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Hydrogen and Fuel Cells for Maritime Applications: From Sandia Feasibility Studies to First Demonstrations

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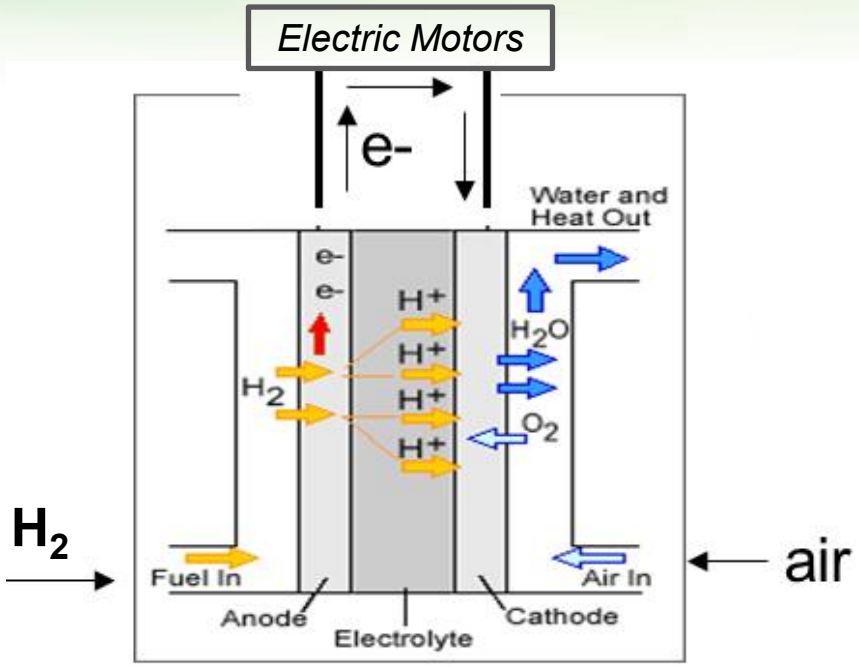
Sandia HQ:
Albuquerque NM

Livermore CA
(SF Bay Area)

- Sandia is the largest National Lab in the U.S.
  - U.S. Department of Energy (DOE) ~12,000 employees
  - ~ US $3.2B/yr from DOE, other federal agencies, and private industry
  - H_2 Program in Livermore, CA (SF Bay Area)
- Hydrogen program: 60+ years of work, in a wide range of areas (H_2 storage, production, delivery, development of regulations, market transformation), which we apply to enable impactful clean energy solutions
- Market Transformation: Zero Emission H_2/Fuel Cell Maritime Program:

H_2 Fuel Cells Produce ZERO Pollution or GHG at the 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

Going In:

H_2 and air

Going Out:

Electricity
Waste Heat
Warm humidified air

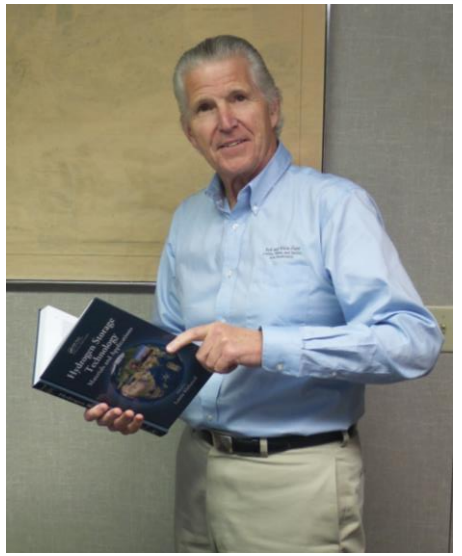
The Sandia Work on H_2 Vessels Originated with Tom Escher of the R&W Fleet

A forward-thinking maritime passenger transportation company offering sightseeing cruises, ferries and charter service in San Francisco.

The R&W Fleet is concerned about the effect of their vessels, and that of all maritime vessels, on the environment and on human health.

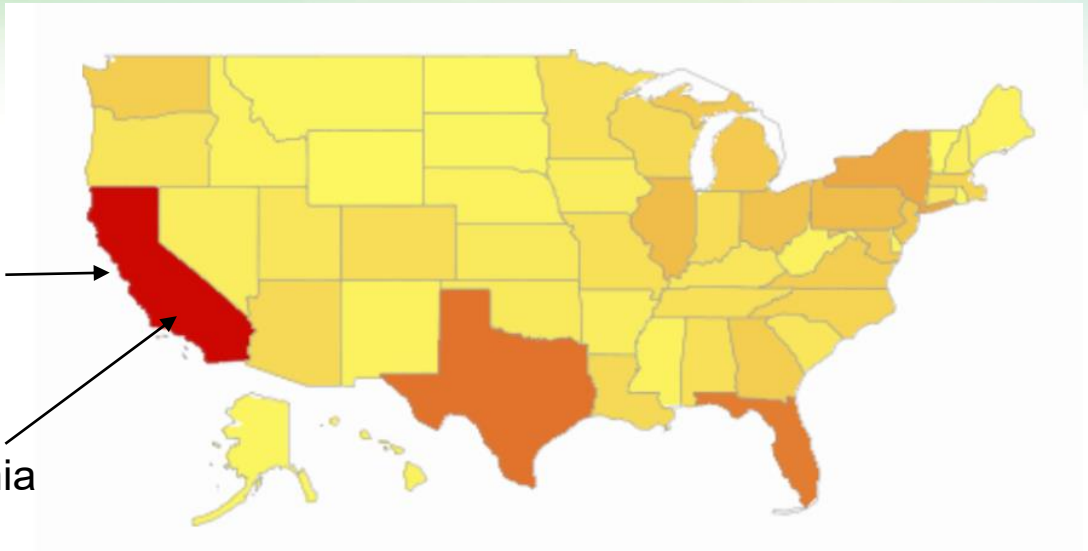
Tom approached Sandia with the question: Can H_2/fuel cell technology reduce vessel emissions to zero? What would be involved?

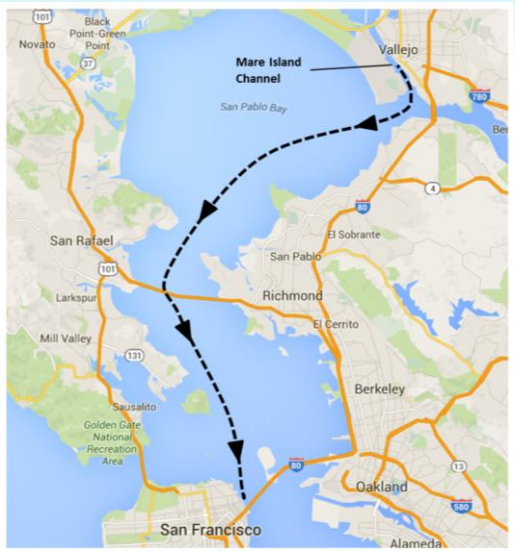
Our initial answer was:
We don't know, let's take a look at it!"



Tom Escher
President of R&W Fleet

(2016) SF-BREEZE: Can H_2 Fuel Cells can be Used to Propel Ships?





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

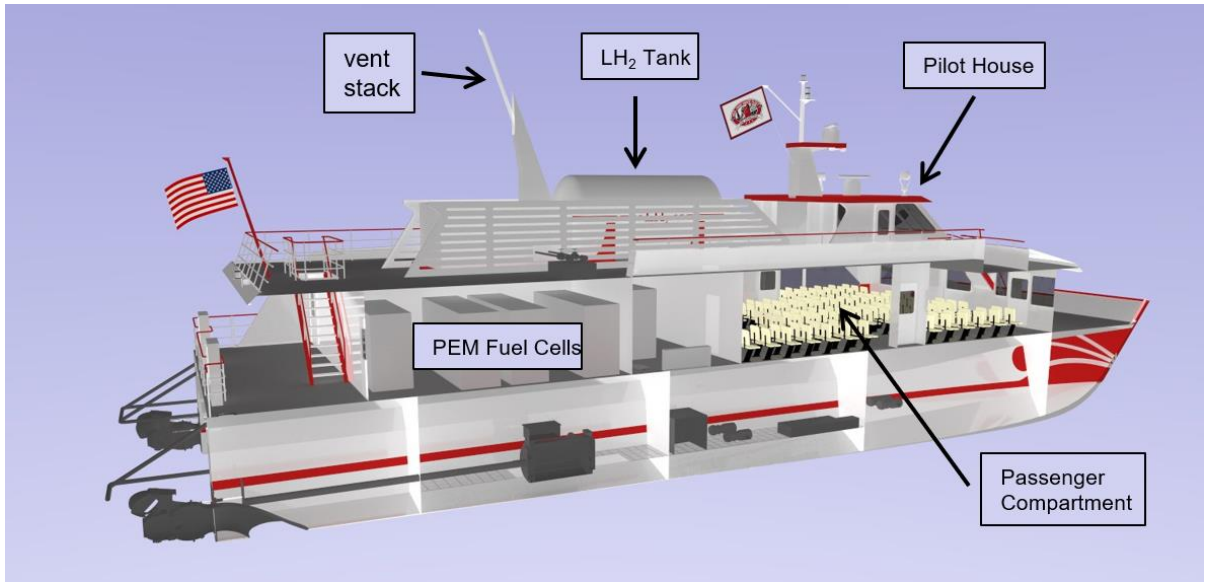
Route:
Vallejo to
San Francisco, CA (24 nm)

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

Elliott Bay Design Group

SF-BREEZE Feasibility Design

- Fuel: ~2,400 kg LH_2 per day
- Propulsion power 4.4 MW
  Total installed Power: 4.92 MW
- Passengers: 150
- Range: 100 nautical miles (NM).
- Service Speed: 35 knots
- Length 109’ x Beam 33’ x Depth 11.25’
  Full Load Draft ~ 4.6’



Status: SF-BREEZE vessel still a concept, but this work informed the design of the “Sea Change,” to be discussed.

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?

Gerd Petra Haugom (L) and Hans-Christian Wintervoll DNV GL

Lennie Klebanoff
Sandia National Laboratories

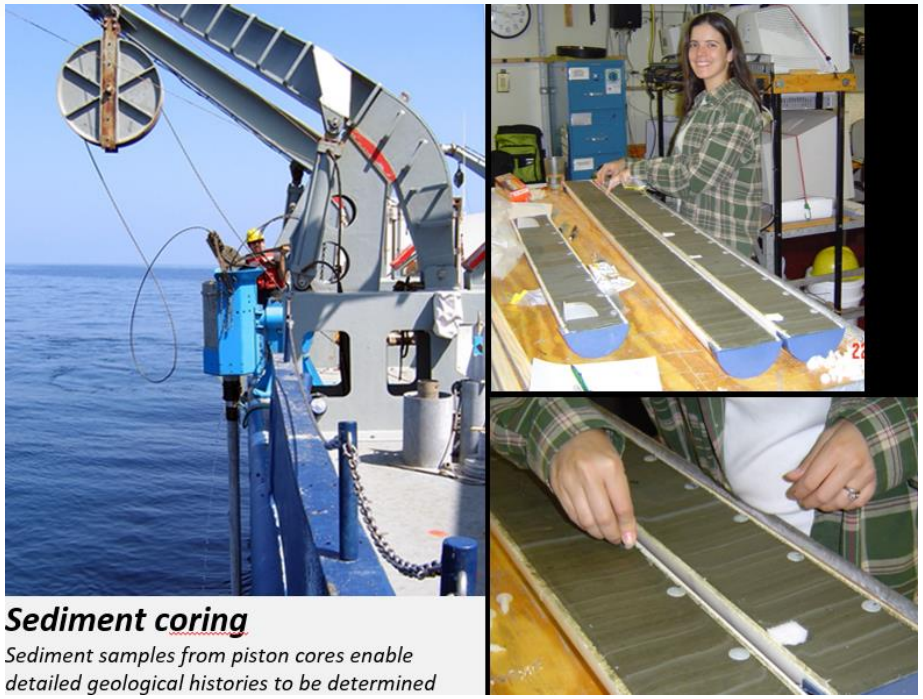
Bruce Appelgate
Scripps Institution of Oceanography

Zoltan Kelety
Scripps Institution of Oceanography

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

Scripps Missions Define the Zero-V Performance Targets

Unmanned underwater vehicles
After deployment, UUVs navigate underwater autonomously to conduct sampling, mapping, sensing and other missions



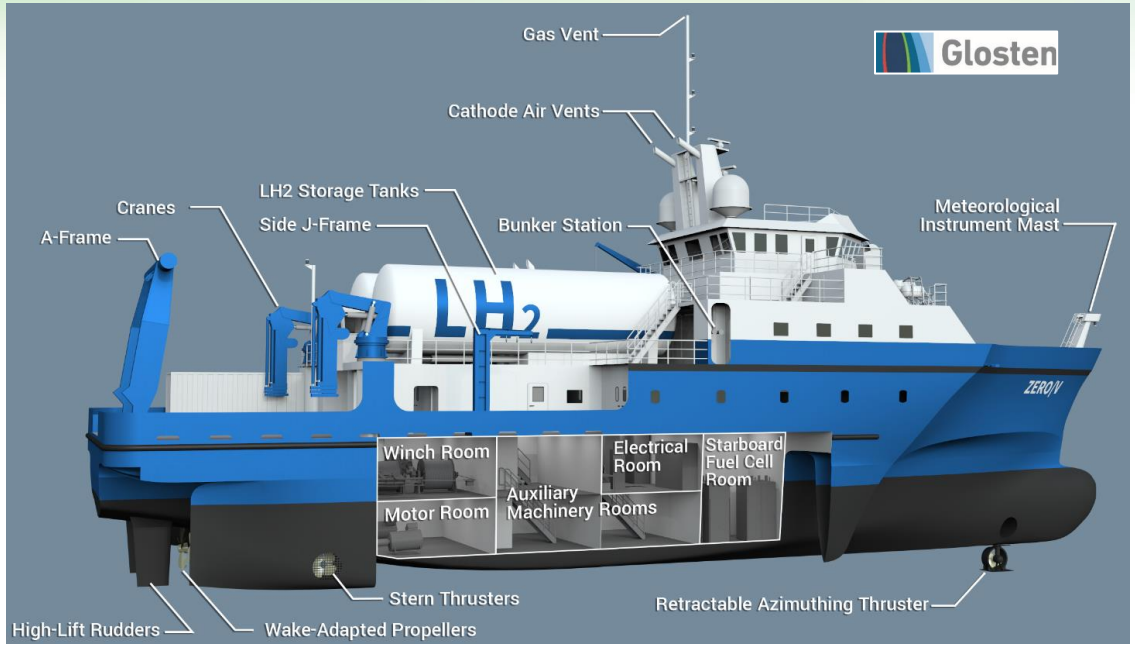
Sediment coring
Sediment samples from piston cores enable detailed geological histories to be determined

Surface mooring deployment
R/V Roger Revelle, Philippine Sea

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).

(2018) A Zero-emission Research Vessel is Feasible



- Coastal/regional oceanographic research vessel.
- 10,900 kg of consumable LH_2.
- 1.8 MW PEM fuel cell power.
- All-electric propulsion: **Quiet!**
- **FEASIBLE** with existing technology.
- Outstanding scientific capabilities.
- Advanced instrumentation.
- Designed for California's educational and R&D needs.

Work Funded by DOT/MARAD's META program.

Status: Zero-V still a concept vessel. Scripps is interested in raising money to build it. Funding TBD.

The zero-emission research vessel (Zero-V) concept vessel has a range of 2,400 nm, speed of 10 knots, with berths for up to 20 scientists. Anticipated cost to build: $80 M.

(2020) What if H_2/Fuel Cells Provide Partial Vessel Power, in a Hybrid Arrangement? What Would That Look Like?

R/V Robert Gordon Sproul

Hydrogen Hybrid Sproul Replacement Vessel

Scripp's 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).

- 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.

Status: H_2 Hybrid Vessel served as the basis for a proposal to the State of CA for funding, which was successful, to be discussed.

Work Funded by DOT/MARAD's META Program.

Comparing the H_2 Hybrid to its Battery Equivalent

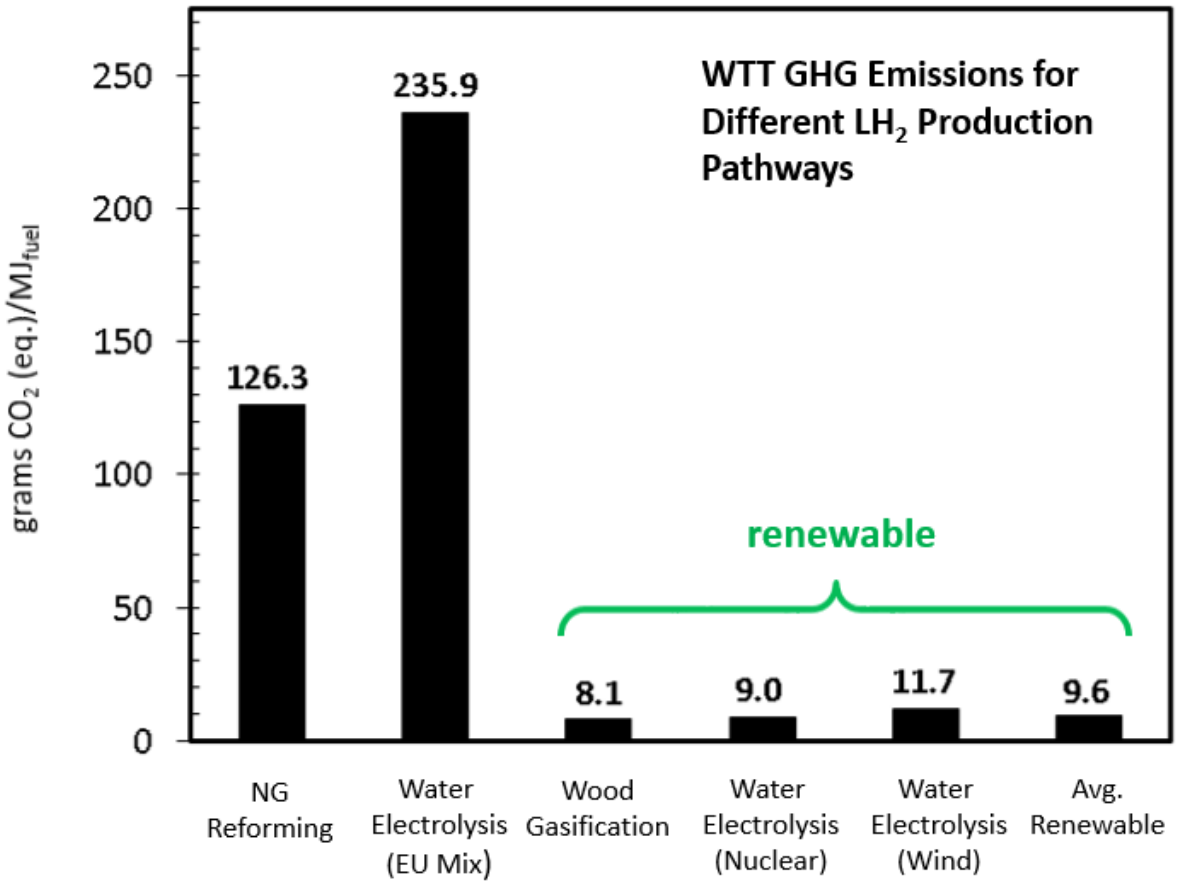
Cruise Speed	Zero Emissions Range (NM)	
	Battery Hybrid	Hydrogen Hybrid
9 knots	37	330
10 knots	25	234

Compared to Li-ion batteries, the H_2 Hybrid offers:

- ✓ 9x better zero-emission range & endurance
- ✓ Commensurate reductions in NOx, HC, PM and GHGs
- ✓ Better suited for ocean-going ships with long missions

These advantages are due to the increased volumetric energy storage density of LH_2 and fuel cells compared to batteries

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

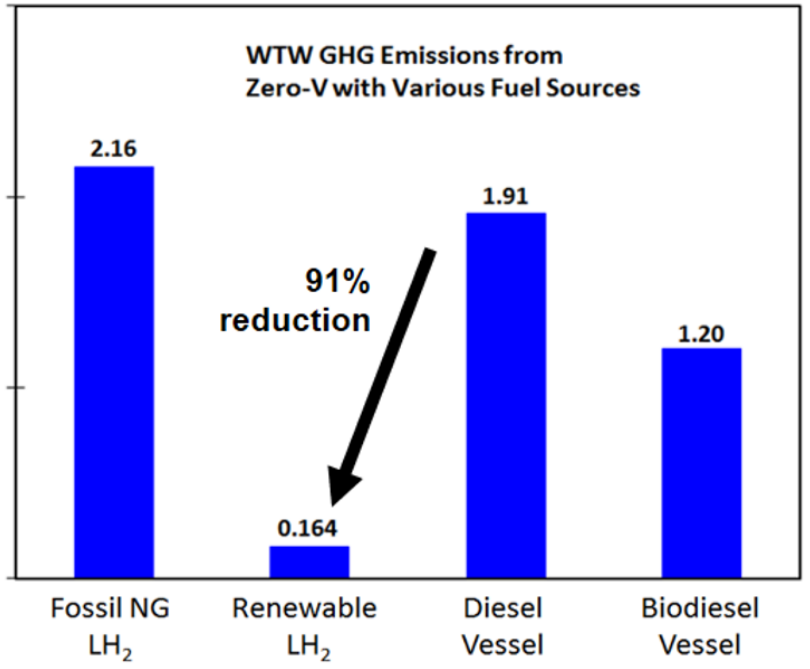


-- the equivalent GHG emissions for diesel fuel is 87.4 grams CO_2 (eq.)/MJ_{fuel}

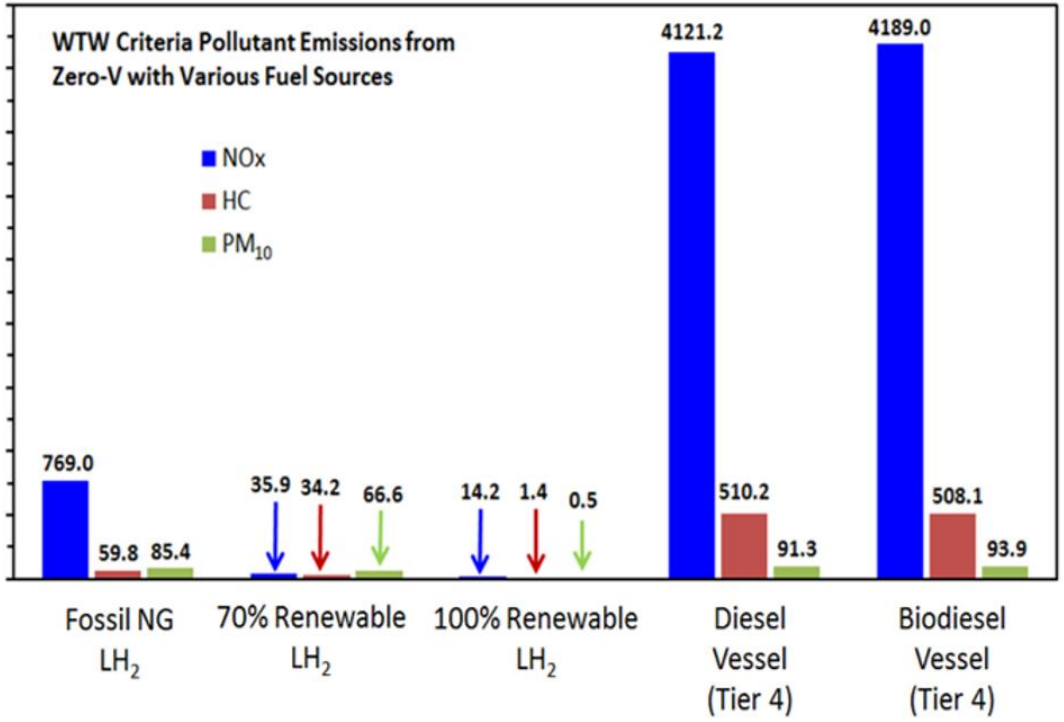
More information on the calculation of GHG emissions from H_2 fuel cell technology can be found in: L.E. Klebanoff , J.W. Pratt et al., Transportation Research D **54**, 250 (2017).

Well-to-Waves Emissions from the Zero-V (LH_2 fuel)

Well-to-Waves Greenhouse Gas Emissions (1,000 MT CO_2 equivalent / year)



Well-To-Waves Criteria Emissions (kg / year)

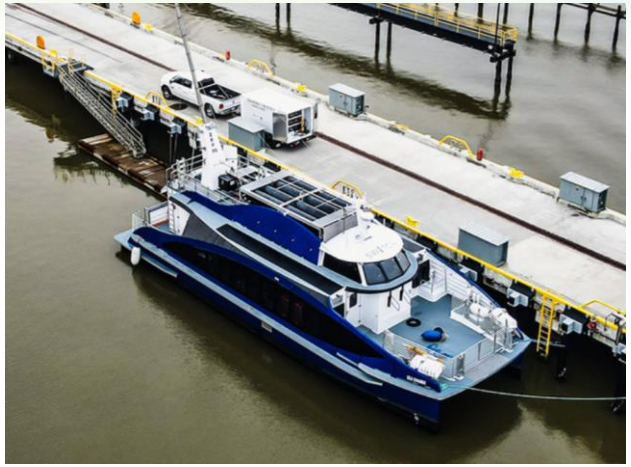


Note: Tier 4 specifies the most stringent regulations of the United States Environmental Protection Agency (EPA) on criteria pollutant emissions from diesel engines.

Using H_2 from any source, dramatic reductions in criteria pollutants below Tier 4 are provided. Using renewable hydrogen, a 91% reduction in CO_2 (eq.) emissions is obtained. Dramatic reductions are needed to survive growth in the fleet.

(2022) Sea Change: The World's First Commercial H_2 Ferry!

Out of the shipyard…..



First H_2 fueling…..

On the water!….

SWITCH

ZERO EMISSION INDUSTRIES

Funding & Administration
CALIFORNIA AIR RESOURCES BOARD
BAY AREA AIR QUALITY MANAGEMENT DISTRICT
This project is supported by the "California Climate Investments" (CCI) program

The first hydrogen fuel cell vessel in the U.S.

- Aluminum catamaran
- 70' long
- 84 passenger (reconfigurable)
- 22 knot top speed
- 242 kg of 250 bar H_2, up to 2 full days of operation
- 360 kW of H_2 PEM fuel cells
- Has passed USCG Sea Trials, will soon arrive in SF Bay

July 23, 2021: Scripps Announces $35M in Funding of the H_2 Hybrid by the State of California

Bruce Appelgate, Scripps Institution of Oceanography, at Press Conference

- ✓ Glosten is the Naval Architect
- ✓ Funding from the State of CA: $35M
- ✓ Funding from Office of Naval Research: $4M
- ✓ 5-Year Design/Build/Qualify Program
- ✓ Project began October 2021
- ✓ Currently in the Design Phase

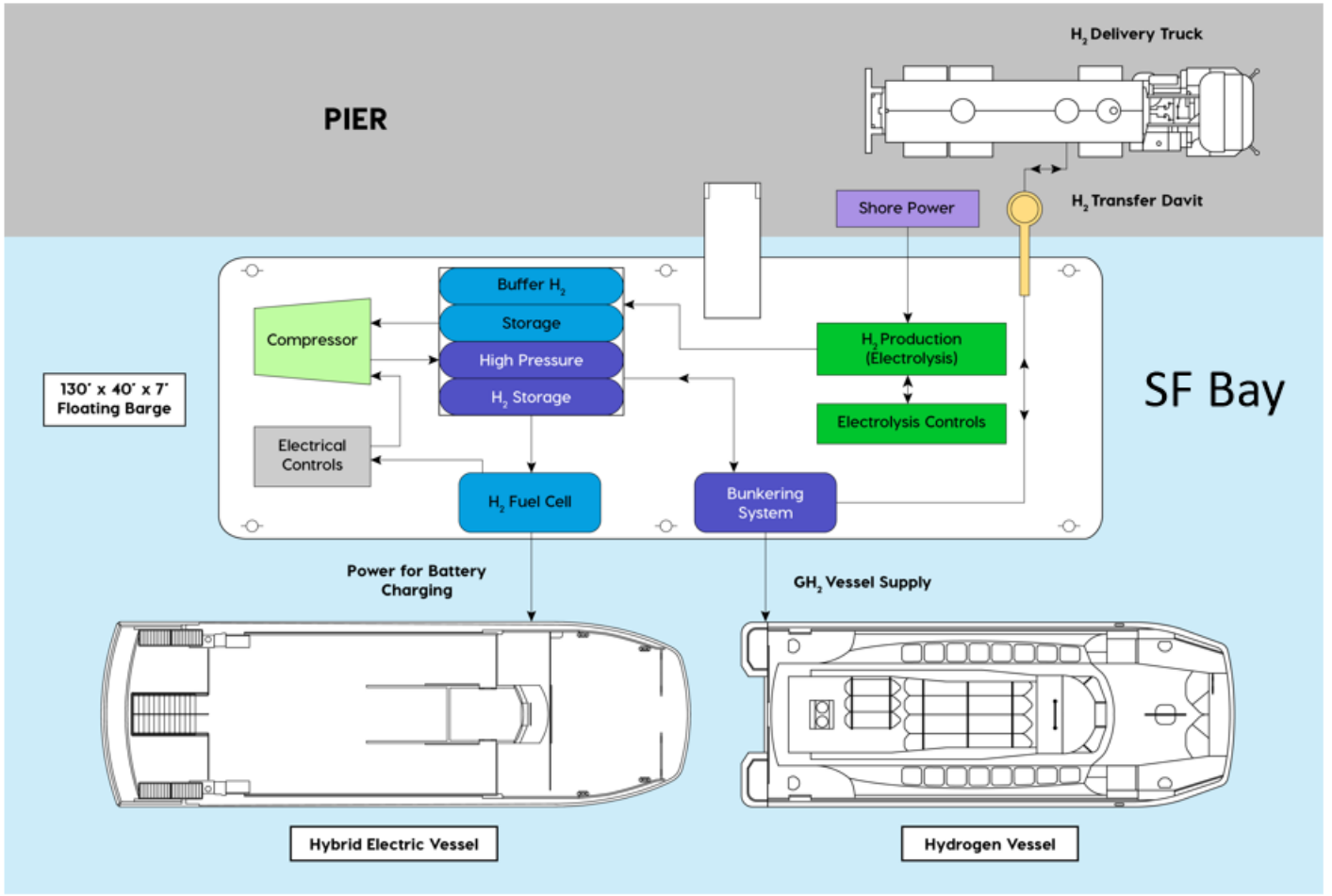
Coming in 2024: Floating Hydrogen Production Facility

The U.S. Department of Energy has funded a project to build a floating hydrogen production facility at the Port of San Francisco!

Key Objectives:

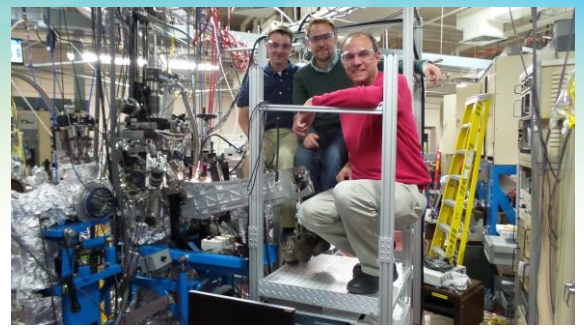
I. Demonstrate the feasibility and viability of H_2 production, storage and fueling in a maritime context.
II. Stimulate and develop a sustainable green hydrogen ecosystem in the San Francisco Bay Area.

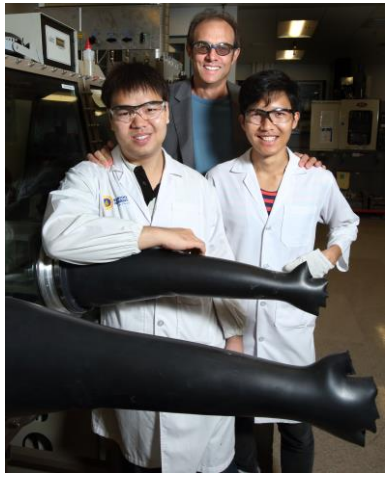
- ✓ Total ~ 500 kg/day renewable H_2 at 450 bar via renewable electrolysis.
- ✓ 200 kg/day dedicated to hydrogen maritime vessels
- ✓ 300 kg/day for land-based fuel cell applications (motive and stationary).
- ✓ First H_2 available 2024.

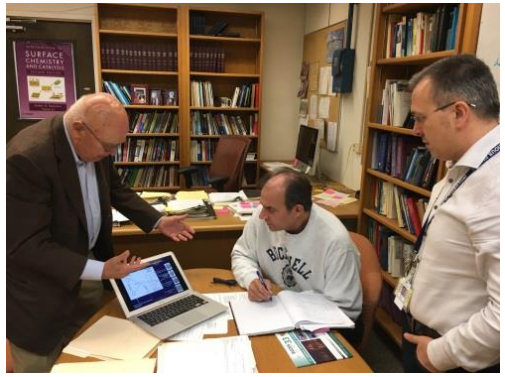


Summary: H_2 Vessel Feasibility Questions Encountered and Passed

- 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 2500 kg of 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 SF Bay Area 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!

Sujit Ghosh, MARAD (retired)

Bryan Vogel, MARAD

Pete Devlin, DOE

An *extra special* Thank You to Sujit Ghosh and Bryan Vogel of the US DOT / Maritime Administration (MARAD) and Pete Devlin of the US DOE for supporting our H_2/maritime work at Sandia.

I ❤ NORWAY!

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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