Update of the SF-BREEZE Feasibility Study With Emphasis on Emissions and Cost Findings

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Sandia National Laboratories

Interagency Working Group on Hydrogen and Fuel Cells

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Motivation for zero emission vessels

- *Only* way to reduce marine greenhouse gas (GHG) emissions. IMO* found:
  - Even the most significant *efficiency improvements do not* lead to a reduction in maritime GHG emissions.
  - *Different maritime fossil fuels* (HFO, MGO, or LNG) have small impact
- Eliminate pollutant emissions and fuel spills.
- Decrease noise from the vessel, health benefits for operators, better experience for the public, protects marine life from noise injury.
- Enable low-cost, multi-use hydrogen infrastructure for fuel-cell vehicles and vessels.
- Potential to grow shipbuilding capability through clean tech

*Third IMO GHG Study 2014

SF-BREEZE: San Francisco Bay Renewable Energy Electric vessel with Zero Emissions

High-speed H_2 Ferry

- Zero-emission Hydrogen Fuel Cell Power
- 150 passenger, 35 kts

Dockside H_2 Station

- Serving vessels, cars, buses and trucks
- 2,500 kg/day capacity

Feasibility Chart

	Ferry	Hydrogen Station
Technical	?	?
Regulatory	?	?
Economic	?	?

The SF-BREEZE project team includes designers, regulators, national experts, and class society

USCG MSC and Design and Eng. Stds.

USCG Sector San Francisco

USCG Liquid Gas Carrier NCOE

American Bureau of Shipping

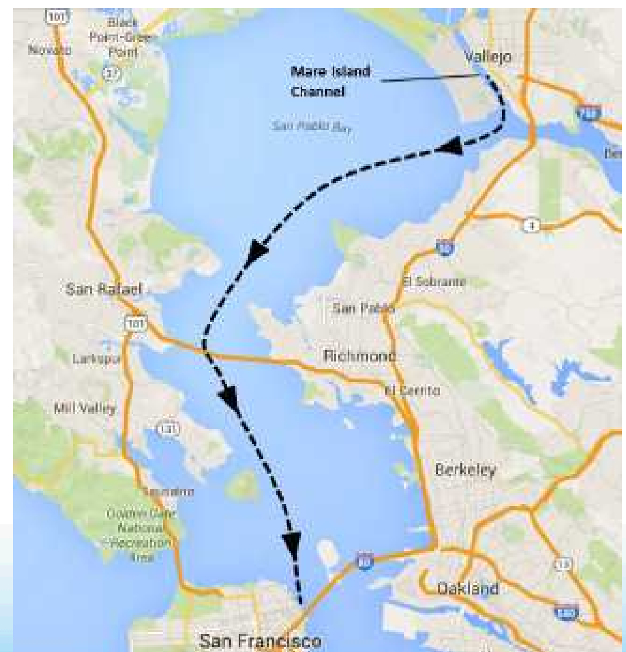
Notable zero emission vessels

- HDW/Siemens submarines
- *FCS Alsterwasser* (Lake Alster, Hamburg)
  - 100 passengers, 8 knots max
  - 96 kW, gaseous hydrogen fuel cell
  - Now usually operated on batteries due to H_2 fueling station closure
- *Nemo H_2* (Amsterdam canals)
  - 87 passengers, 4-6 knots
  - 60-70 kW, gaseous hydrogen fuel cell
  - Converted to batteries-only due to inability to site H_2 fueling station.
- *Ampere*
  - 360 passenger + 120 cars, 10-12 knots
  - 900 kW, battery, 10 min charge

SF-BREEZE Requirements

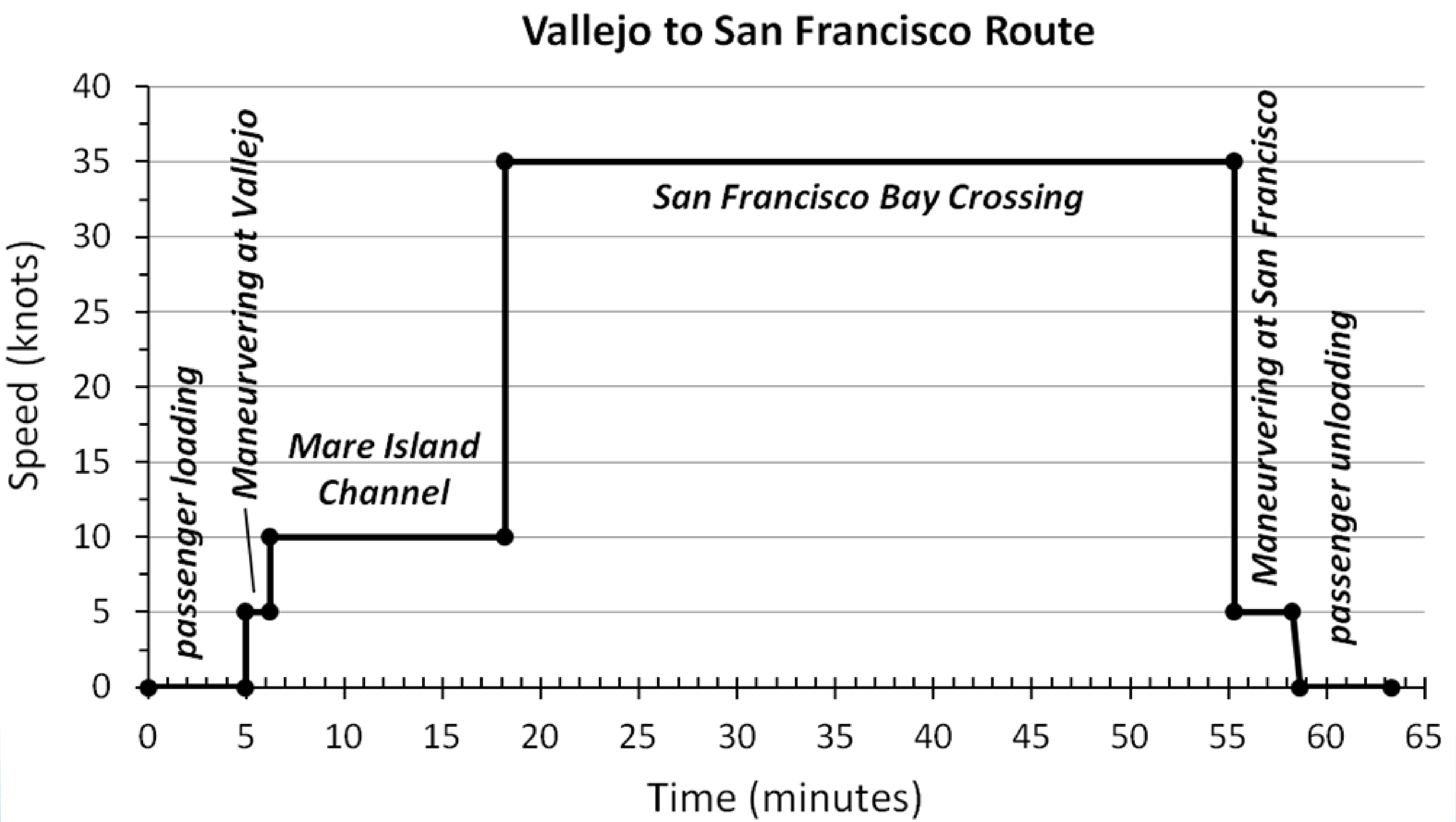
- High-speed commuter ferry in an ocean bay environment, NOT a low-speed tour boat on a lake
- Must be competitive with other modes of transportation (car, bus, train, other ferries)
- 35 kts top speed, 23 nm one-way
- Each round trip uses about 400 kg LH_2
- Daily logistics:
    1. Two morning round trips (~100 nm)
    2. Refuel in less than 1 hr at midday
    3. Two afternoon round trips (~100 nm)
    4. Refuel again at night

Current high-speed diesel ferry in SF Bay



SF-BREEZE route profile

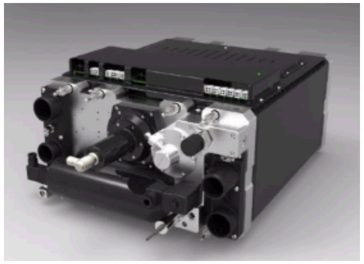
Route details



Potential Zero Emission Powerplants

Low temperature fuel cells

- Proton exchange membrane (PEM)
  - 50-100 °C
- Alkaline (AFC)
  - 50-200 °C
- Phosphoric Acid (PAFC)
  - 220 °C



High temperature fuel cells

- Molten Carbonate (MCFC)
  - 650 °C
- Solid Oxide (SOFC)
  - 500-1000 °C

Batteries

Zero Emission Engine Evaluation Summary

Power Plant (Engine)	Technically Viable for SF-Breeze	Commercial Product	Zero Emission
Diesel Combustion	✓	✓	✗
LNG / Natural Gas Combustion	✓	✓	✗
Combustion-Electric Hybrid	✓	✓	✗
Natural Gas Fuel Cell	✗	✓	✗
Hydrogen Fuel Cell			
• Solid Oxide	✗	✗	✓
• Molten Carbonate	✗	✗	✓
• Phosphoric Acid	✗	✓	✓
• Polymer Electrolyte (PEM)	✓	✓	✓
Battery Electric	✗	✓	✓

Types of Hydrogen Storage Systems

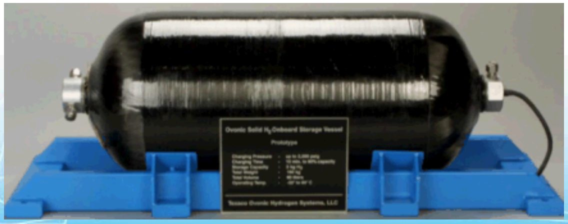
Gaseous tanks

~2,000 psi steel or aluminum

5,000-10,000 psi carbon fiber composite assemblies

Liquid hydrogen

Metal Hydride



Hydrogen Storage Methods for 1,000 kg of H_2

Storage method	Storage Tank Weight	Storage Tank Volume
Gas – standard 2,200 psi steel cylinder	228,000 lb	28,000 gal
Gas – 5,000 psi composite cylinder	39,500 lb	14,500 gal
Gas – 10,000 psi composite cylinder	52,700 lb	12,800 gal
Gas – Metal Hydride	139,000 lb	6,200 gal
Liquid - low pressure cryogen	19,100 lb	6,400 gal*

1,000 kg will allow the ferry to run approximately 2 round trips, or half a day
**total volume including insulated space – 1,000 kg of LH_2 is ~3,700 gallons)*

Weight is the most critical parameter for a high-speed ferry

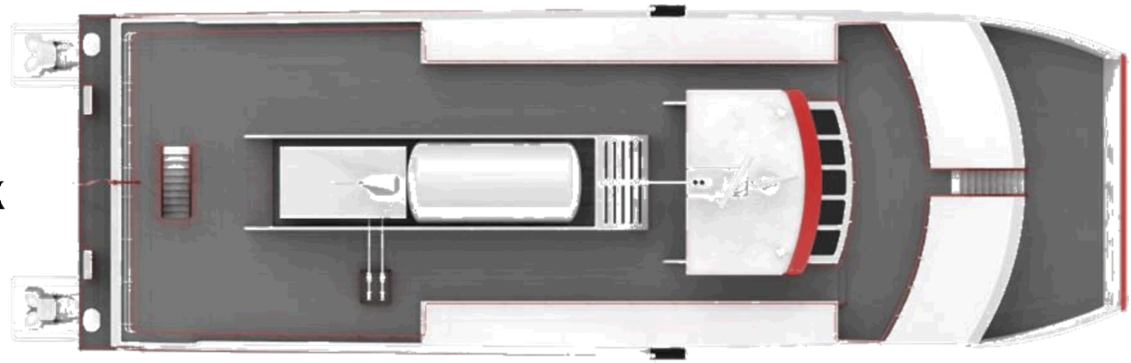
Vessel Design

Current Design

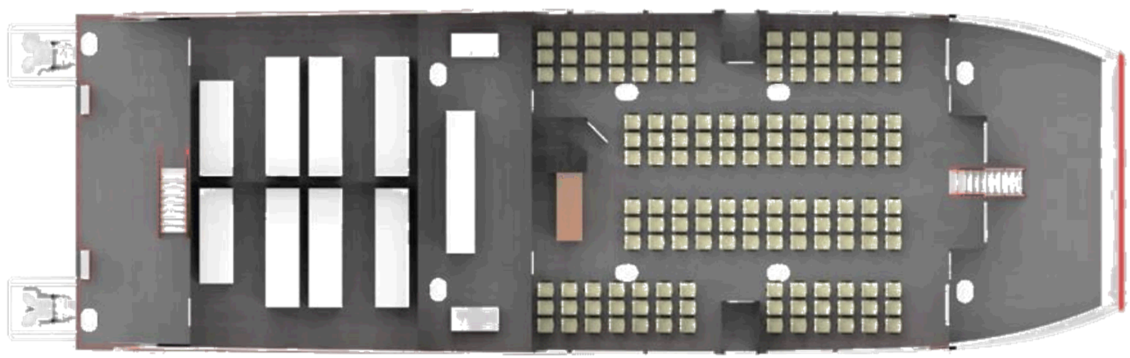
Design generated by Elliott Bay Design Group

Current Design

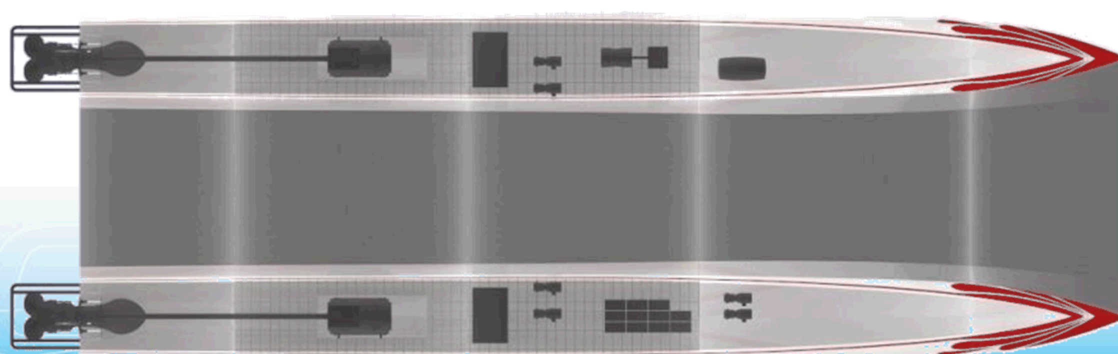
Upper Deck



Main Deck

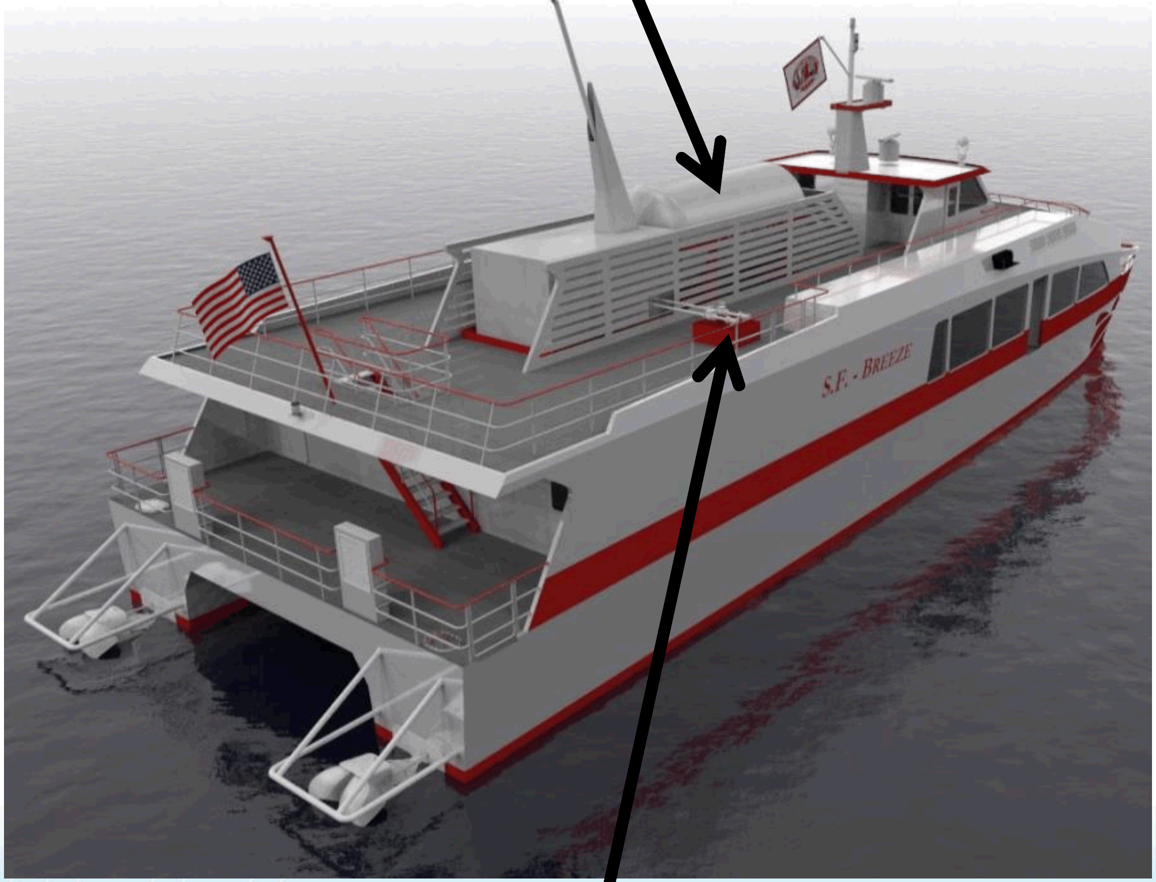


Hulls



Ferry Fueling Characteristics

1,200 kg (~4,800 gallons) LH_2 tank

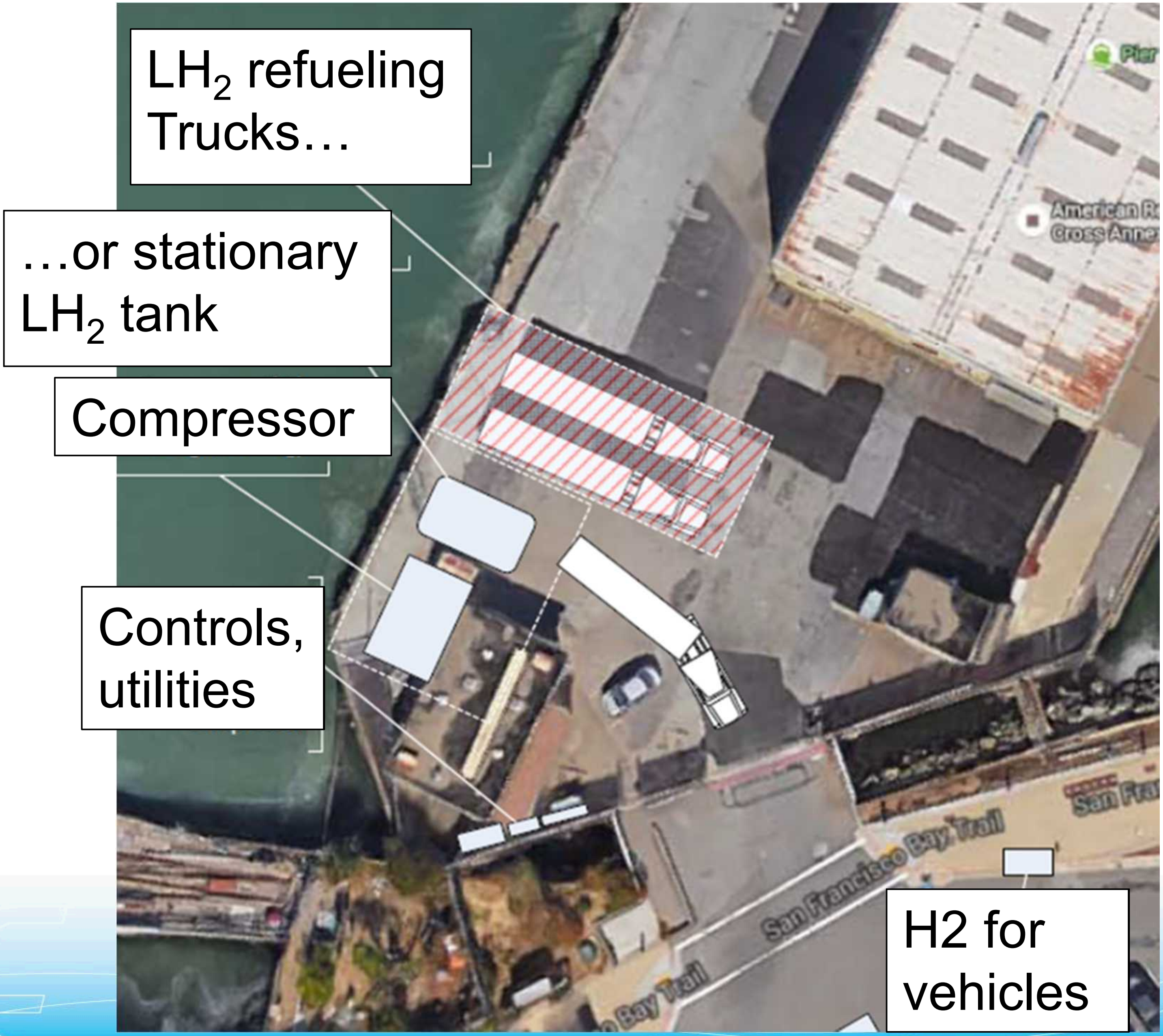


Bunkering connection

*The ferry uses **liquid** hydrogen because it is currently the lightest and most compact method to store hydrogen, and operates at low pressure*

The Port of San Francisco identified Pier 54 as a viable refueling location for both the vessel and FCEVs

A viable hydrogen fueling complex designed by Linde at the Port of San Francisco

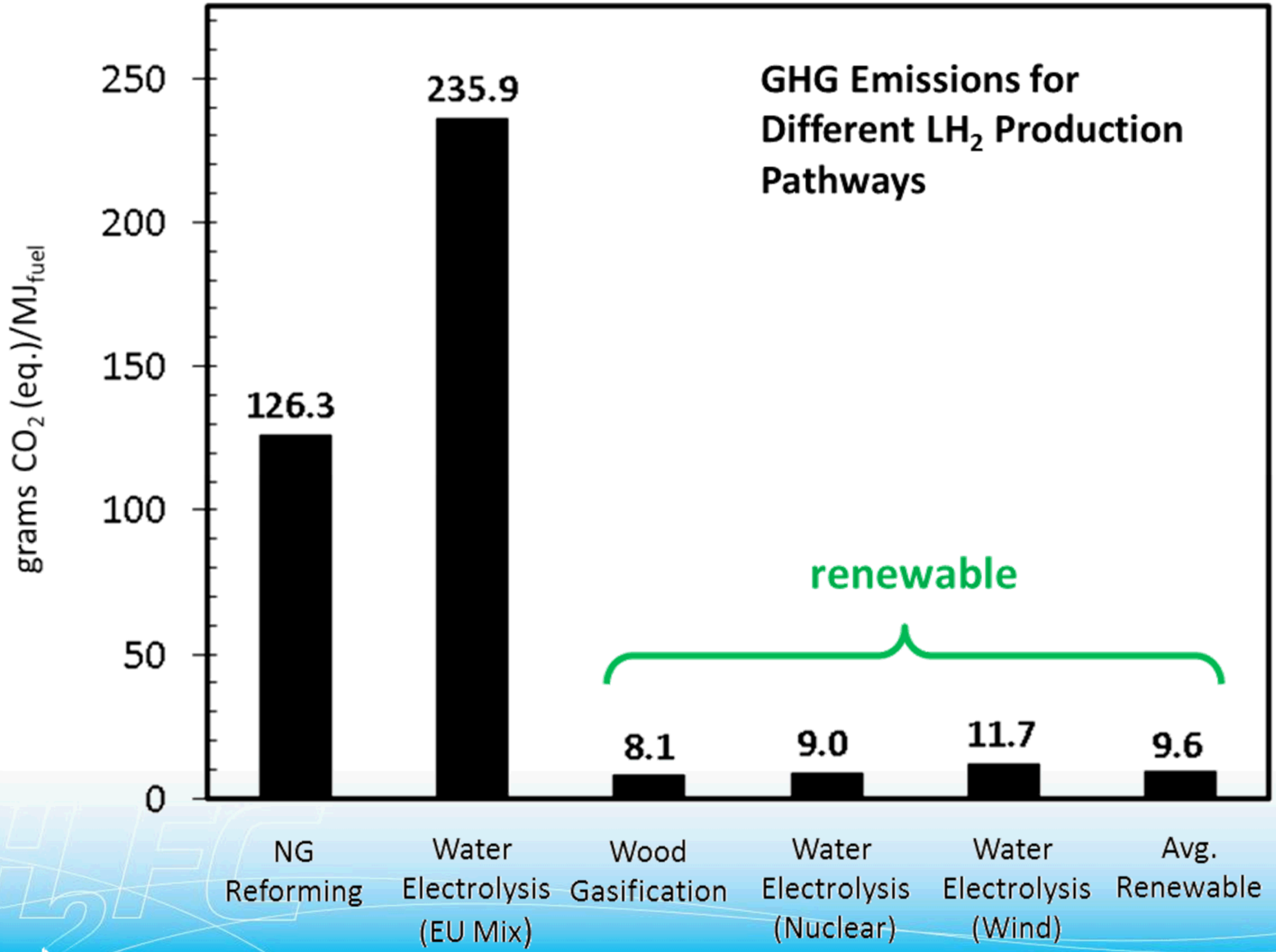


Overall emissions analysis is done with comparison to the existing, similar sized ferry on the same route

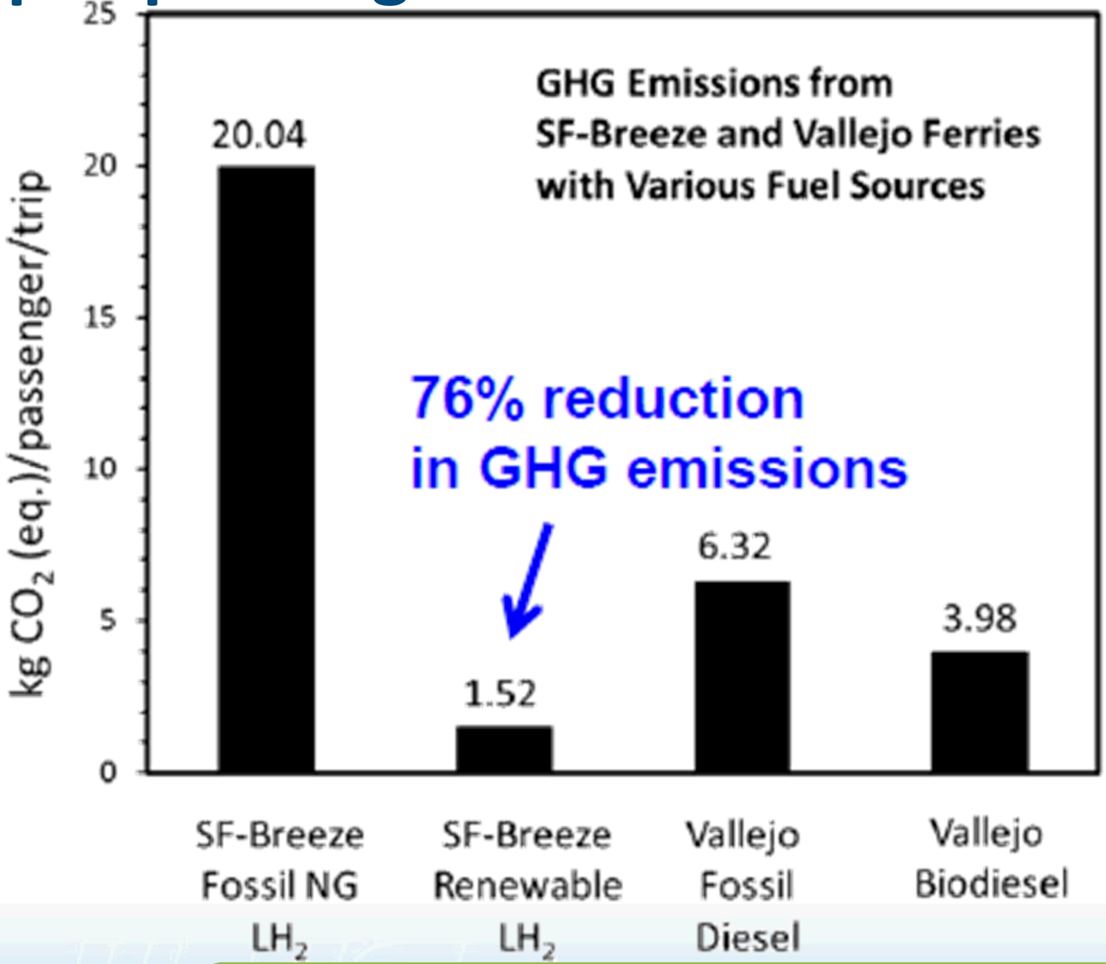
SF-BREEZE
Top Speed: 35 knots
Power Plant: PEM fuel cells
Fuel: Liquid Hydrogen
Passenger Capacity: 150

Vallejo
Top Speed: 35 knots
Power Plant: Diesel engine
Fuel: Ultra low sulfur diesel
Passenger Capacity: 300

Different ways of making liquid hydrogen have different GHG emissions



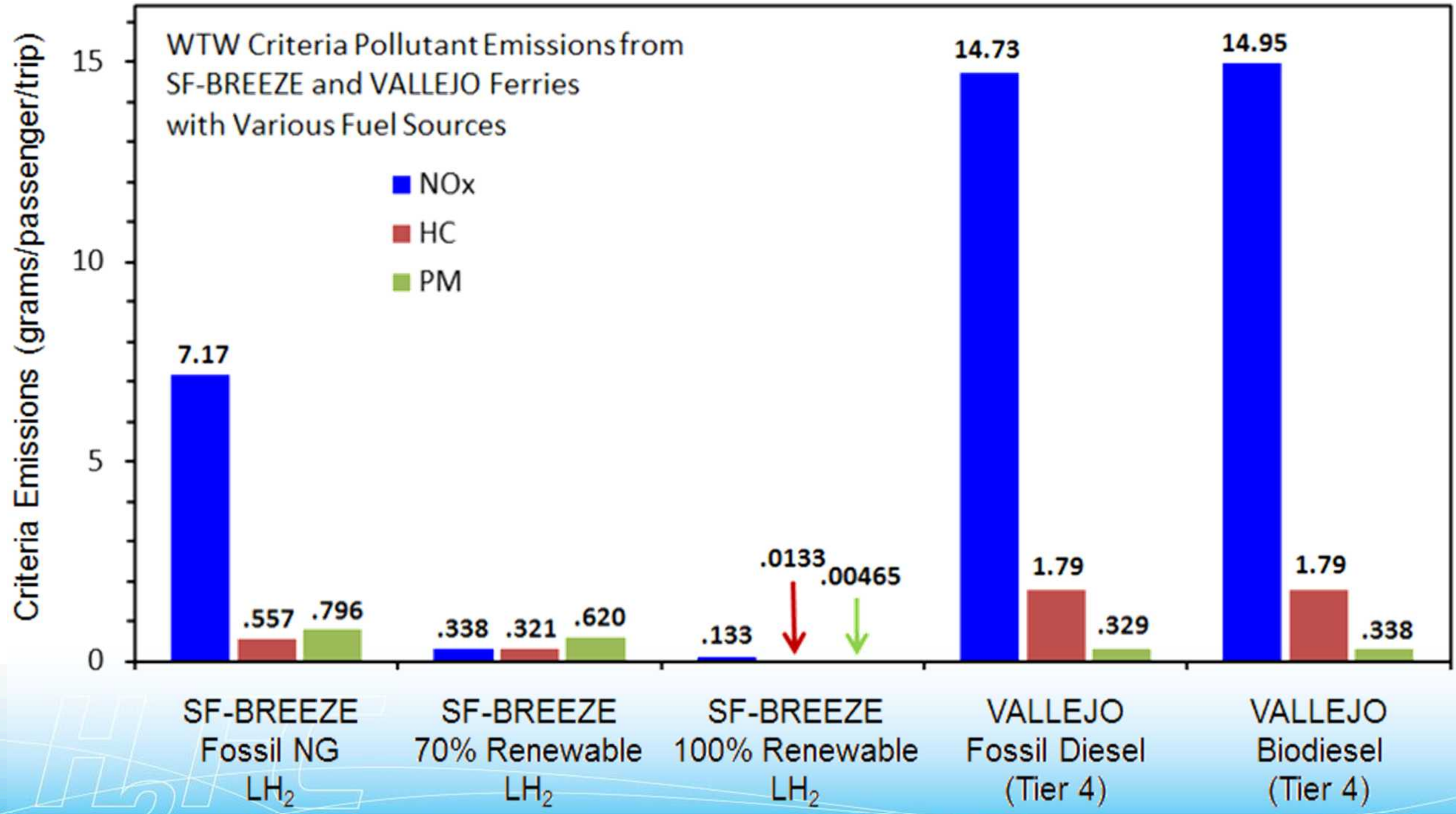
As designed, the SF-BREEZE can achieve dramatic per-passenger GHG emissions with *renewable* LH_2



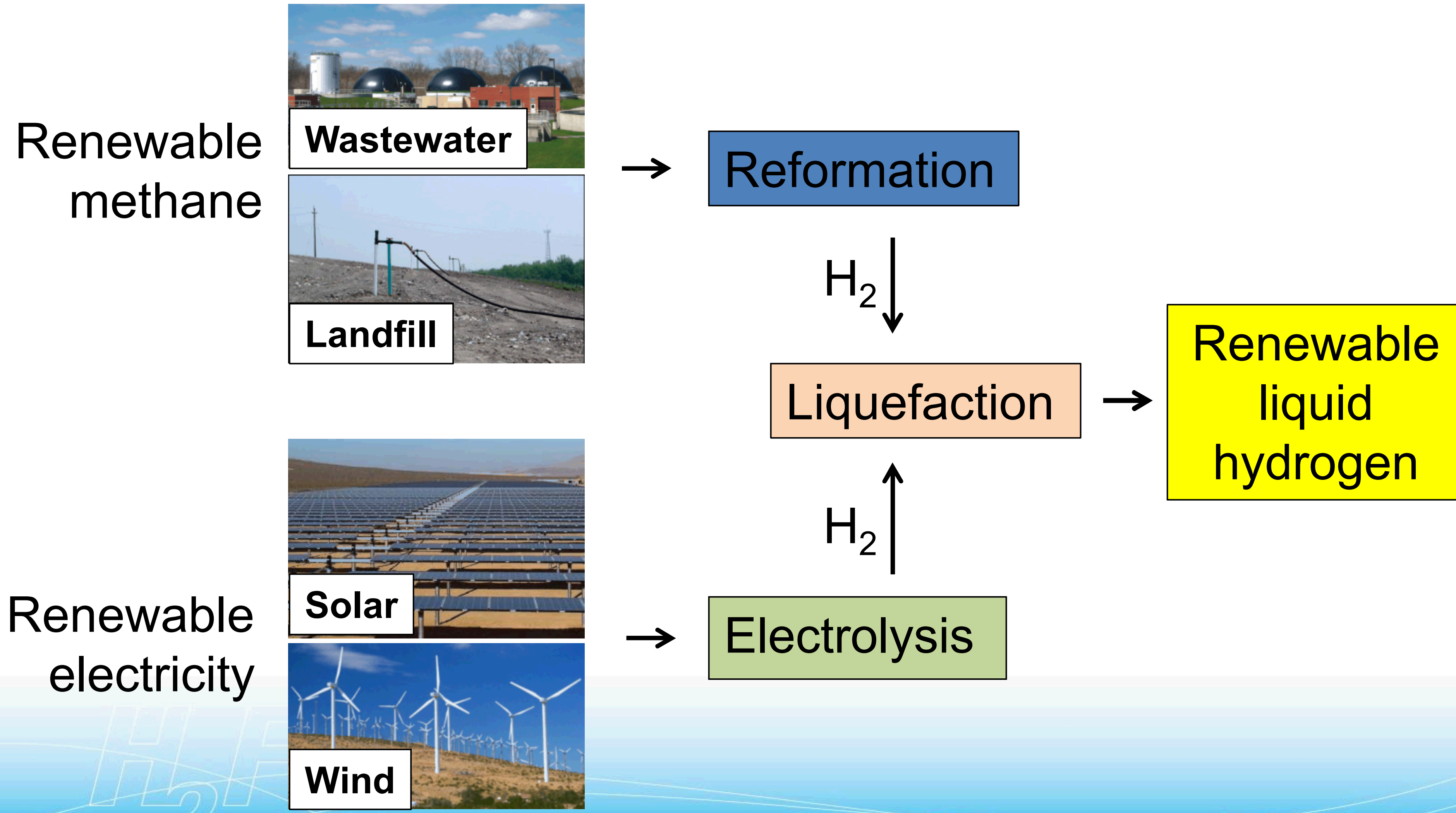
All SF-BREEZE emissions are due to the LH_2 production path; the SF-BREEZE is zero emission at the point of use

The SF-BREEZE also completely eliminates pollutant emissions (particulate matter, unburned hydrocarbons, and NOx)

The SF-BREEZE drastically reduces pollutant emissions compared to the most advanced (Tier 4) marine diesel ferries.



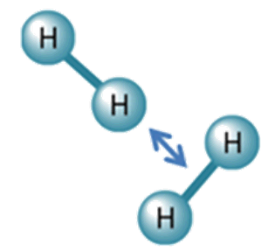
Renewable liquid hydrogen is available today

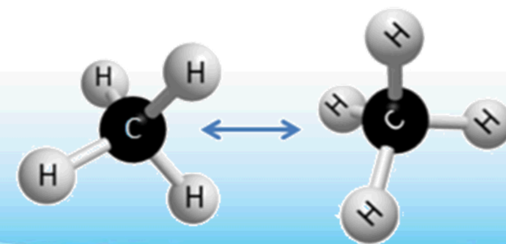


LNG and LH_2 are similar fuels, and maritime experience with LNG is opening the door for LH_2

Key similarities and differences:

- LH_2 and LNG vessels have very similar design philosophies: avoid fuel leaks, minimize ignition sources, minimize confined spaces, provide ample ventilation for confined spaces, and monitor the enclosed spaces.
- LH_2 and LNG are similar in their combustion properties, but LH_2 fires are shorter and produce less thermal radiation.
- LH_2 is colder than LNG.
  - LH_2 can condense and freeze oxygen and nitrogen
  - Because LH_2 evaporates more easily, it cools surfaces less than LNG.





Physical Properties of LH_2 and LNG

LH_2:

Liquid Normal Boiling Point = 20 K (-253 C).
Liquid Density = 71 g/L
Lower Heating Value = 120 MJ/kg

LNG (LCH_4):

Liquid Normal Boiling Point = 111 K (-162 C).
Liquid Density = 422 g/L
Lower Heating Value = 45 MJ/kg

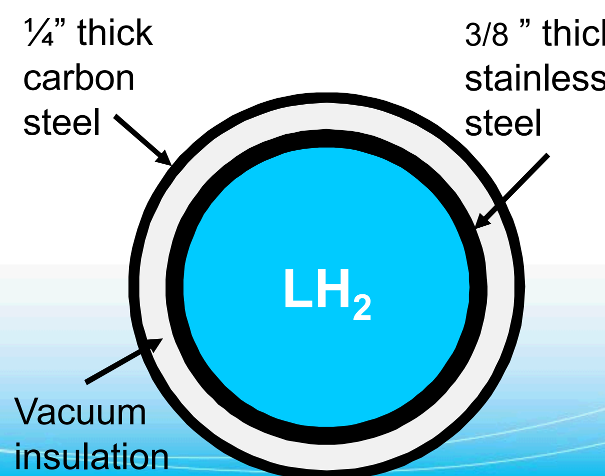
Both LH_2 and LNG are cryogenic fluids. For the same amount of stored energy, LH_2 has 0.38 times the mass of LNG, but has 2.4 times the volume.

They are stored in similar ways:

LH_2 Storage Tank on Trailer

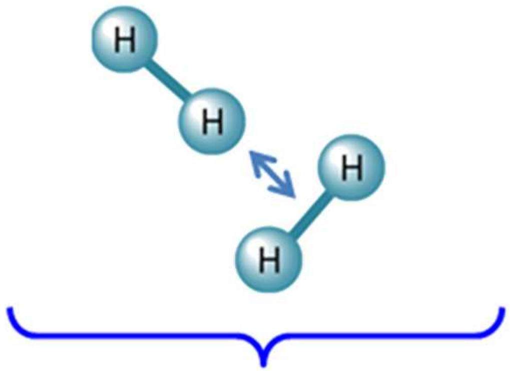
LNG Storage Tank on Trailer

SF-Breeze LH_2 Tank Design



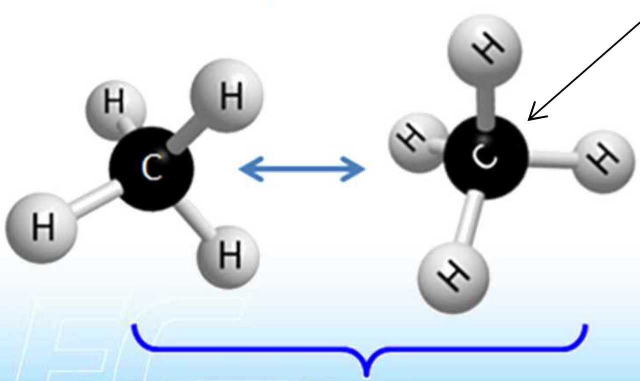
H_2 and CH_4 Molecules

LH_2:



H_2 molecules barely interact at all

LNG (CH_4):



CH_4 molecules interact a bit more

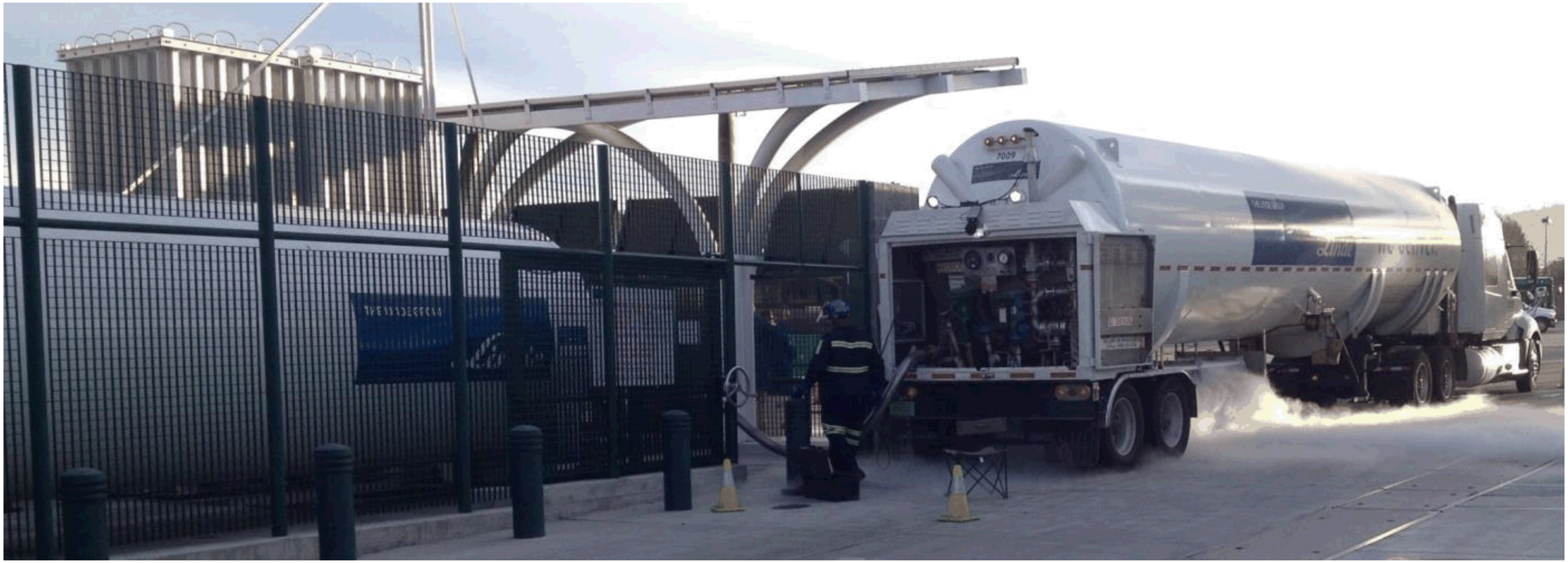
Assume NG is the same as methane (CH_4). Typically, 92% of NG is methane.

The C in CH_4 makes methane
much heavier than H_2

80% of the atoms in methane are H atoms.

If you make H_2 from CH_4, the C comes out as CO_2

LH_2 has been safely used for decades



LH_2 tanks are double walled vacuum insulated stainless steel tanks with steel shell.

A typical trailer can deliver 4000 kg (~15,000 gallons) at a time.

Economic case parallels that of fuel cell vehicles: Not currently at cost parity (but there are customers) and projected cost decreases ahead.

	SF-BREEZE (as designed)			Conventional Diesel	
	Low	High	Future	Low	High
Capital cost	$21,990,000	$29,220,000	$17,166,000	$8,000,000	$15,200,000
Yearly Powerplant O&M	$1,081,000	$1,796,000	$375,200	$226,650	$480,480
5-year non-renewable fuel	$9.7M	$15.6M	Higher	$3.90M	
5-year 100% renewable fuel	$16.7M	$48.7M	Lower	N/A	N/A
Fueling infrastructure	$970,000	$1,595,000	Lower	$1,500	$338,000

A lifetime societal economic benefit due to decreased health risks and environmental impact is between **$2.6M - $11M** for each SF-BREEZE ferry built instead of a Tier 4 diesel ferry.

Delivered Fuel Cost Estimate Details

Type of LH_2	Low	High
Natural gas, marginal renewable content	\$5.43/kg	\$7.40/kg
33% renewable content	\$5.68/kg	\$8.14/kg
100% renewable biogas and electricity	\$8.68/kg	\$21.58/kg

- Conventional (SMR) LH_2 estimates from two IGCs at nominal 1,600 kg/day with annual usage factors, five year agreement
  - \$6.35/kg and \$7.40/kg (no minimum)
  - \$5.90/kg if guaranteed minimum ("take or pay")
- 33% renewable LH_2
  - One IGC estimated 10% increase over conventional (CA case)
  - Cost premium calculations (see below) find similar but slightly higher result
- 100% renewable LH2 estimates not available from IGCs (too new)
  - Calculated feedstock cost premium assuming 100% biogas instead of natural gas
  - Calculated electricity cost premium for 100% renewable power
- Low Carbon Fuel Standard (LCFS) Credits in CA: \$0.50-\$2.50/kg

Consulted IGCs: Air Liquide, Air Products, Linde, Praxair

Would customers pay this much for zero emission fuel cell technology?

- Capital cost: 2-3 times higher
- Fuel cost: 2-3 times higher

They already are:

Toyota Camry (gasoline engine)
MSRP: ~$25,000
Fuel price: $2.80/gallon

Toyota Mirai (H_2 Fuel Cell)
MSRP: $57,500
Fuel price: $10-$14/kg*

Is cost parity necessary? What is the necessary price?

*only half the hydrogen is needed for the same range because a fuel cell is ~2-times more efficient than a gasoline engine

SF-BREEZE Cost Reduction Strategies

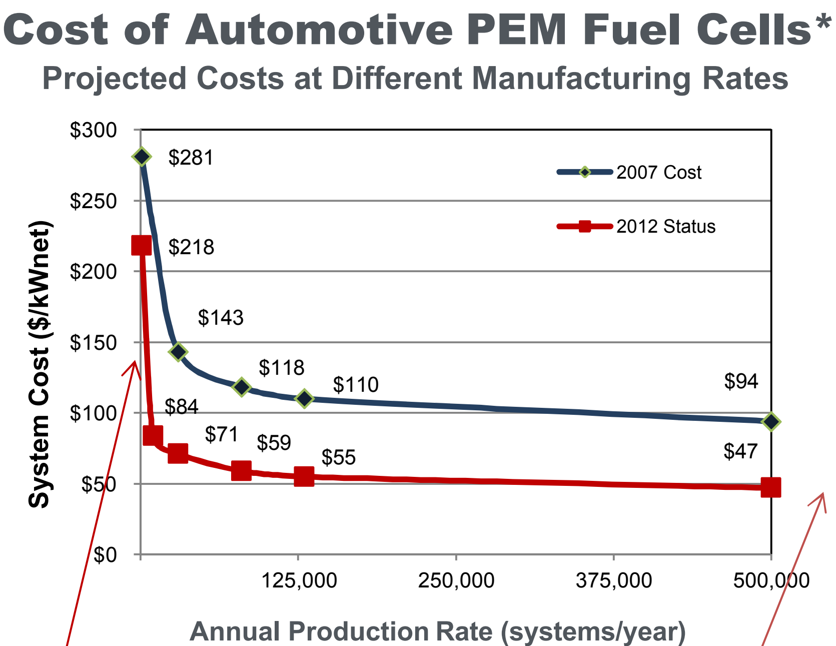
Today

- Design changes and performance specification optimization to increase per-passenger energy efficiency (*project started, funded by MARAD*)
- Initial use of non-renewable LH_2, if done in conjunction with above to ensure per-passenger GHG emissions below comparable diesel
- Federal, state, and local grants for building the SF-BREEZE and its hydrogen station

Future

- Fuel cell cost reduction through the mass manufacturing associated with a mature fuel cell electric vehicle market

PEM fuel cell costs will come down as they are deployed in automobiles and elsewhere.



*Based on state-of-the-art lab scale technology projection to high-volume manufacturing (500,000 units/year).- Strategic Analysis

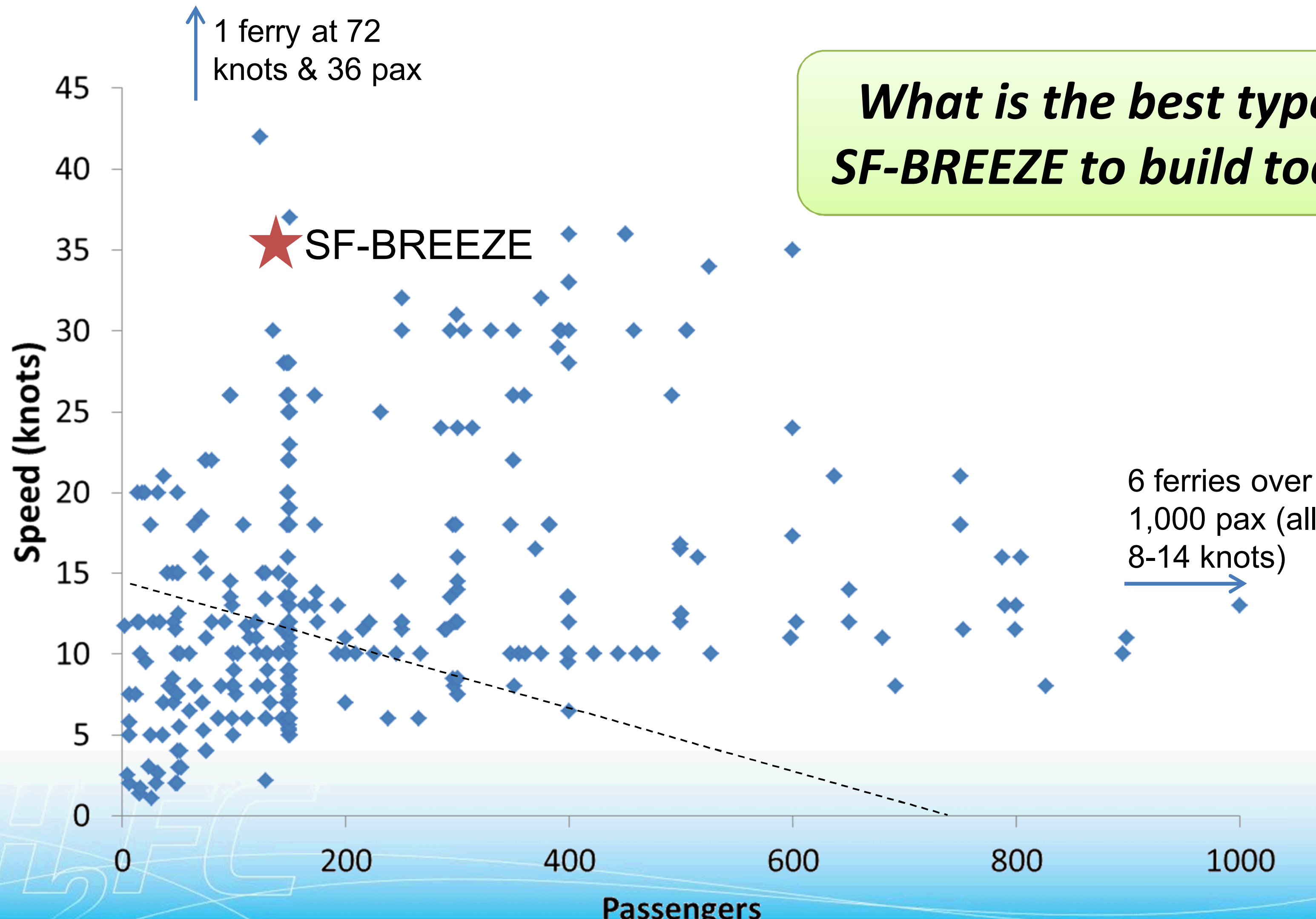
Estimated cost of a 120 kW module today: **$2,500/kW**

Estimated cost of 100-1,000 units in 3 years: **$1,000/kW**

Longer term cost: **$100-$200/kW** for auto PEM fuel cell at 10,000 units year

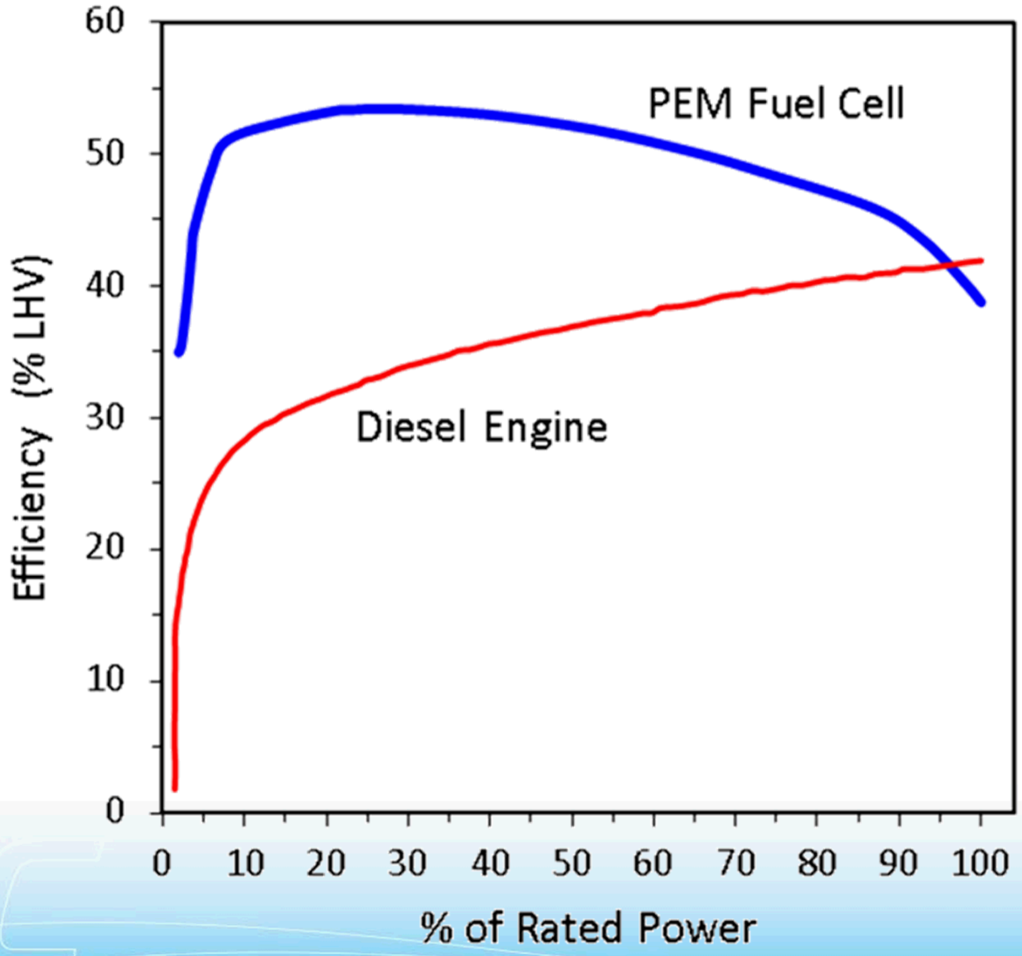
Long term DOE high-volume cost target: **$30/kW**

The SF-BREEZE's performance requirements are not mainstream for US ferries



What is the best type of SF-BREEZE to build today?

Routes with long durations at peak power lessen the efficiency gains when compared to conventional engines



Summary

The SF-BREEZE feasibility study has shown that it is possible to build and operate a 150 passenger, high speed, zero emission hydrogen-powered ferry considering not only the technical aspects but also with full regulatory acceptance. The commercial feasibility has a promising future and may be viable today.

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

Next Steps

Five project phases

Phase 1: Feasibility study (complete)*

Phase 2: Optimization of the vessel (starting)*

Phase 3: Detailed design of the H_2 ferry and station

Phase 4: Build the H_2 ferry and station

Phase 5: Operate the H_2 ferry and station

Phase 6: Extend to H_2 cars, buses and trucks

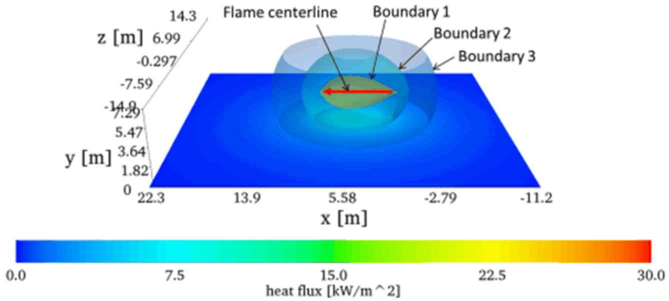
*Phases 1 and 2 funded by US DOT / Maritime Administration

Sandia's *Zero Emission Maritime* Work

ZERO/V: ocean-going research vessel (study)

SF-BREEZE
150 passenger high speed ferry (initial feasibility, and optimization)

Fuel Cell Generator
100 kW generator for ports and ships (deployment)



Codes and Standards
International maritime hydrogen code development using science-based expertise

Lead of the
Zero Emission Hydrogen Vessel Working Group

Building international collaboration

Touring the *Vision of The Fjords* (Flam, Norway)

International Workshop on the Safety of Liquid Hydrogen Carriers at the IMO (London, UK)

Visiting Norled's *Ampere* (Oppedal, Norway)

Presenting to researchers and local industry at the Royal Institute of Technology (Stockholm, Sweden)

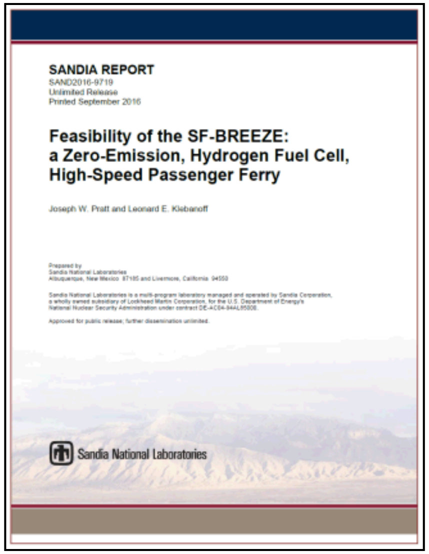
In the engine room of the Viking *Grace*

Visiting the Meyer Turku shipyard and tour of the *Tallink* (Turku, Finland)

For more information…

SF-BREEZE Feasibility Study Final Report -
Download from: **maritime.sandia.gov**

- All ferry design documents and drawings
- LH_2 fuel assessment (with comparison to LNG)
- Economics – capital, O&M, H_2 fuel
- Emissions
- Fueling
- Regulations



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a Zero-Emission, Hydrogen Fuel Cell,
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