Feasibility of Hydrogen Fuel Cell Research Vessels

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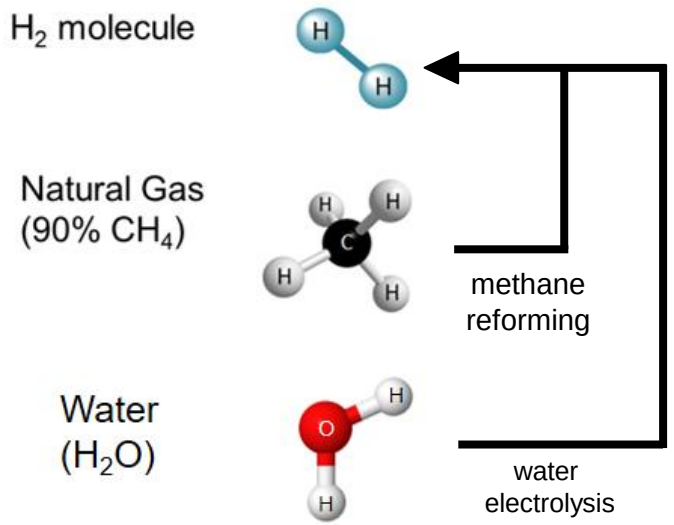
Hydrogen Properties:



- Is typically a gas, but can be a liquid (LH_2) if made very cold (20 K).
- LH_2 evaporates very fast (4,000 gallons will evaporate in ~6 seconds)
- More buoyant than helium. Goes straight up at ~40 mph.

Overall, H_2 is very similar to natural gas (which is ~ 90% methane, CH_4).

H_2 is NOT a Greenhouse Gas, unlike natural gas which is a potent GHG.

If spilled, LH_2 evaporates from the water leaving no residue.

H_2 can be ignited given an ignition source and the right H_2/air mixture.

Energetically, a kg of H_2 has about the same energy as a gallon of diesel fuel.

H_2 Has Been Delivered and Used for Decades

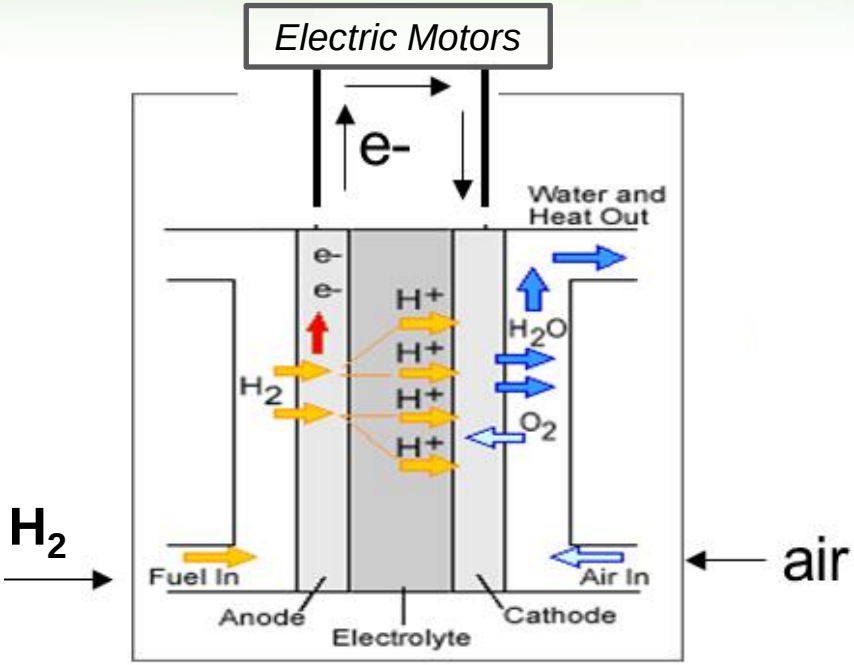
LH_2 Refueling Trailer, Emeryville CA

A typical LH_2 trailer can deliver 4000 kg of hydrogen at a time.

350 bar H_2 Refueling Trailer, SFO

A typical high-pressure delivery trailer can deliver ~ 300 kg at a time.

When hydrogen is used in a *Fuel Cell* it produces ZERO pollution or greenhouse gas at point of use



Photos Courtesy Ryan Sookoo, Hydrogenics

$2\ H_2 + O_2 \rightarrow 2\ H_2O$

-- commercially available
-- more energy efficient than diesel generators
-- eliminates emissions at the point of use
-- eliminates fuel spills, greatly reduces noise
-- emissions can only arise from H_2 production/delivery
-- no "thermal runaway" possible (unlike batteries)

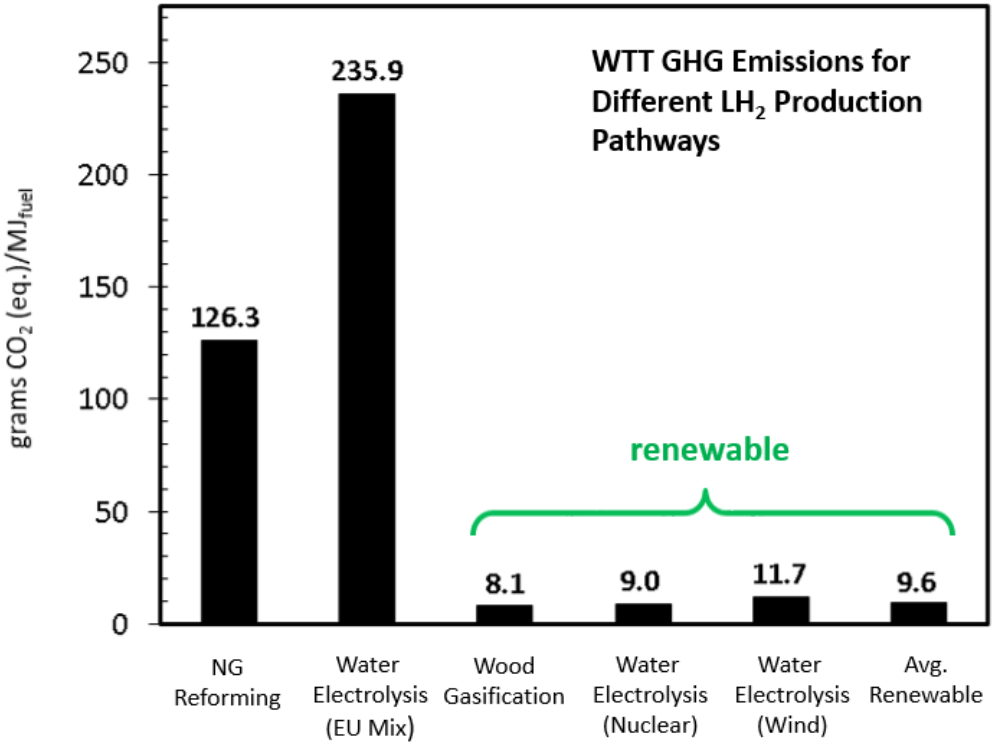
Going In:

H_2 and air

Going Out:

Electricity
Waste Heat
Warm humidified air

The GHG Reduction from Using H_2 technology REALLY depends on How the H_2 is Made



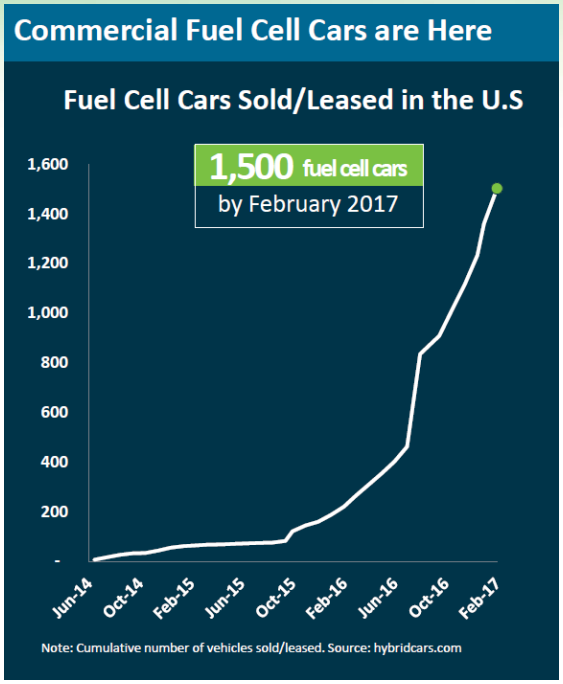
-- the equivalent GHG emissions (making & burning) for diesel fuel is 87.4 grams CO_2 (eq.)/MJ_{fuel}

-- the "criteria pollutant" (smog) emissions like NO_X, PM, HC is dramatically reduced with fuel cell technology, no matter how the hydrogen is made (not shown).

The GHG-reducing potential for H_2 fuel cell technology lies in using renewable hydrogen.

More information on the calculation of GHG emissions from H_2 fuel cell technology can be found it: L.E. Klebanoff , J.W. Pratt et al., Transportation Research D **54**, 250 (2017).

Hydrogen Technology is Here and Growing



Fuel Cell Electric Vehicles Can:

- ✓ Refuel in 5 minutes
- ✓ Have a 300 - 400 mile range (limited by H_2 storage)
- ✓ Only clean water vapor as the tailpipe emissions
- ✓ No need to plug in.

And it's not just fuel cell cars:

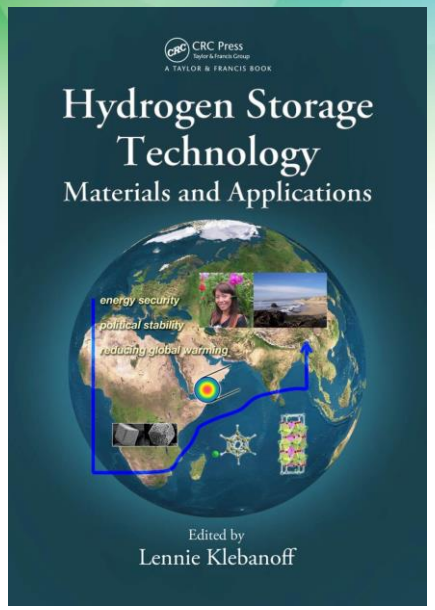
Fuel Cell Forklifts

Fuel Cell Buses

Fuel Cell Lighting

Open - Retail	47
Open - Legacy Retail	1
Currently Unavailable	3
In Construction	10
In Permitting	30
Proposed	15
TOTAL	**106**

H_2 Stations in CA
(CA Fuel Cell Partnership)



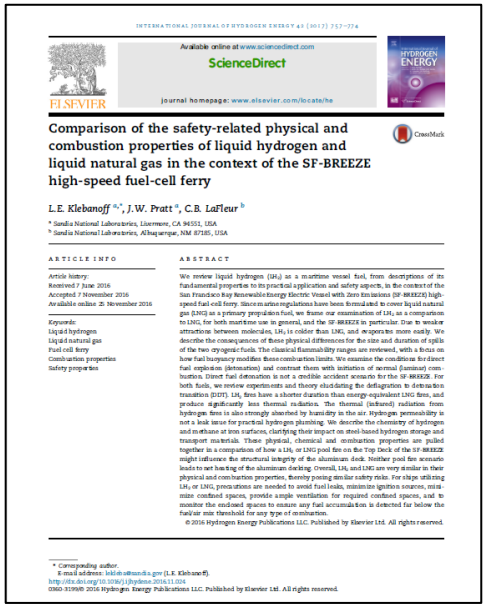
If you want to learn more about hydrogen technology…..

--published by CRC Press in 2012

Topics:

- Ways of storing hydrogen
- Hydrogen fuel cells and IC engines
- H_2 Storage Systems
- H_2 Codes and Standards

-- available on Amazon



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Comparison of the safety-related physical and combustion properties of liquid hydrogen and liquid natural gas in the context of the SF-BREEZE high-speed fuel-cell ferry

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ABSTRACT

We review liquid hydrogen (LH_2) as a maritime vessel fuel, from descriptions of its fundamental properties to its practical application and safety aspects, in the context of the San Francisco Bay Renewable Energy Electric Vessel with Zero Emissions (SF-BREEZE) high-speed fuel-cell ferry. Since maritime regulations have been formulated to cover liquid natural gas (LNG) as a primary propulsion fuel, we frame our examination of LH_2 as a comparison to LNG, for both maritime use in general, and the SF-BREEZE in particular. Due to weaker attractions between molecules, LH_2 is colder than LNG, and evaporates more easily. We describe the consequences of these physical differences for the size and duration of spills of the two cryogenic fuels. The classical flammability ranges are reviewed, with a focus on how fuel buoyancy modifies these combustion limits. We examine the conditions for direct fuel explosion (detonation) and contrast them with initiation of normal (laminar) combustion. Direct fuel detonation is not a credible accident scenario for the SF-BREEZE. For both fuels, we review experiments and theory elucidating the deflagration to detonation transition (DDT). LH_2 fires have a shorter duration than energy-equivalent LNG fires, and produce significantly less thermal radiation. The thermal (infrared) radiation from hydrogen fires is also strongly absorbed by humidity in the air. Hydrogen permeability is not a leak issue for practical hydrogen plumbing. We describe the chemistry of hydrogen and methane at iron surfaces, clarifying their impact on steel-based hydrogen storage and transport materials. These physical, chemical and combustion properties are pulled together in a comparison of how a LH_2 or LNG pool fire on the Top Deck of the SF-BREEZE might influence the structural integrity of the aluminum deck. Neither pool fire scenario leads to net heating of the aluminum decking. Overall, LH_2 and LNG are very similar in their physical and combustion properties, thereby posing similar safety risks. For ships utilizing LH_2 or LNG, precautions are needed to avoid fuel leaks, minimize ignition sources, minimize confined spaces, provide ample ventilation for required confined spaces, and to monitor the enclosed spaces to ensure any fuel accumulation is detected far below the fuel/air mix threshold for any type of combustion.

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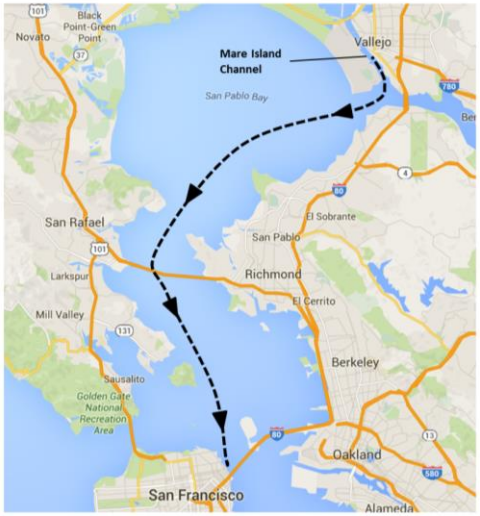
0360-3199/

More information about hydrogen gas (H_2) and liquid hydrogen (LH_2) can be found in:

L.E. Klebanoff et al., International Journal of Hydrogen Energy **42**, 757 (2017).

SF-BREEZE: The first study to show that H_2 fuel cells can be used in maritime propulsion, and how to do it.

High-speed H_2 Ferry



Route:
San Francisco to Vallejo, CA

	Ferry	Hydrogen Station
Technical	✓	✓
Regulatory	✓	✓
Economic	*Higher than conventional now, today's market acceptance to be determined*	

Work Funded by The U.S. Department of Transportation (DOT), Maritime Administration (MARAD) through MARAD's Maritime Environmental and Technical Assistance (META) program.

The SF-BREEZE Project Led to the Zero-V Hydrogen Fuel Cell Research Vessel

Overall Feasibility Question: Is it technically and economically possible to create a zero-emissions H_2 fuel cell research vessel that meets or exceeds the requirements of such vessels operating along U.S. coastlines?

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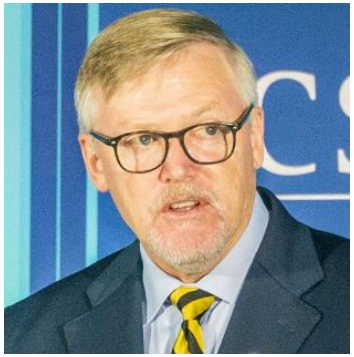
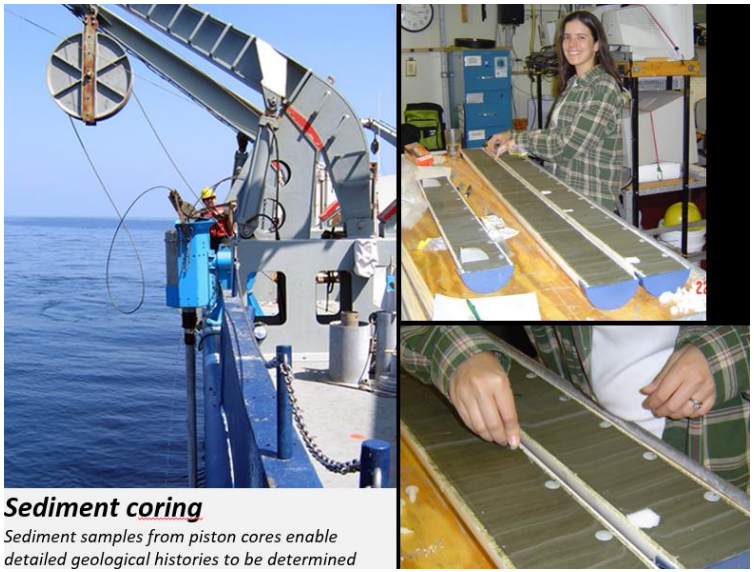


Zoltan Kelety Scripps Institution of Oceanography

Glosten Participants: (L-R) Ian McCauley, Sean Caughlan, Robin Madsen and Catherine Farish.

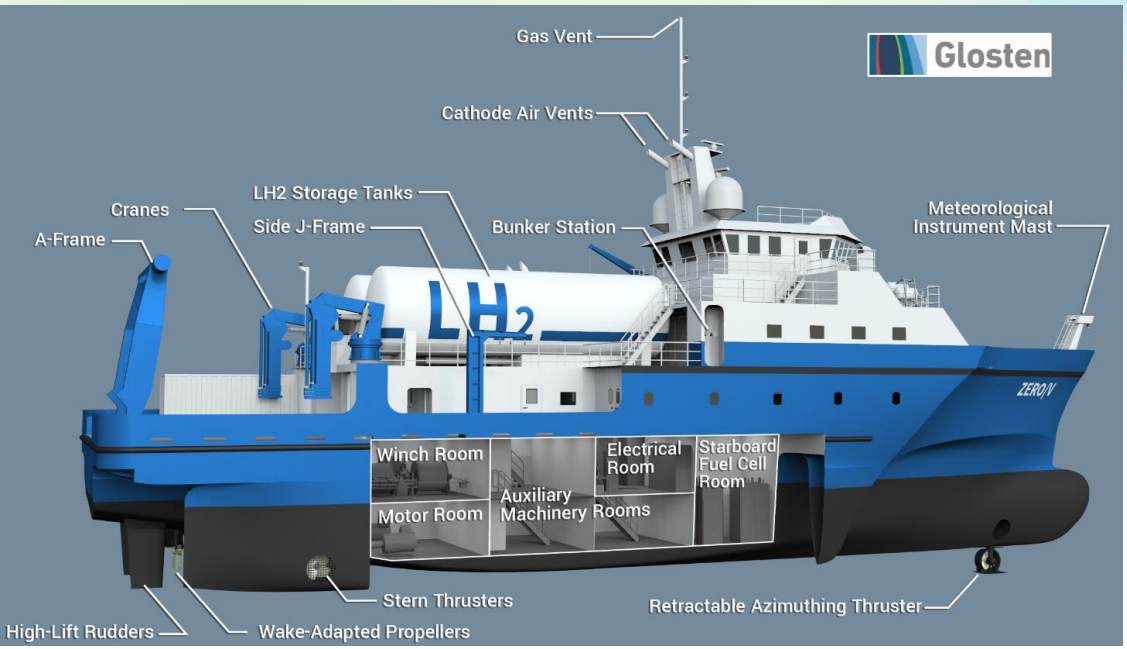
Scripps Missions Define the Zero-V Performance



The Zero-V has very different performance needs:

- Desired calm water speed: 10 knots (instead of 35 knots for the SF-BREEZE)
- Desired range: 2,400 nautical miles (instead of 100 nm for the SF-BREEZE)
- Endurance: 14 days (instead of 4 hours for the SF-BREEZE).

A zero-emission research vessel is feasible NOW using existing technology



- Oceanographic research vessel for coastal / regional operations
- Range: 2400 nm
- Speed: 10 knots
- 10,900 kg of LH_2
- Berths: 20 scientists
- Cost to Build: $80M
- Quiet
- No Fuel Spills, No engine emissions
- Feasible with today's technology
- Designed for California's educational and R&D needs

Work Funded by The U.S. Department of Transportation (DOT), Maritime Administration (MARAD) through MARAD's Maritime Environmental and Technical Assistance (META) program.

Scripps is seeking funding through federal sources because $80M is beyond their traditional State funding channels.

Final Zero-V Project Report: maritime.sandia.gov

What if H_2/Fuel Cells Provide Partial Vessel Power, in a Hybrid Arrangement? What Would That Look Like?

R/V Robert Gordon Sproul

The Scripps Institution of Oceanography (SIO) current coastal/local research vessel, the *R/V Robert Gordon Sproul,* is nearing the end of its service life and will soon require replacement. We compared three potential "variants" for an *R/V Sproul* replacement vessel (SRV): a Baseline SRV consisting of a traditional diesel-electric powertrain, a Battery Hybrid SRV (battery/diesel-electric) and a Hydrogen Hybrid SRV (hydrogen fuel cell/diesel-electric).

Hydrogen Hybrid Sproul Replacement Vessel

- Diesel engines supplemented with H_2/Fuel Cells
- LH_2 Storage: 733 kg
- Diesel Engines: ~ 1200 kW; Fuel Cells: ~ 800 kW
- Capital Cost: ~ $34M
- ~ 27% annual reduction in GHG emissions
- 75% of the Sproul Missions can be performed on H_2 alone.
- Much better performance than a Battery Hybrid

Work Funded by The U.S. Department of Transportation (DOT), Maritime Administration (MARAD) through MARAD's Maritime Environmental and Technical Assistance (META) program.

July 23, 2021: Scripps Announces $35M in Funding of the Hydrogen Hybrid by the State of California

Bruce Appelgate, Scripps Institution of Oceanography, at Press Conference

"Our vision is to build an uncompromising, fully capable oceanographic research vessel that can be powered independently from fossil fuels, and be free from the criteria pollutants and greenhouse gas emissions that diesel-powered ships emit," said Bruce Appelgate, associate director and head of ship operations at Scripps Oceanography. "In doing so, we hope to both serve our scientists and students while being a world leader for transformational change to clean, nonpolluting shipboard power systems."

- ✓ Funding from the State of CA: $35M
- ✓ 3-Year Design/Build/Qualify Program
- ✓ Project to begin October 2021

Press Release: https://scripps.ucsd.edu/news/uc-san-diego-receives-35-million-state-funding-new-california-coastal-research-vessel

H_2 Vessel Feasibility Questions Encountered and Passed

- Will they float? ✓
- Can they go fast enough, up to 35 knots? ✓
- Can they carry a decent number of people (~150)? ✓
- Do they have sufficient range before needing refueling? ✓
- Can the hydrogen suppliers provide the needed LH_2 per day? ✓
- Can the hydrogen suppliers provide renewable LH_2? ✓
- Can they be refueled fast enough for commuter service ? ✓
- Would the technology be supported by CA Ports? ✓
- Are there deep cuts in well-to-waves (WTW) GHG emissions? ✓
- Are there deep cuts in WTW criteria pollutant emissions? ✓
- Can they satisfy regulatory requirements to gain an Approval in Principal? ✓
- Would the U.S. Coast Guard find any "show stopping" issues? ✓
- Would it be commercially attractive? **TBD**
- Can suitable refueling sites be found for these vessels? ✓
- Would there be support from local government (City Hall, others)? ✓

Thanks to all my friends and colleagues!

For more information on H_2/Fuel Cell Maritime Projects visit:
https://maritime.sandia.gov

- Past and current maritime projects
- Download reports

Thank You!

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