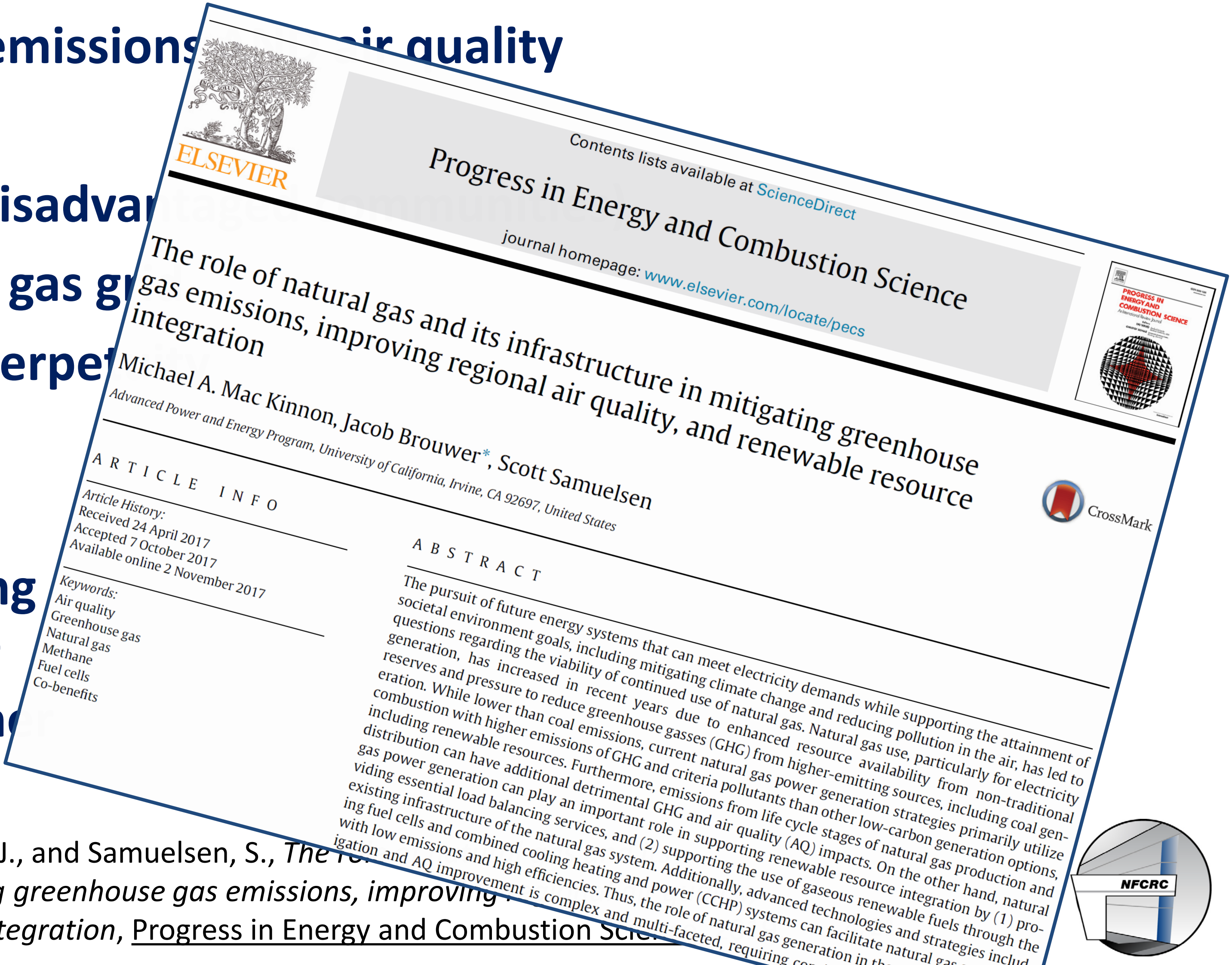
Davis *et al.*, *Science* **360**, 1419 (2018)   29 June 2018



Current Natural Gas Infrastructure & Transformation

Many jurisdictions around the world agree – objective analysis always points to transformation of both "electric grid" AND "gas grid" to zero emissions

- Consider both greenhouse gas (GHG) emissions ... air quality
- Consider all sectors of economy
- Consider all communities (especially disadvan...
- Consider reliability & safety of current gas gr...
- Must deal with bio-waste streams in perpet...
- Current use of natural gas has enabled electric grid transformation
- Current use of natural gas (and weaning off over time) can immediately deliver air quality and health benefits and usher in the zero emissions hydrogen future



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Contents lists available at ScienceDirect

Progress in Energy and Combustion Science

journal homepage: www.elsevier.com/locate/pecs

The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration

Michael A. Mac Kinnon, Jacob Brouwer*, Scott Samuelsen

Advanced Power and Energy Program, University of California, Irvine, CA 92697, United States

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Natural gas
Methane
Fuel cells
Co-benefits

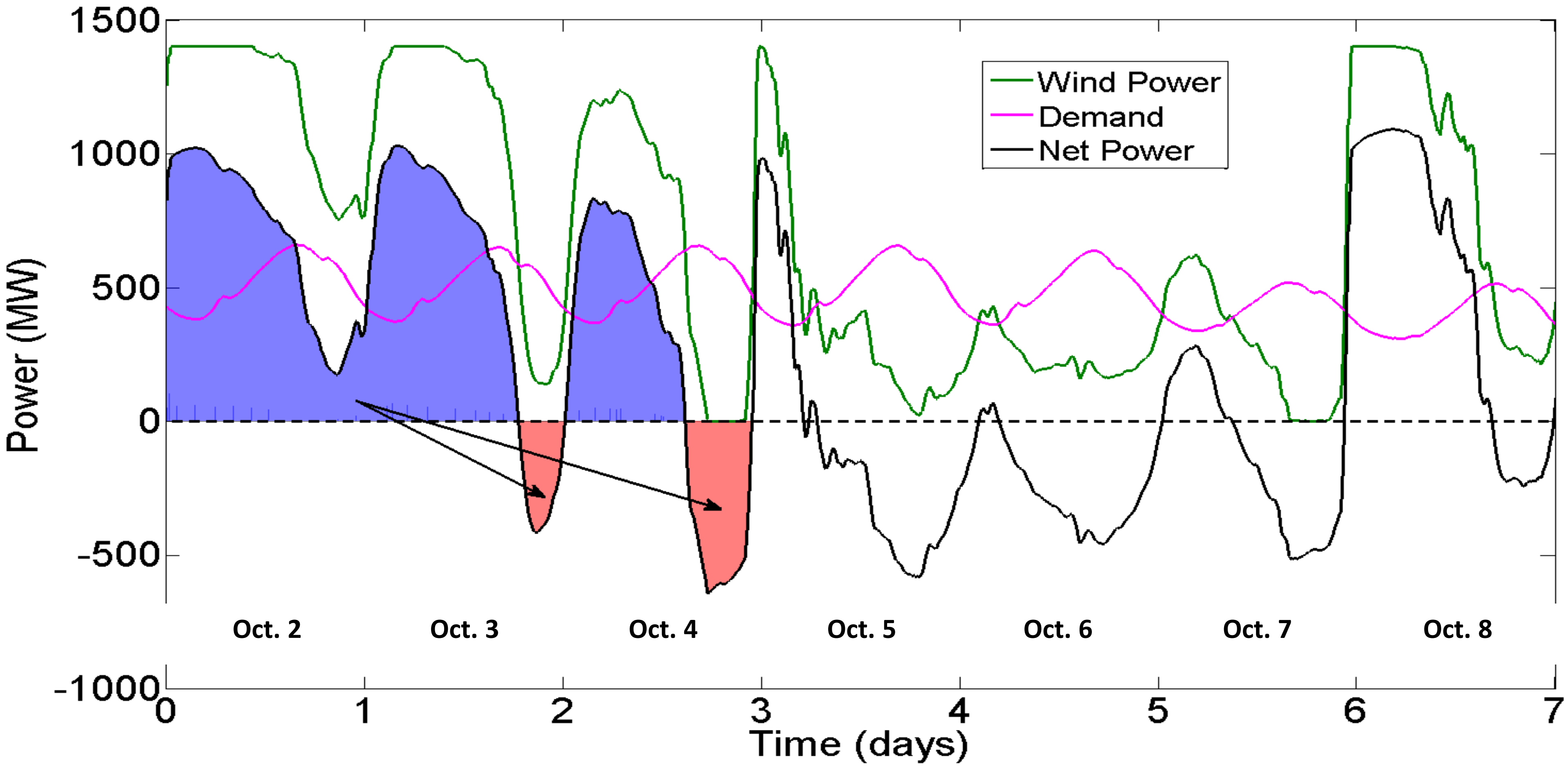
ABSTRACT

The pursuit of future energy systems that can meet electricity demands while supporting the attainment of societal environment goals, including mitigating climate change and reducing pollution in the air, has led to questions regarding the viability of continued use of natural gas. Natural gas use, particularly for electricity generation, has increased in recent years due to enhanced resource availability from non-traditional reserves and pressure to reduce greenhouse gasses (GHG) from higher-emitting sources, including coal generation. While lower than coal emissions, current natural gas power generation strategies primarily utilize combustion with higher emissions of GHG and criteria pollutants than other low-carbon generation options, including renewable resources. Furthermore, emissions from life cycle stages of natural gas production and distribution can have additional detrimental GHG and air quality (AQ) impacts. On the other hand, natural gas power generation can play an important role in supporting renewable resource integration by (1) providing essential load balancing services, and (2) supporting the use of gaseous renewable fuels through the existing infrastructure of the natural gas system. Additionally, advanced technologies and strategies including fuel cells and combined cooling heating and power (CCHP) systems can facilitate natural gas ... with low emissions and high efficiencies. Thus, the role of natural gas generation in the ... igation and AQ improvement is complex and multi-faceted, requiring ...

Mac Kinnon, M., Brouwer, J., and Samuelsen, S., *The ro... infrastructure in mitigating greenhouse gas emissions, improving ... and renewable resource integration*, Progress in Energy and Combustion Scie...

Hydrogen Energy Storage Dynamics

- **Compressed Hydrogen Storage complements Wind & Power Demand Dynamics in Texas**



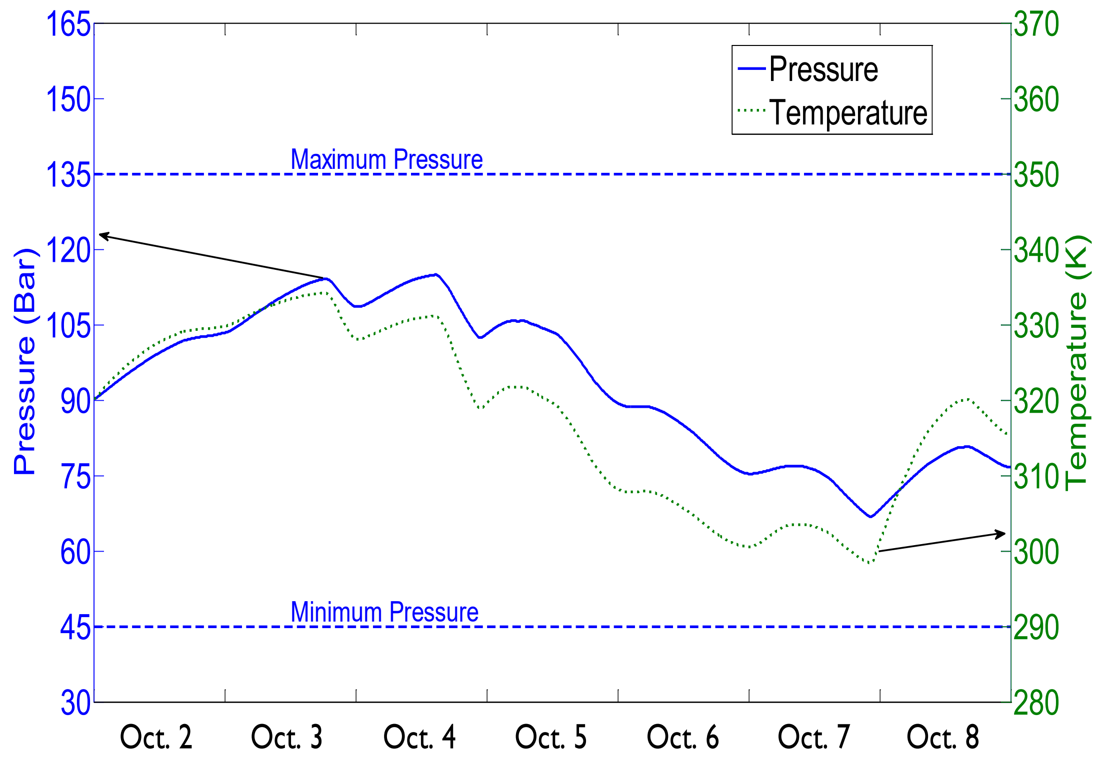
- **Load shifting from high wind days to low wind days**
- **Hydrogen stored in adjacent salt cavern**

Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

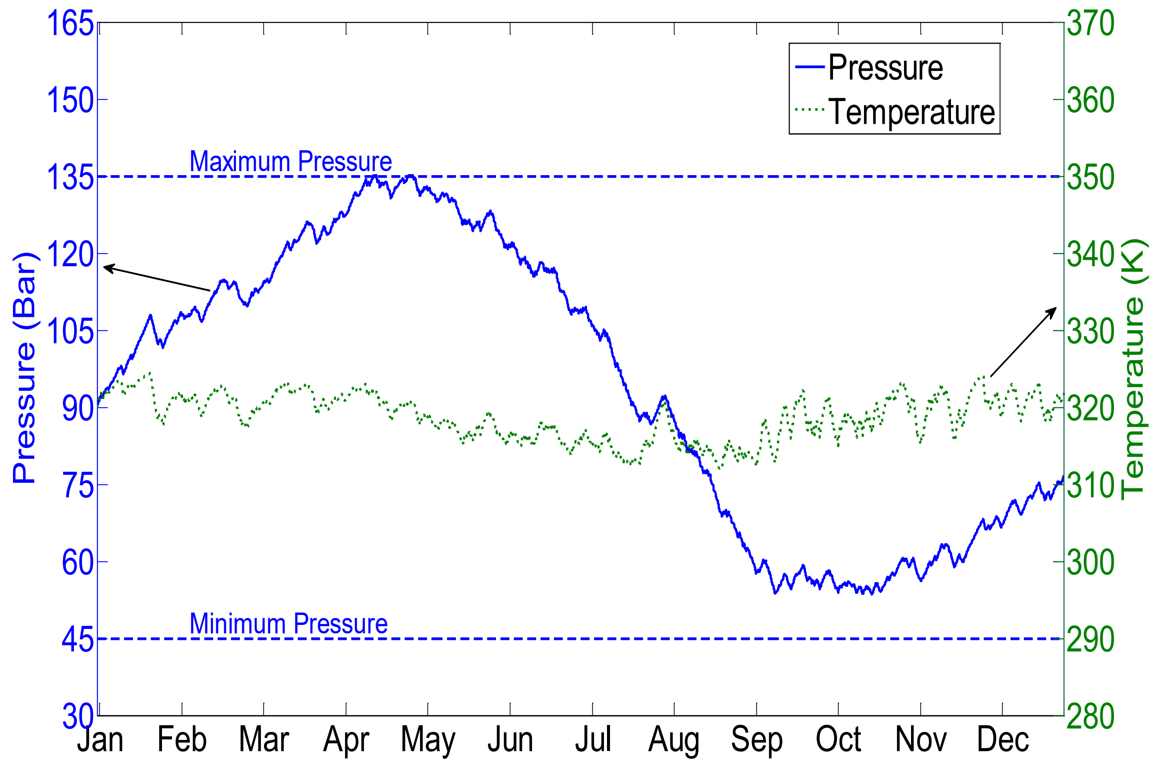
Hydrogen Energy Storage Dynamics

- Weekly storage and seasonal storage w/ H2, fuel cells, electrolyzers – all zero emissions!
  - ○

Weekly



Seasonal

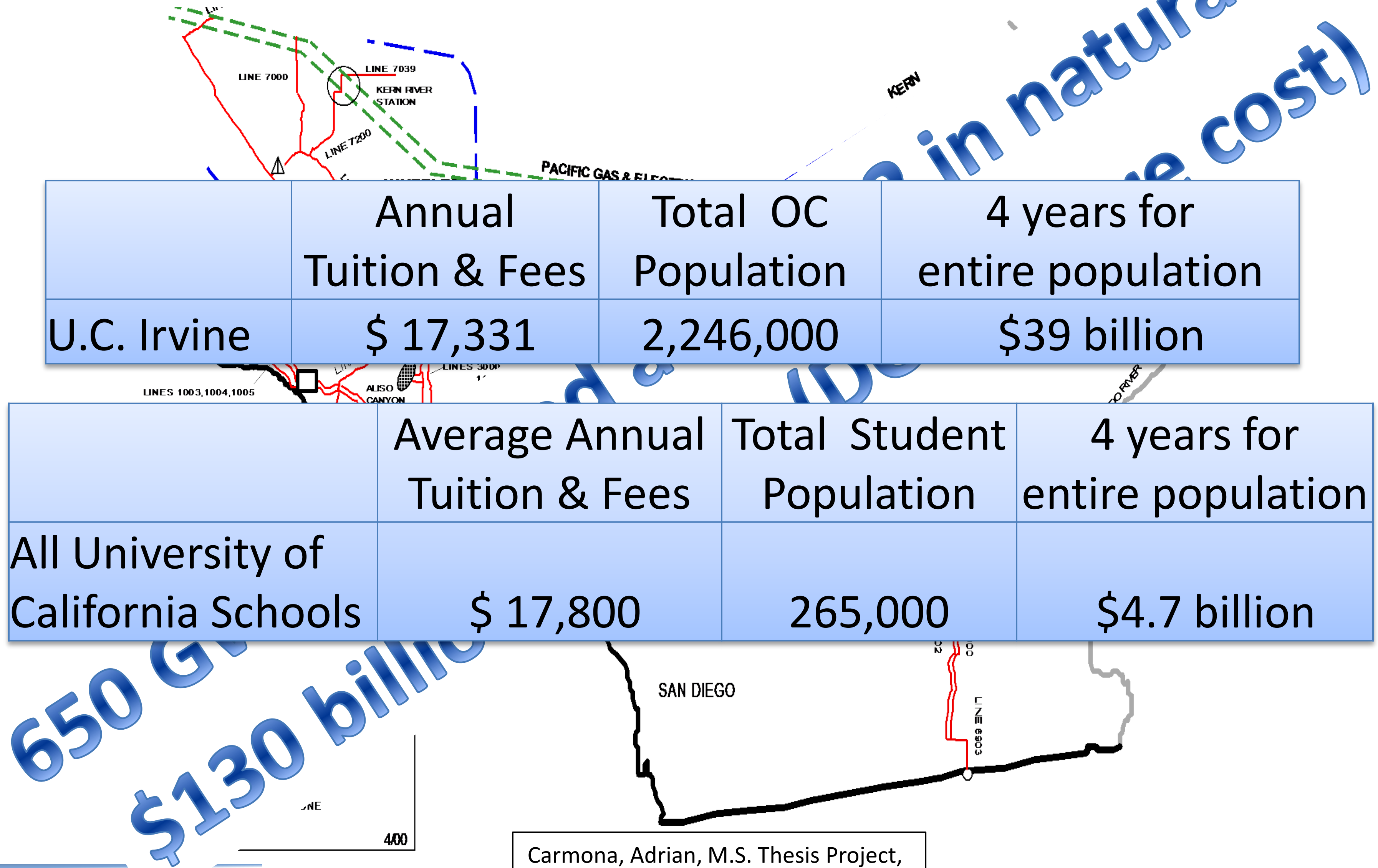


But what can we do if we don't have a salt cavern?

Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

“Natural” Storage & Transmission/Distribution Resource

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



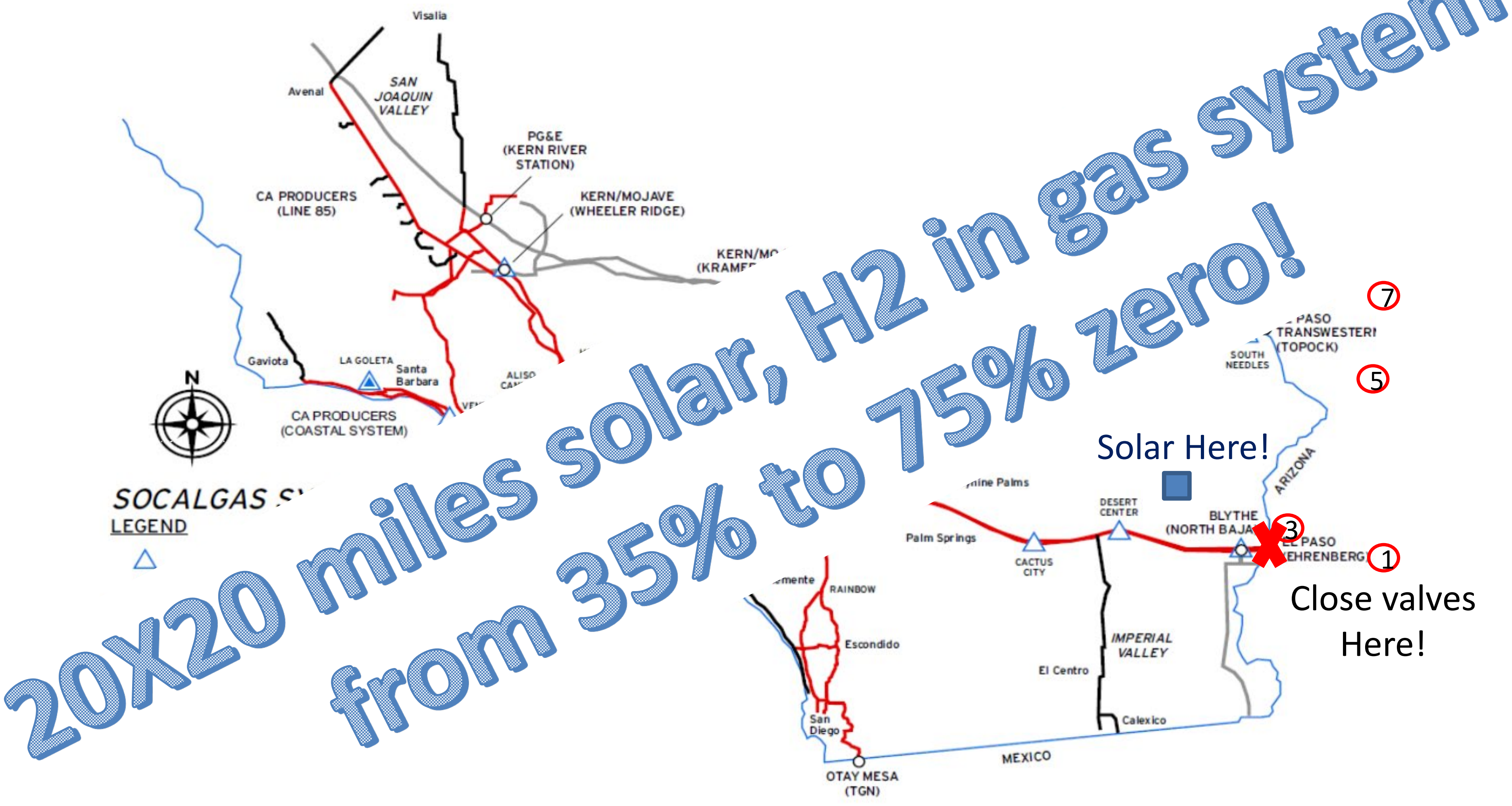
	Annual Tuition & Fees	Total OC Population	4 years for entire population
U.C. Irvine	$ 17,331	2,246,000	$39 billion

	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.

Brief Gedanken experiment

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



20X20 miles solar, H2 in gas system from 35% to 75% zero!

January 2020: Canada,
Chetwynd Hydrogen
3% pipeline injection

- **Description:**
  - Coupled electrolysis plant and wind farm to produce green hydrogen to inject into natural gas pipelines at 3% concentration
- **Project Plan:**
  - Build dedicated wind farm as well as the electrolysis plant
  - Negotiate agreement to inject hydrogen into natural gas pipeline
- **Goal:**
  - 22,000 tons green hydrogen produced/year

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GREEN HYDROGEN COALITION

https://fuelcellsworks.com/news/canada-macquarie-capital-to-finance-new-200-plus-million-renewable-hydrogen-plant-in-chetwynd

February 2020: Netherlands NortH2 Project, 10 GW

- **Description:**
  - Shell plans to have 10GW of turbines off the Netherlands coast to power green hydrogen production
- **Project Plan:**
  - 2027 – start with 3-4 GW
  - 2040 – 10 GW target
- **Goal**:
  - 800,000 tons of green H2 produced/year

NOTE: 12% Hydrogen in NG already a standard throughout most of Holland

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https://www.rechargenews.com/wind/shell-unveils-worlds-largest-offshore-wind-plan-to-power-green-hydrogen/2-1-763610

May 2020: Infinite Blue Energy secures $300 million for largest green hydrogen project in Western Australia

Description:

- The Arrowsmith Hydrogen Project will produce 25 tons of green hydrogen daily using wind and solar energy
- This project will reduce CO2 emissions by 78,000 tons annually

Project Plan:

- Construction start date by mid 2020
- Operational by 2022

Goals

- Part I of a series of green hydrogen installations in Australia by Infinite Blue Energy
- Develop export market for green hydrogen, specifically targeting Japan and South Korea

NOTE: Ships for international trading/shipping of H_2 are part of Australia/Japan collaboration

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GREEN HYDROGEN COALITION

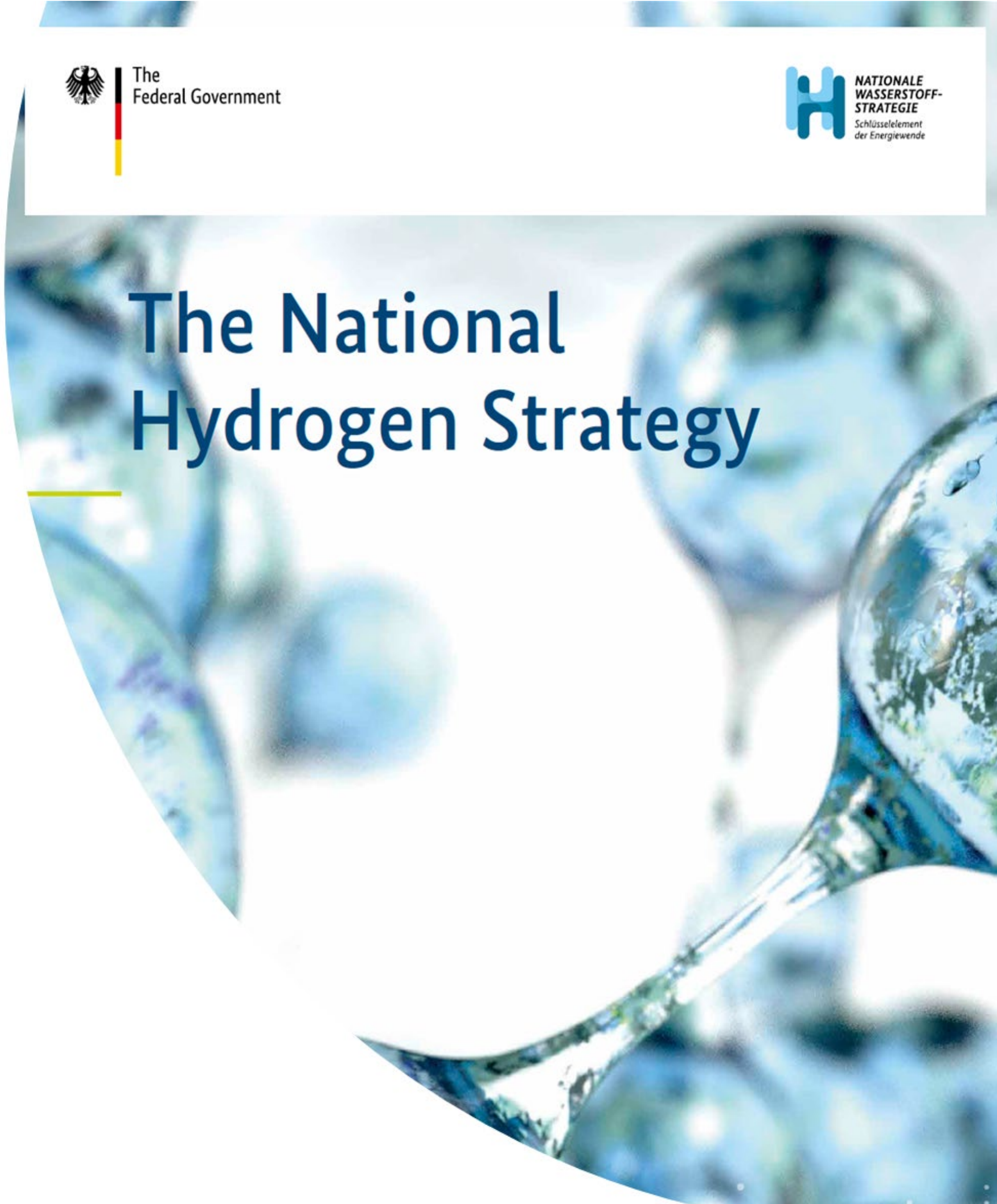
June 2020: Recognizing the Potential and Harnessing the Opportunities of Hydrogen (Germany)

Description:

- German Government will invest 9 billion euros
- National strategy will invest in 38 specific measures in 10 hydrogen topics

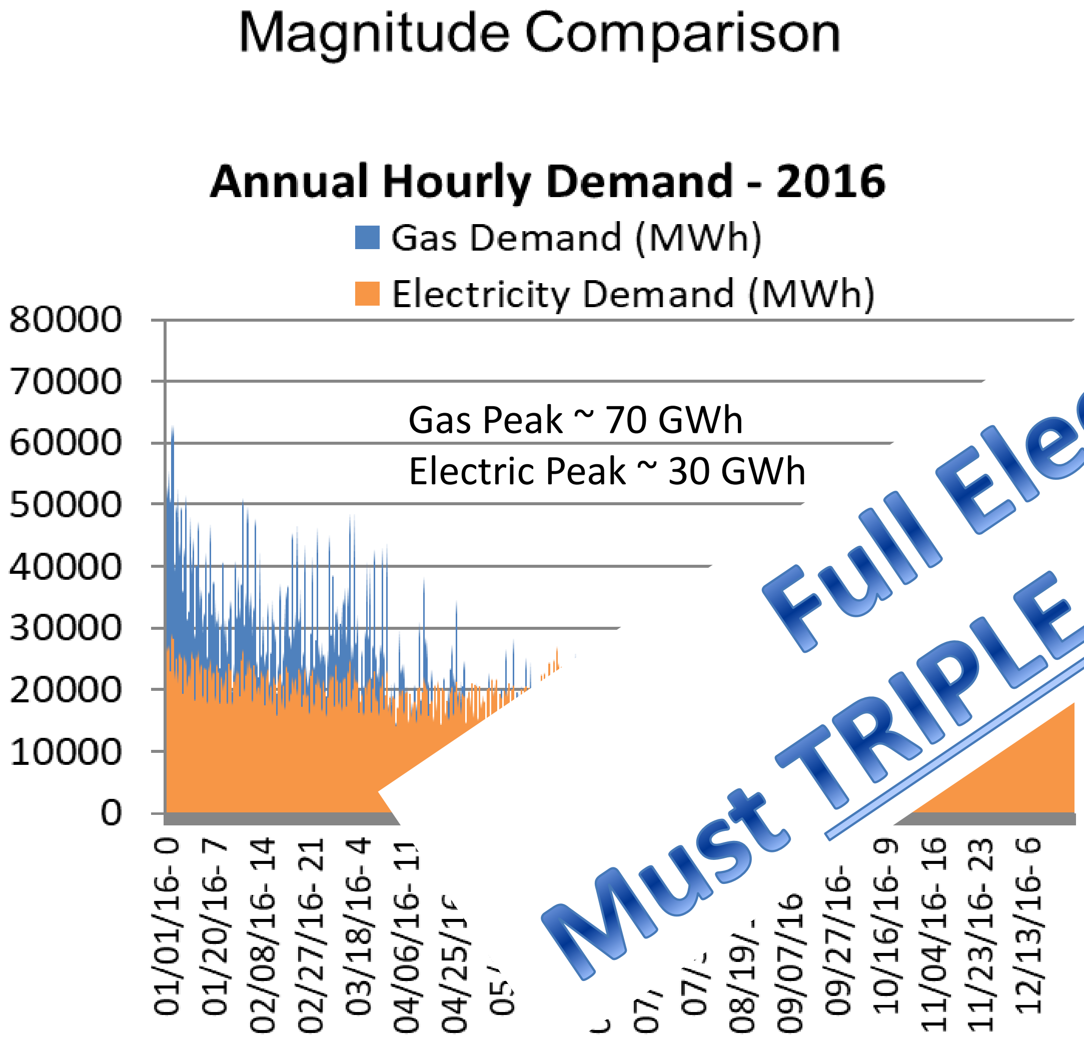
Representative Goals

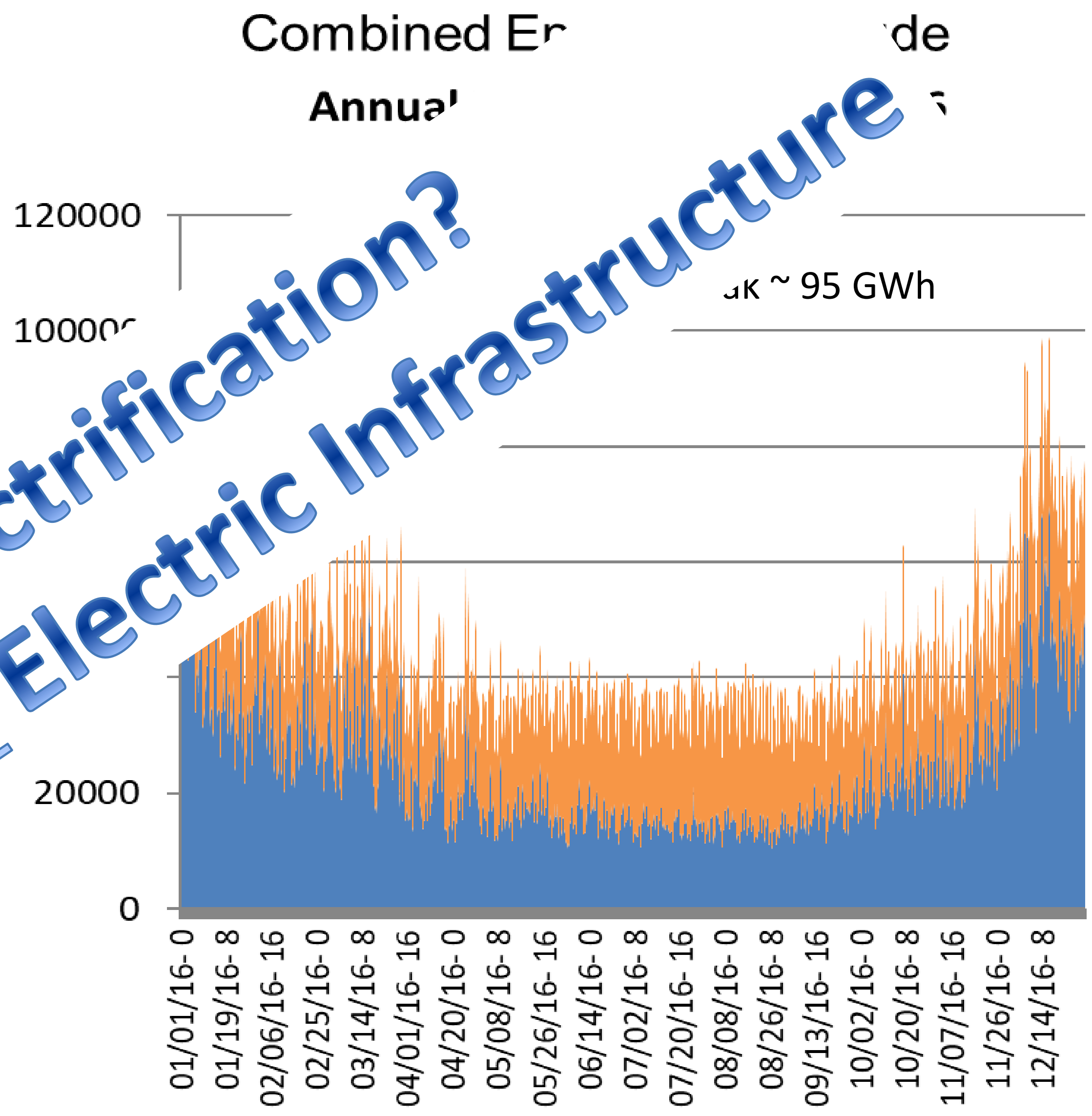
- Making hydrogen a competitive option
- Developing a domestic market for hydrogen technology
- Making hydrogen a sustainable base material for the industrial sector
- Enhancing transport and distribution infrastructure
- Shaping and accompanying transformation processes
- Establishing international markets and cooperation for hydrogen
- Develop export market for green hydrogen, specifically targeting Japan and South Korea



Infrastructure Issue #1: Economics of Alternatives for 100% Zero

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





Full Electrification?

Must TRIPLE Electric Infrastructure

Infrastructure Issue #2: Hydrogen Safety

Tests for Hydrogen Safety

Fire

Excessive Tank Pressure (Blocking all safety valves)

Mechanical Damage

Courtesy: BMW Group, 2000
and Garrity, Murdoch Univ., 2002

Hydrogen Leak **Gasoline Leak**

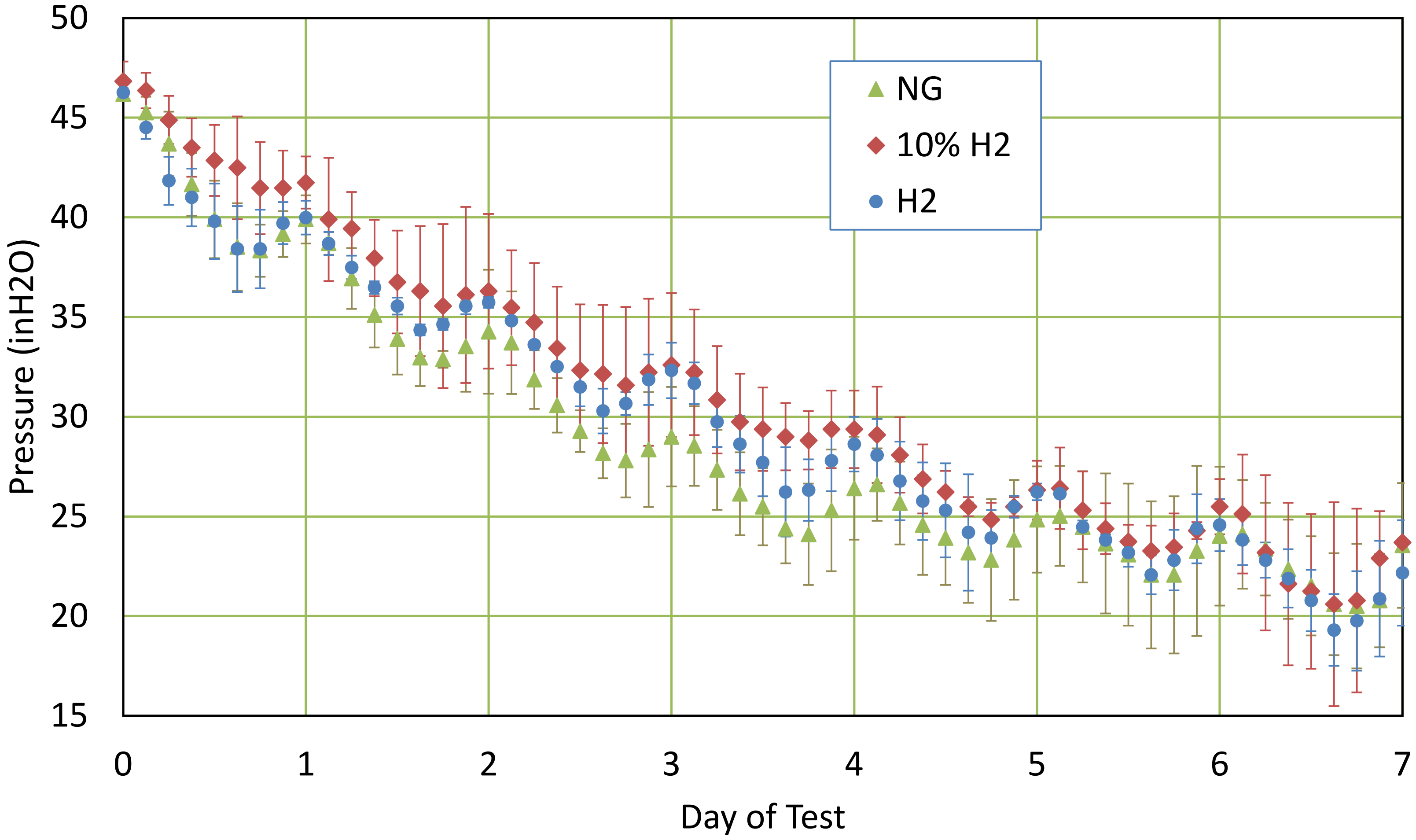
Infrastructure Issue #2: Hydrogen Safety

- Hindenburg and the Hydrogen Bomb
  - No nuclear reactions
  - Hindenburg disaster caused by paint and skin
- H_2 characteristics
  - Broadest flammability limits
  - Low ignition energy (at stoichiometric)
  - Highest diffusivity
  - Lowest density
- Can be safer than gasoline!
  - In the event of an accident – creation and ignition of a flammable mixture is less likely with hydrogen than with gasoline
- But, fire marshals, codes, standards, regulations, are not currently friendly
- Recently – disinformation

Infrastructure Issue #3: Hydrogen Injection/leakage from NG Infrastructure

H2 injection into existing natural gas infrastructure (low pressure)

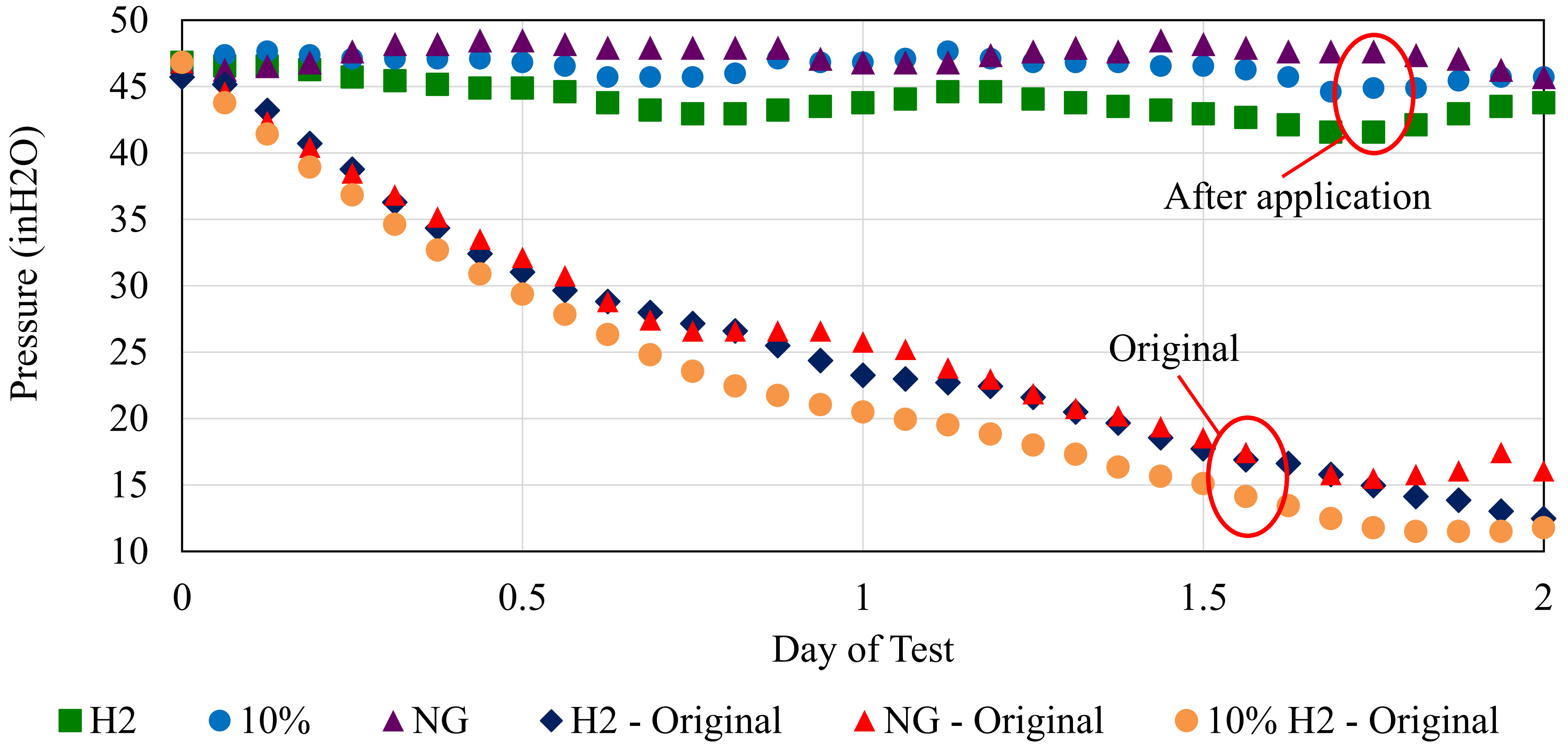
- **NG, H_2/NG mixtures, H_2 leak at same rate**



Infrastructure Issue #3: Hydrogen Injection/leakage from NG Infrastructure

H2 injection into existing natural gas infrastructure (low pressure)

- Copper epoxy applied (Ace Duraflow®) to mitigate H_2 leaks



Infrastructure Issue #3: Hydrogen Injection/leakage from NG Infrastructure

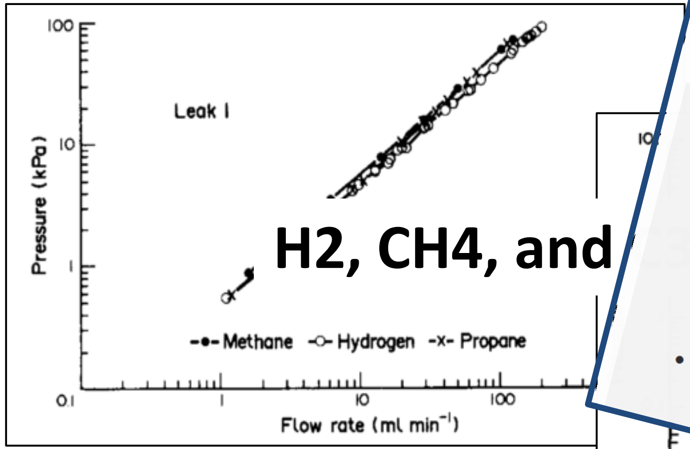
- **Results from a previous study (1992) su… our recent findings!**

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

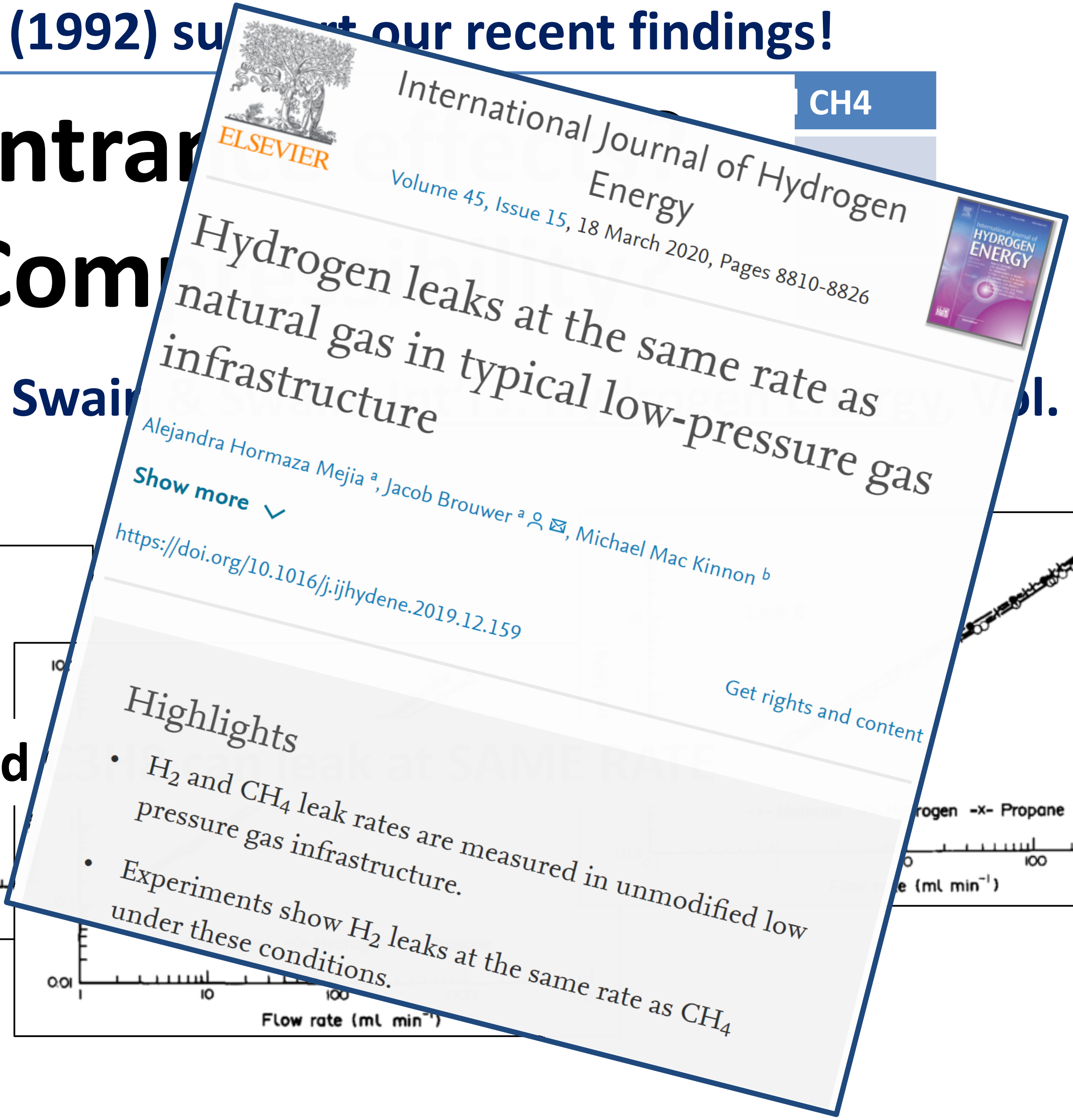
Entran…

Com…

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



H2, CH4, and …



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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

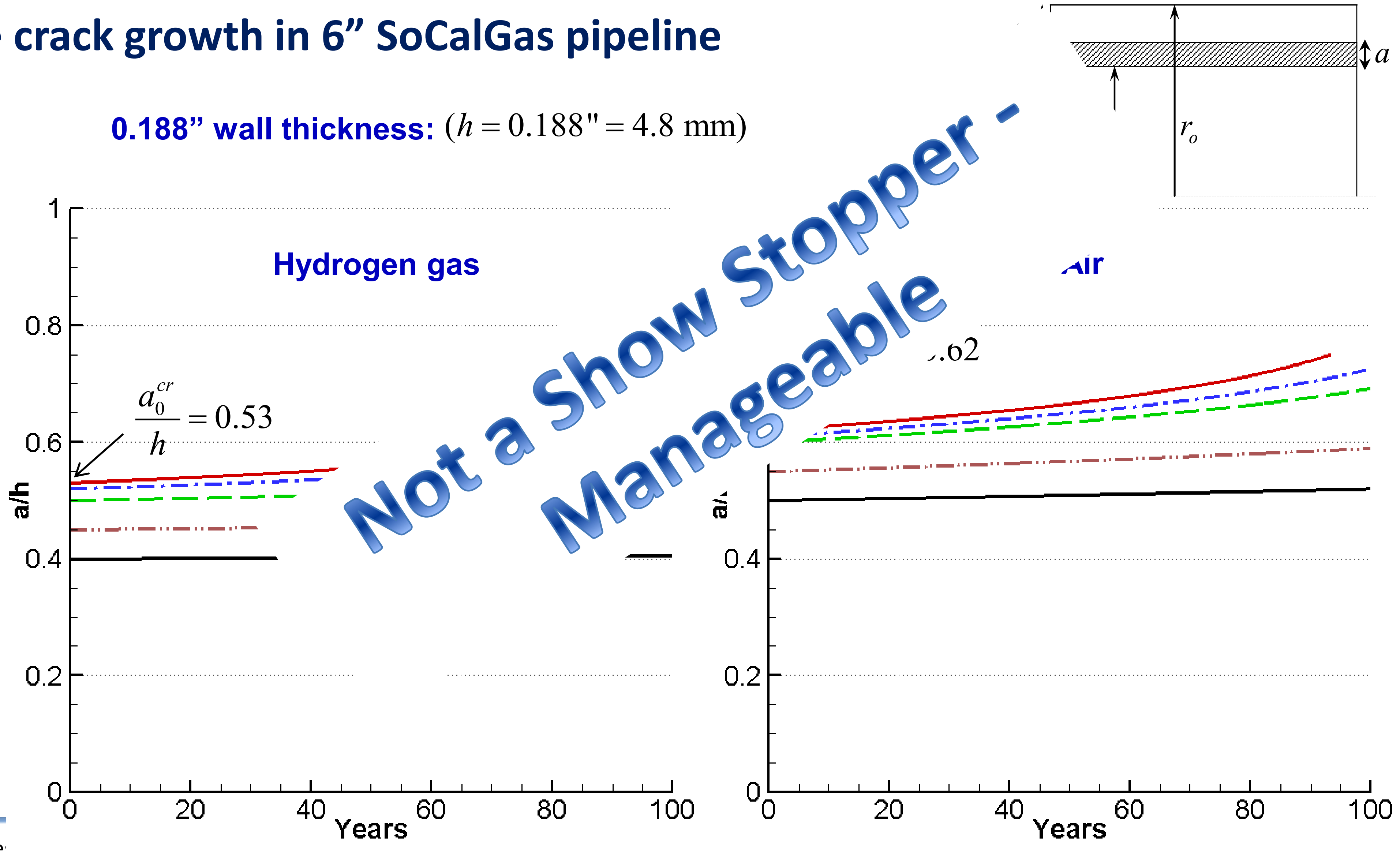
- H_2 and CH_4 leak rates are measured in unmodified low pressure gas infrastructure.
- Experiments show H_2 leaks at the same rate as CH_4 under these conditions.

Infrastructure Issue #4: Existing Pipeline Embrittlement

Simulation of H2 embrittlement and fatigue crack growth with UIUC

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

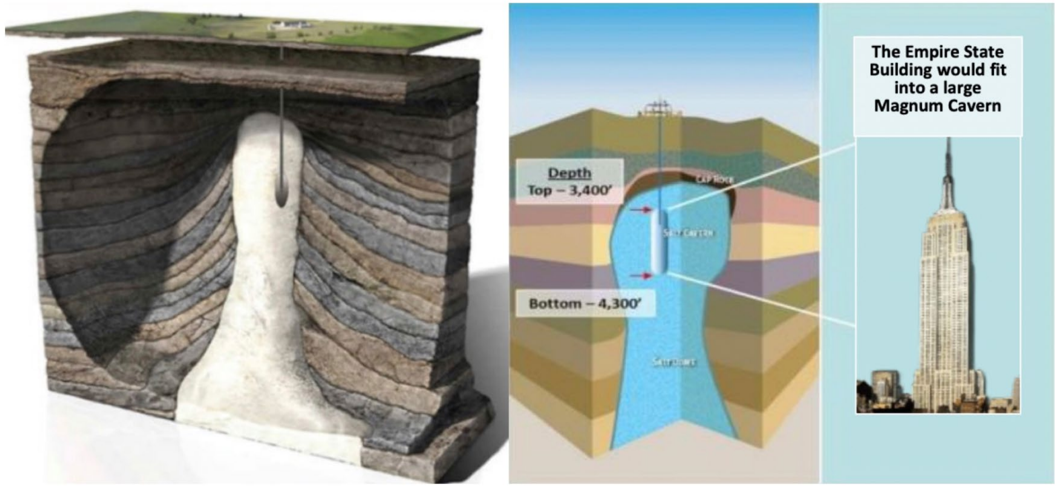
0.188" wall thickness: $(h = 0.188'' = 4.8 \text{ mm})$



Infrastructure Issue #5: Massive Storage Facility Transformation

Salt Caverns already widely used and proven

- 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

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

Do We Really Need Hydrogen Infrastructure?

Californi...

Absolutely Yes!

...uly 15, 2020

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