Hydrogen and Fuel Cells Program
SAND2016-2186C

Feasibility Study on a Zero Emission High Speed Hydrogen Ferry, and Synergies with FCEVs

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Working Group Meeting

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Project Concept

High-speed H_2 Ferry

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

Dockside H_2 "ZEP" Station

- Serving vessels, cars, buses and trucks
- 2,500 kg/day capacity & 80% base utilization

Engineering model of the SF-BREEZE

Example existing dockside hydrogen station in Hamburg, Germany

Near Term and Long Term Impacts

- Eliminates diesel emissions and fuel spills.
- Dramatically decreases noise from the vessel, providing health benefits for operators, a better experience for the public and protects marine life from noise injury.
- Extends U.S., California, and San Francisco leadership in hydrogen fuel-cell technology into the maritime application.
- Enables low-cost, multi-use hydrogen infrastructure for fuel-cell vehicles and vessels.
- Potential to grow U.S. shipbuilding capability through clean tech
- Reduced vessel emissions may help ports meet expansion needs

Approach

Five project phases:

Phase 1: Deeper feasibility study: Project Month 6

- <u>Go/No-Go based on feasibility study results</u>

Phase 2: Detailed design of the H_2 ferry and station: Month 12

Phase 3: Build the H_2 ferry and station: Month 30

Phase 4: Operate the H_2 ferry and station: Month 42

Phase 5: Extend to H_2 cars, buses and trucks: Month 48

Summary timeline (Pending phase 1 findings): 48 months

Phase 1 feasibility study funded by US DOT / Maritime Administration

Goals of the Feasibility Study

Primary question:

Is it technically possible and commercially viable to build a high-speed, zero emission passenger ferry and associated fueling facility, both of which satisfy all applicable codes and regulations?

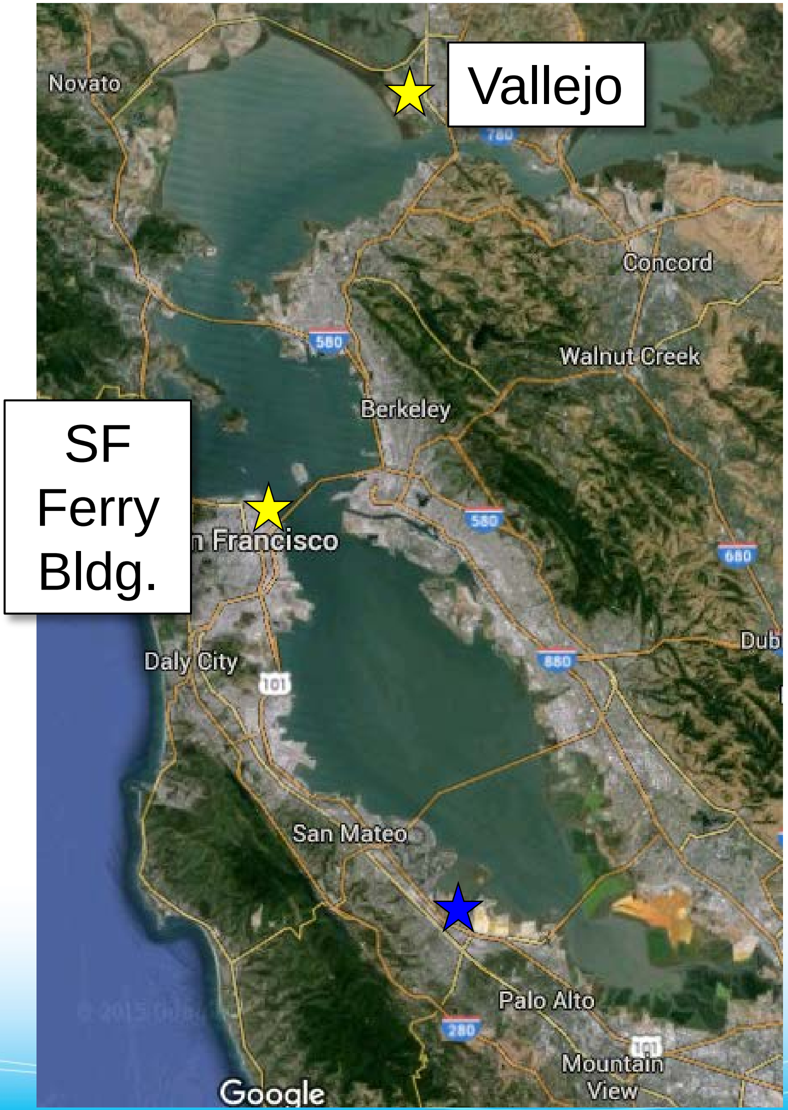
Feasibility Chart

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

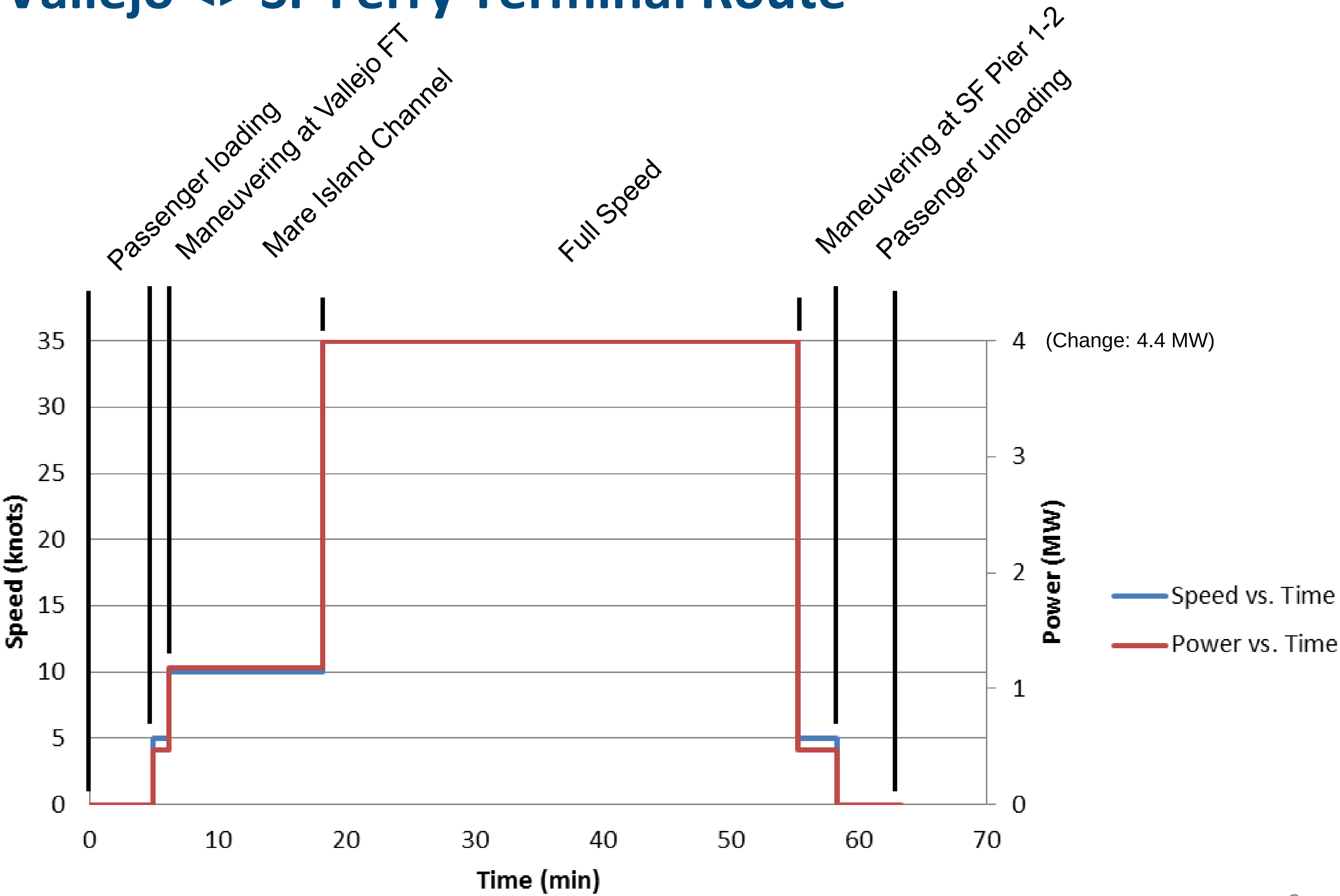
Technical - Ferry

Ferry Operating Logistics

- 23 nm one-way, 35 kts top speed
- Each round trip uses about 500 kg LH_2
- Daily logistics:
  - Two morning round trips
  - Refuel in less than 1 hr.
  - Two afternoon round trips
- Designing the ferry to meet the long distance of the Vallejo-SF route gives it maximum flexibility in eventual route choice, including a SF-South Bay route.



Vallejo <> SF Ferry Terminal Route



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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	✗	✓	✓

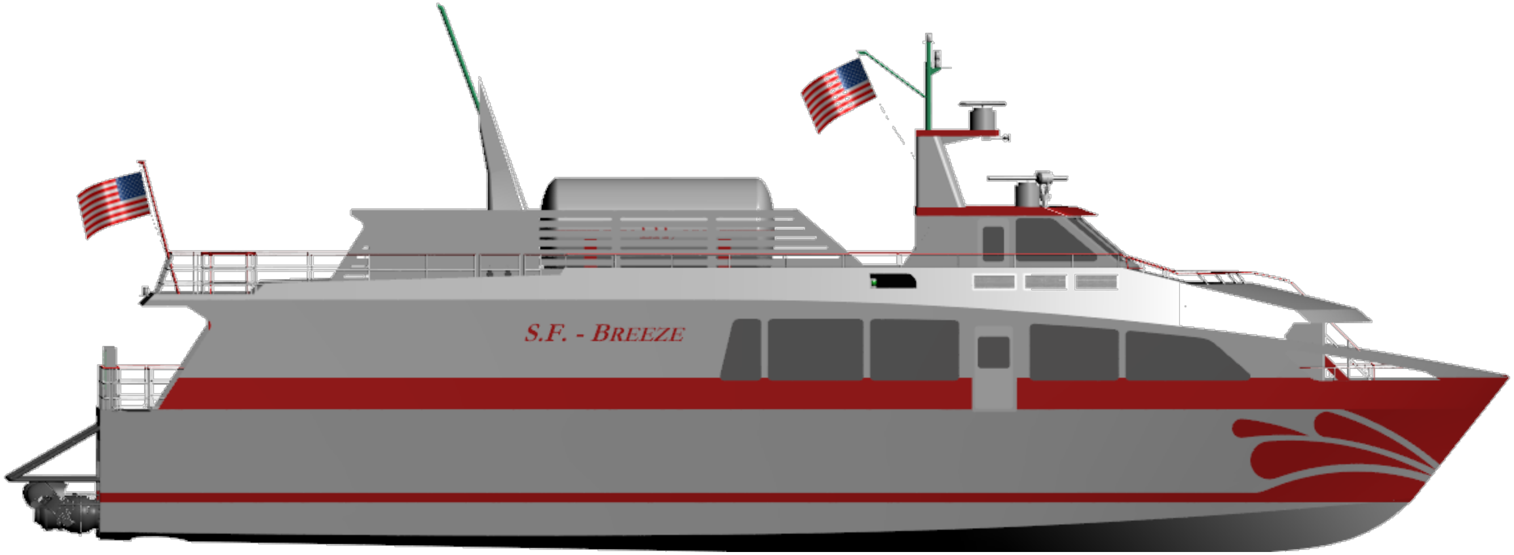
Hydrogen Storage Methods for 1,000 kg of H_2

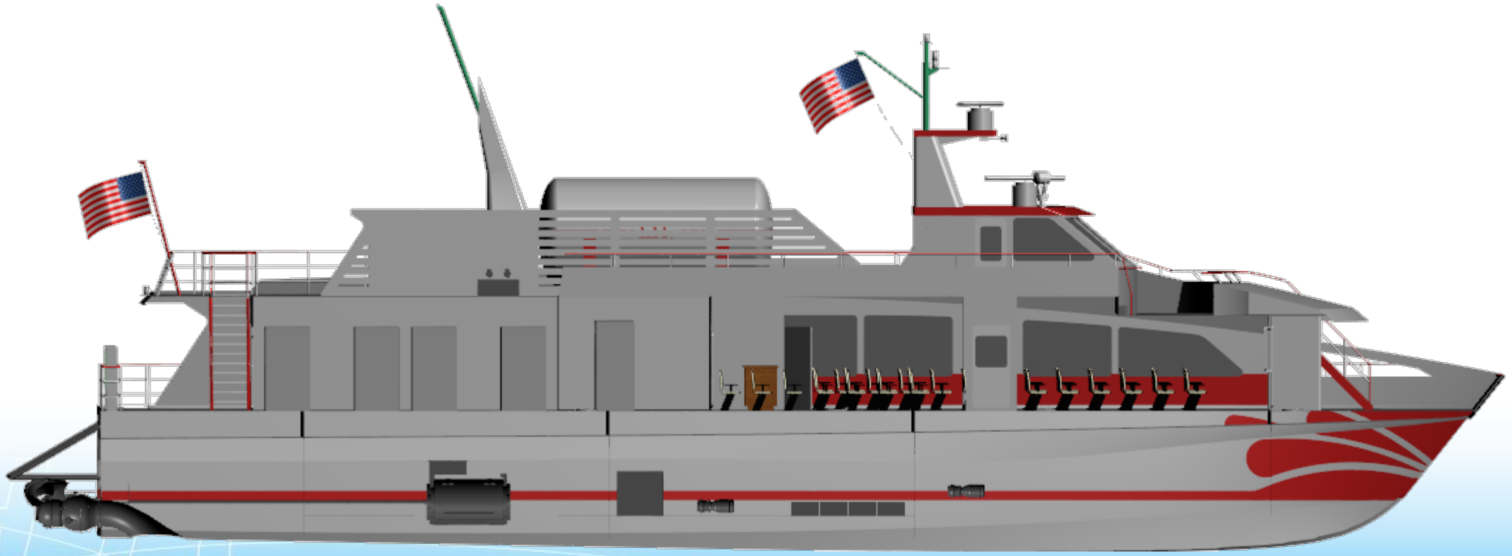
Storage method	Storage Tank Weight	Storage Tank Volume
Gas – standard 2,200 psi steel cylinder	228,000 lb	28,000 gal
Gas – 5,000 psi composite cylinder	39,500 lb	14,500 gal
Gas – 10,000 psi composite cylinder	52,700 lb	12,800 gal
Gas – Metal Hydride	139,000 lb	6,200 gal
Liquid - low pressure cryogen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

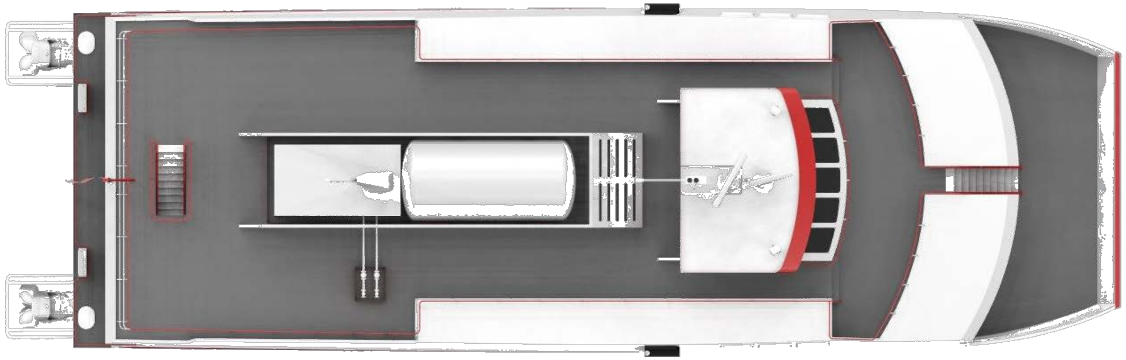
Current Design



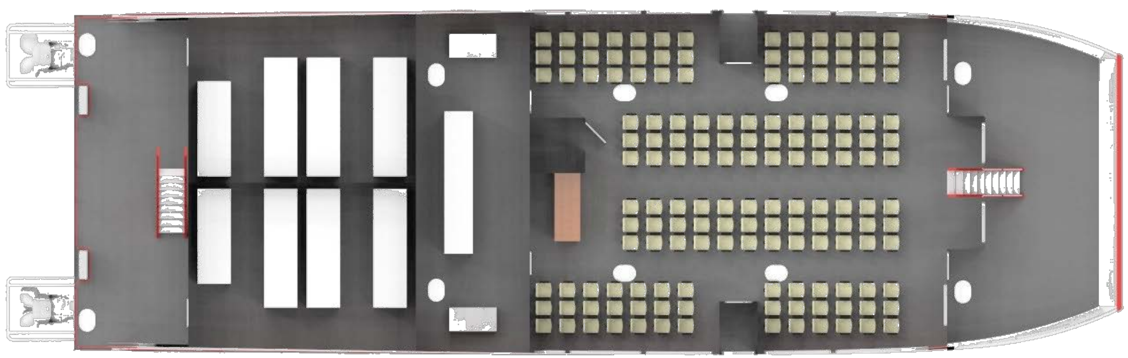


Current Design

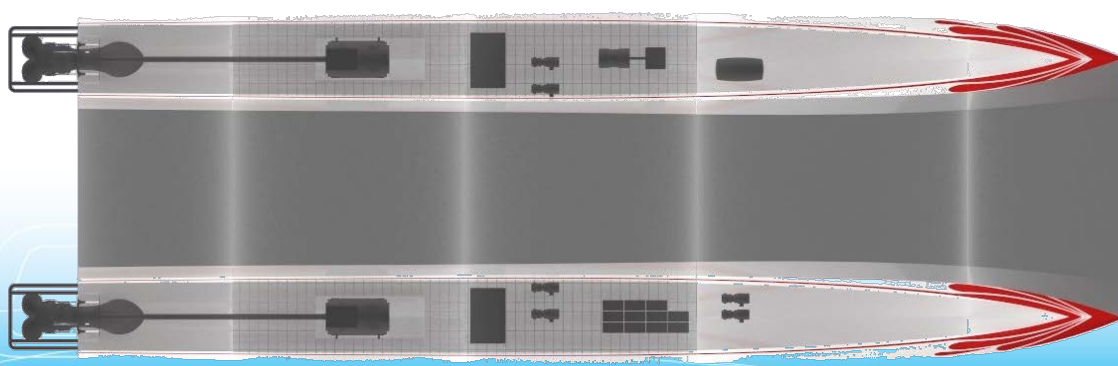
Upper Deck



Main Deck

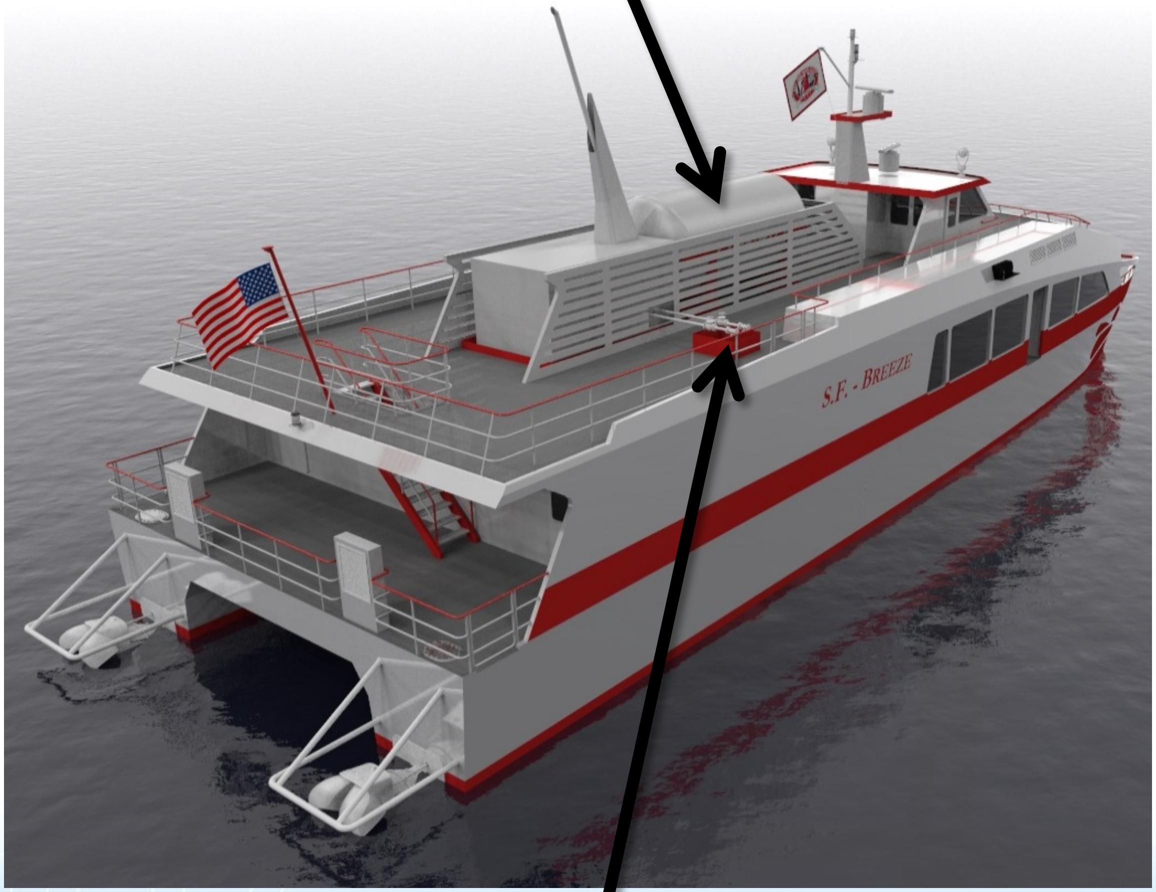


Hulls



Technical - Fueling

Ferry Fueling Characteristics

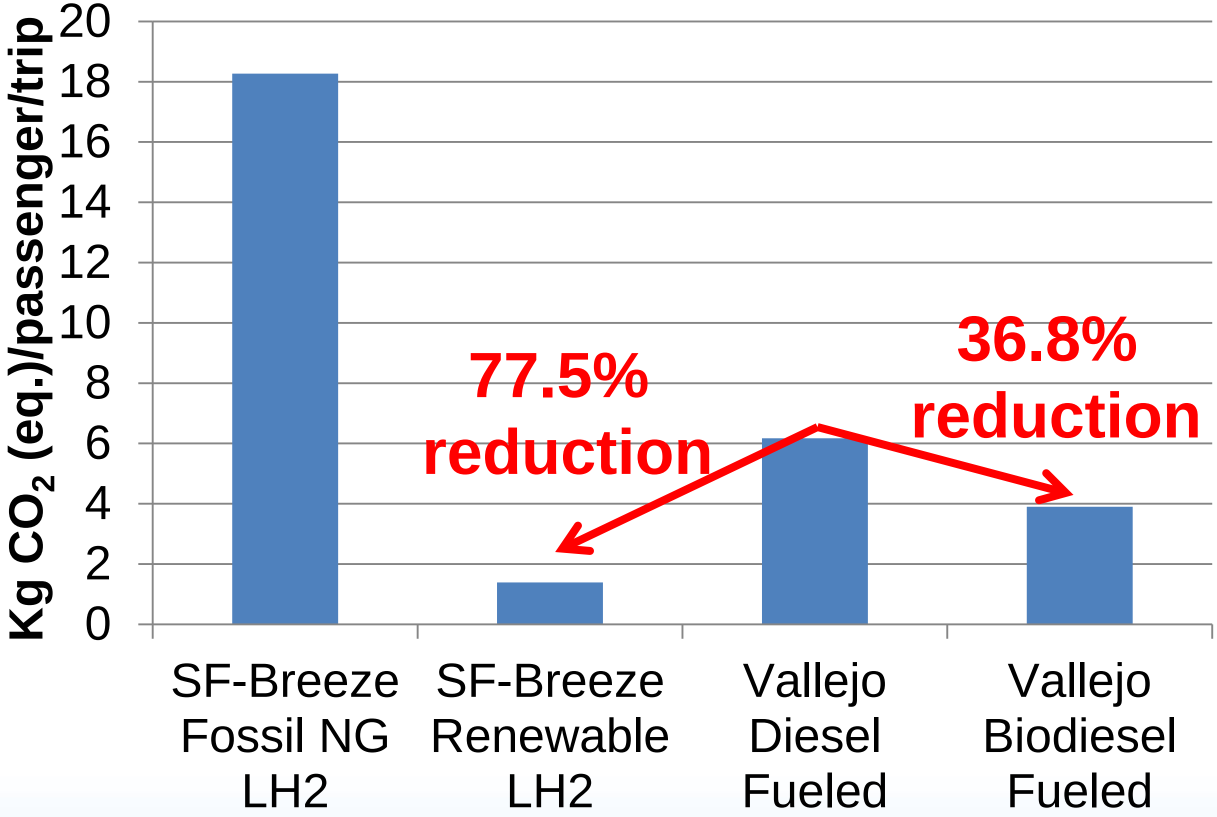


*The ferry uses **liquid** hydrogen because it is currently the lightest and most compact method to store hydrogen, and operates at low pressure*

LH_2 has been routinely handled and transferred between tanks for decades.

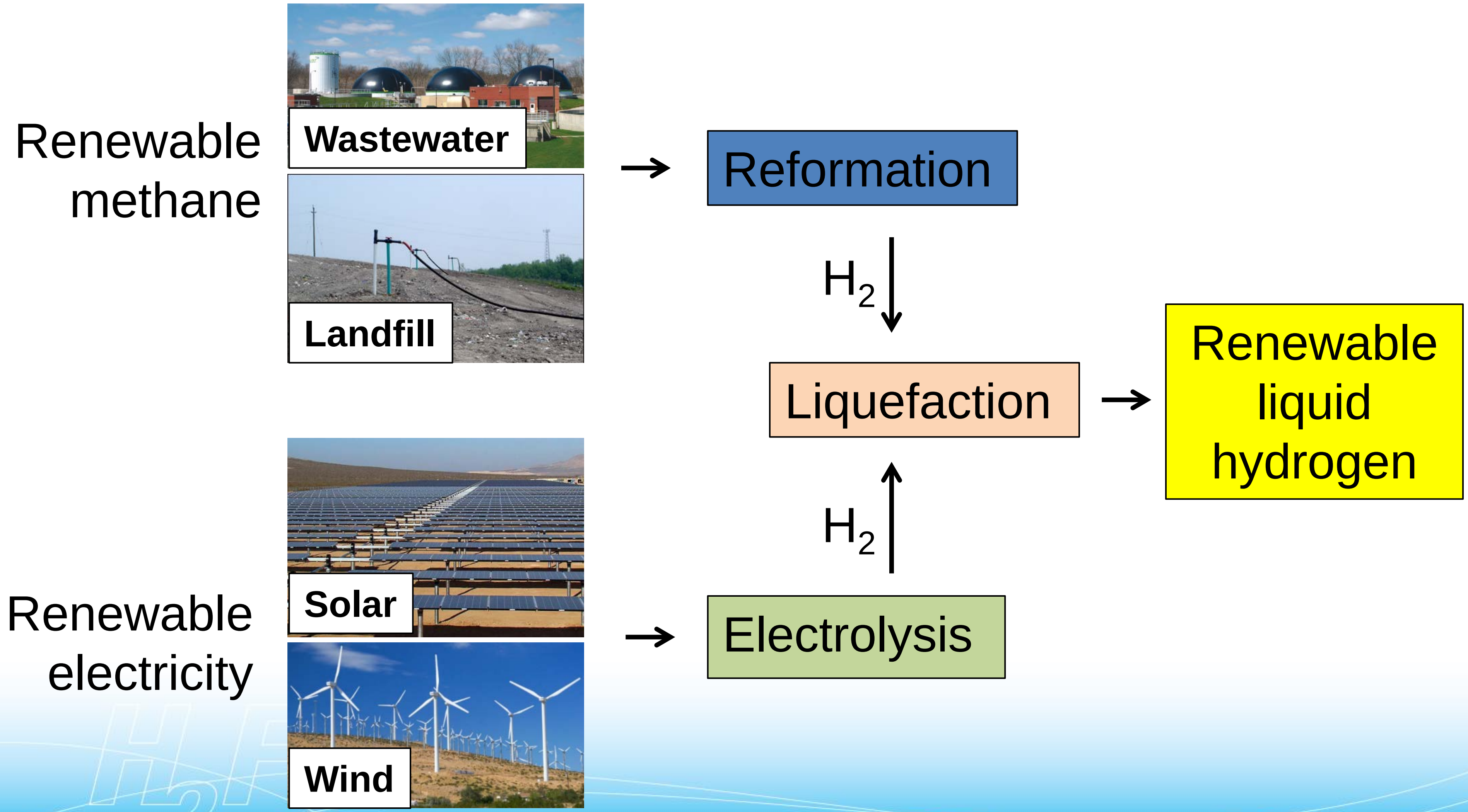
Thank you to Linde, Air Products, and Praxair for hosting our visits and teaching us about LH_2!

Dramatic reductions in GHG emissions are achievable with the SF-Breeze, but it requires the use of renewable LH_2



All SF-Breeze emission due to LH_2 production path; the SF-Breeze is Zero Emissions at the point of use

Renewable liquid hydrogen is available. The cost is higher than non-renewable hydrogen.



Refueling process will be similar to LNG bunkering

(1) Shoreside storage tank (or refuel directly from truck).

(2) Piping and connecting the fueling arm

(3) Transferring the fuel

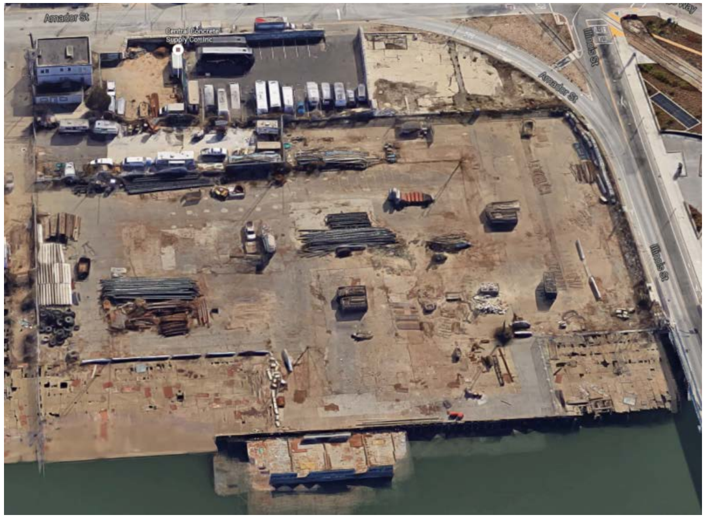
(4) Underway

See complete video at: youtu.be/oZWuTWtp5Rs

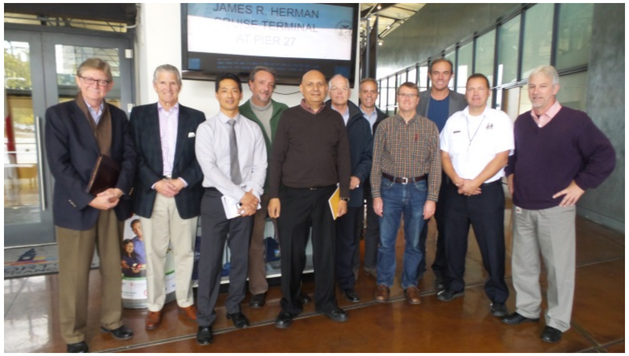
Important difference between LH_2 and LNG:
Hydrogen is non-toxic and is not a greenhouse gas. *If vented or spilled it quickly and completely evaporates with no harm to personnel or the environment.*

Working with the ports, three Bay Area ZEP station locations have been identified as feasible

Port of SF – Pier 90



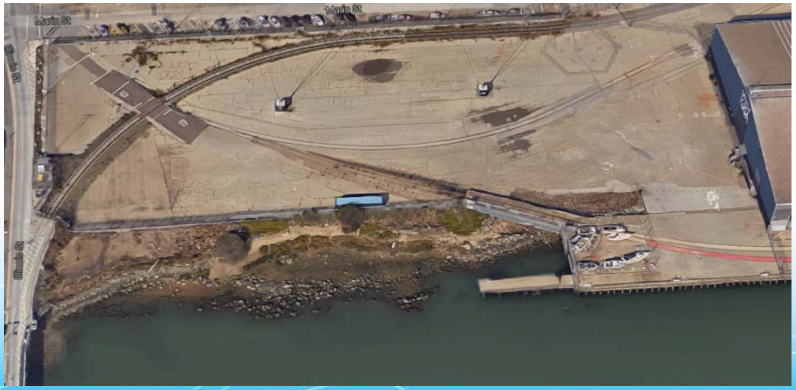
Port of San Francisco



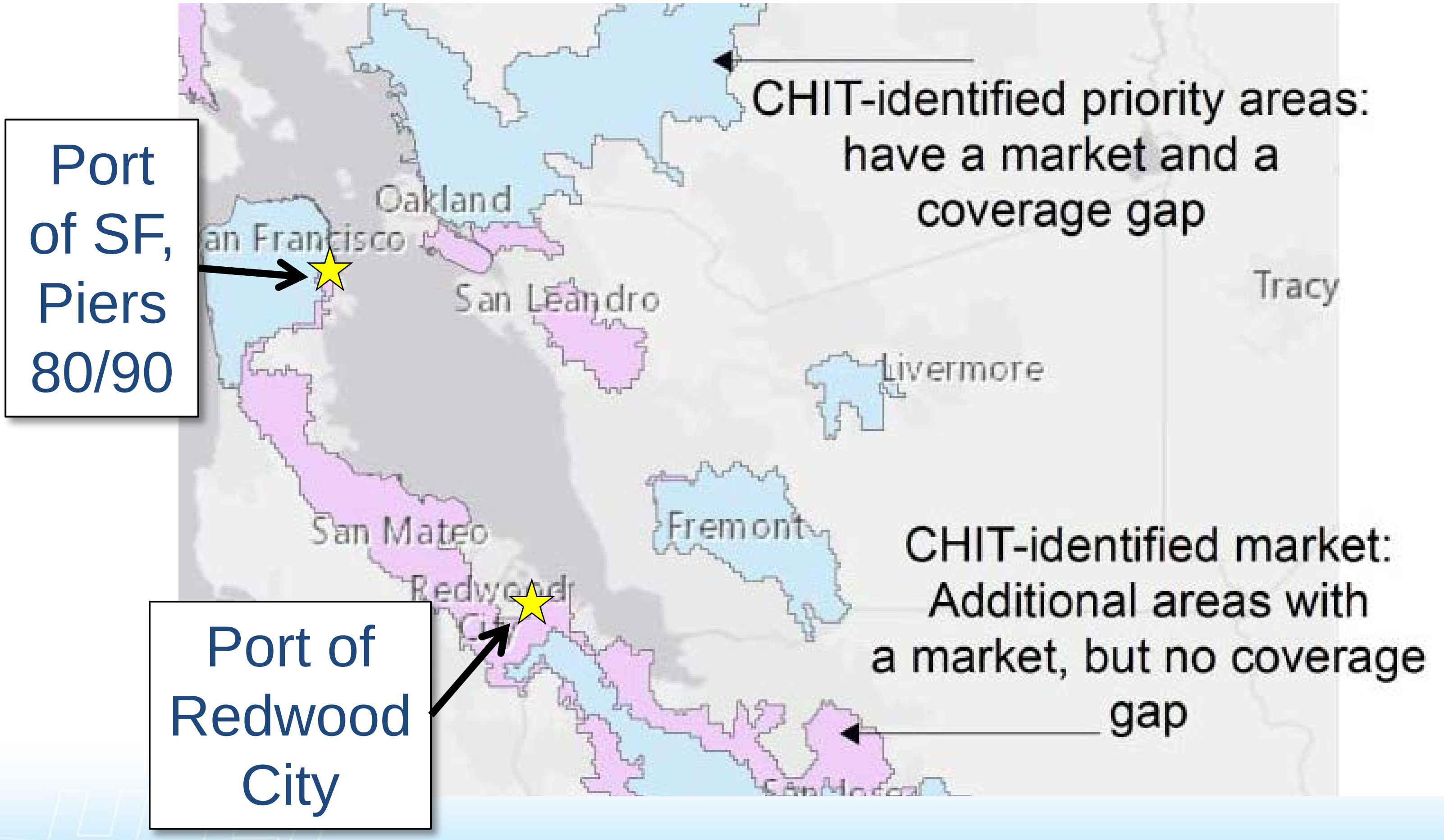
Port of Redwood City

Port of Redwood City – Wharf 5

Port of SF – Pier 80



The identified locations are within areas identified by CARB as near-term hydrogen markets.

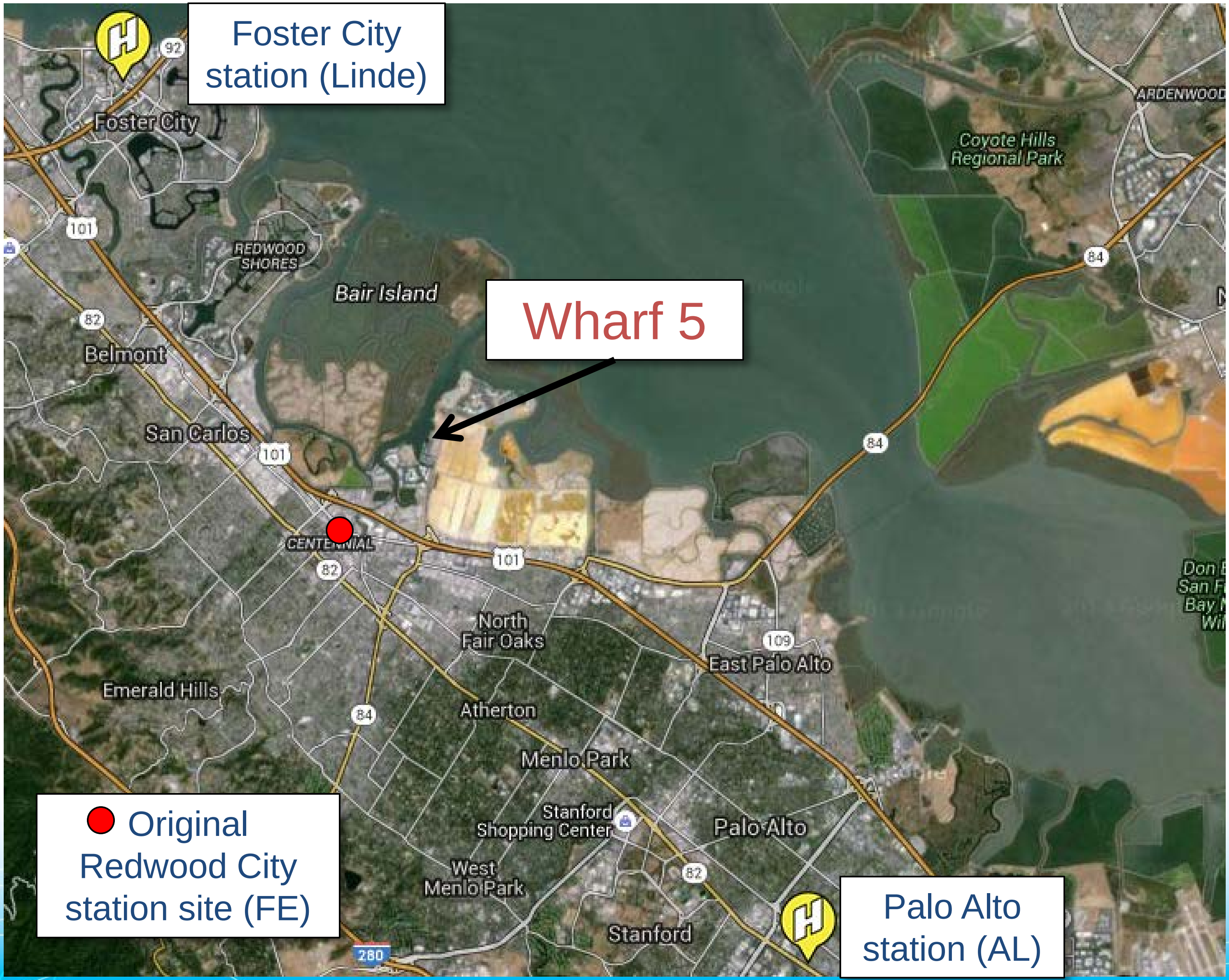


Map from the California Hydrogen Infrastructure Tool (CHIT) courtesy of Andrew Martinez, CARB

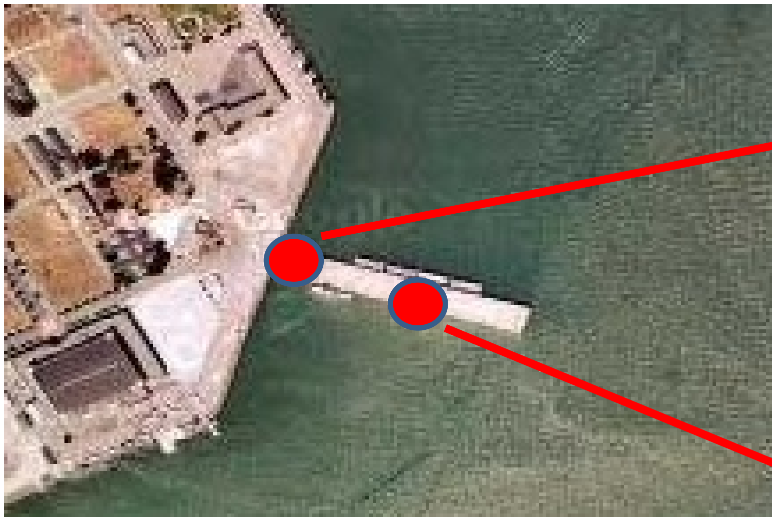
Perspective on the Port of SF locations (looking north)

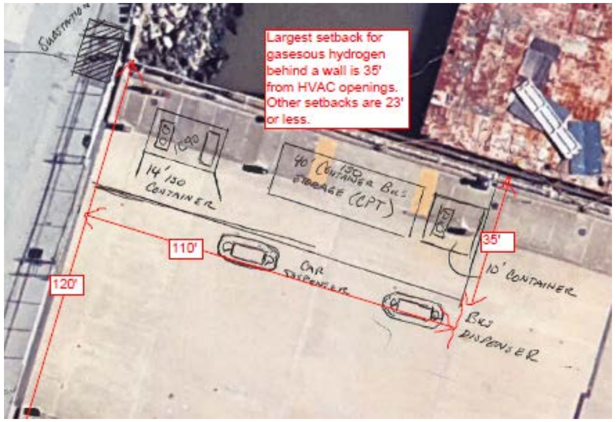
South San Francisco FE station is 8 miles south. Union Square (downtown SF) is 4 miles north.

Perspective on the Port of Redwood City location



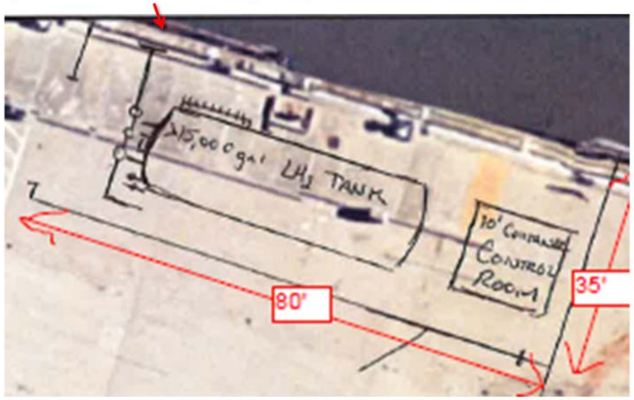
Layout of the fueling facility is flexible and can be adapted to the site.





For refueling fuel cell cars, buses and trucks (400 kg/day)

(Connection stanchion and fueling boom)



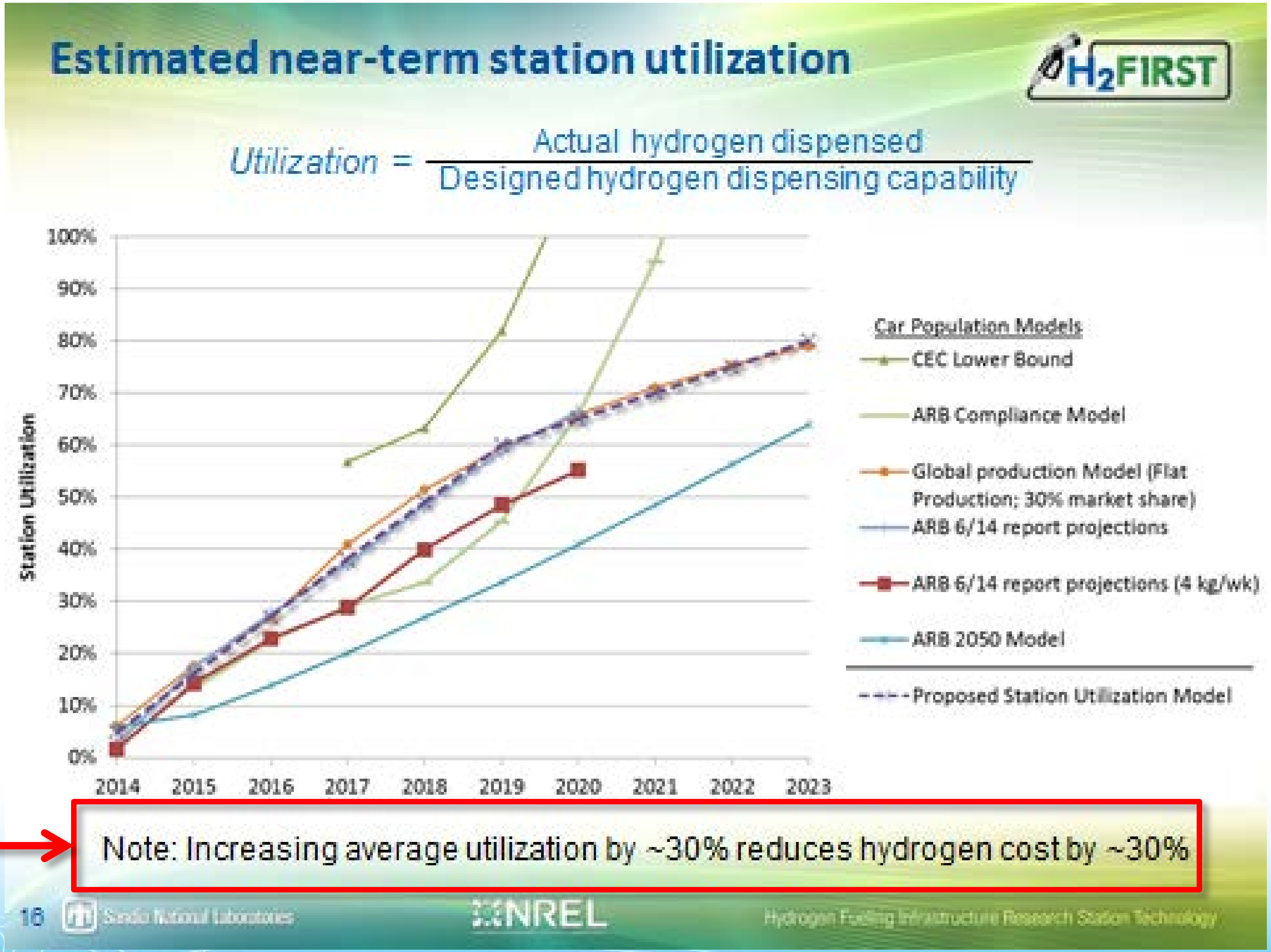
For refueling the SF-BREEZE ferry (2,000 kg/day)

The station's high throughput can reduce the hydrogen cost for the ferry and the vehicles.

All facility components are commercially available.

Sketches courtesy of Linde

Reduced hydrogen cost is expected for all users (ferry and vehicles) due to high utilization (>80%)



Slide from H2FIRST Reference Station project

Regulatory

The project team includes designers, regulators, national experts, and class society working together.

Elliott Bay Design Group

Sandia National Laboratories

USCG MSC and Design and Eng. Stds.

USCG Sector San Francisco

USCG Liquid Gas Carrier NCOE

American Bureau of Shipping

A long-range impact of involving the regulators is *establishing regulations that make sense* for this and future LH_2 vessels

Design Basis

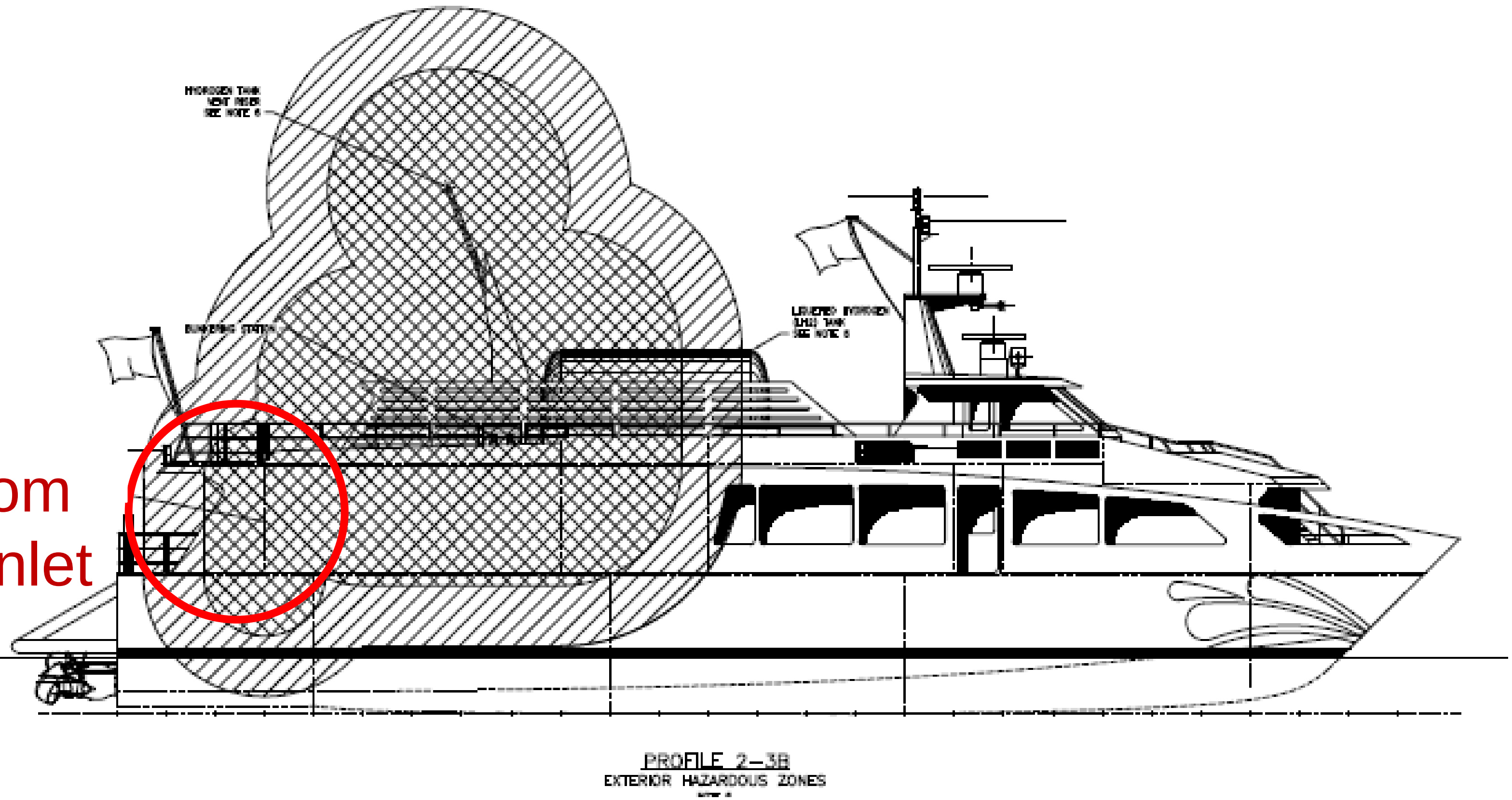
Principle regulation governing the design of the vessel:

- **46 CFR Subchapter T – Small Passenger Vessels**

Other documents are used as guidance, since no official regulations yet exist which specifically apply to a hydrogen powered, high speed, aluminum ferry.

- ✓ IMO MSC 95/22/Add.1 (Adopted IGF Code)
- ✓ IMO CCC 2/3/1 (IGF Code with Fuel Cell Additions)
- ✓ ABS Guide for Propulsion and Auxiliary Systems for Gas Fueled Ships
- ✓ ABS Rules for Building and Classing High-Speed Craft
- ✓ IEC 60092-502 Electrical Installations on Ships
- ✓ IEC 60079-10 Electrical Apparatus for Explosive Gas Atmospheres
- ✓ 46 CFR Subchapter J – Electrical Engineering
- ✓ 46 CFR Subchapter F – Marine Engineering
- ✓ ASME B31.12 Hydrogen Piping and Pipelines
- ✓ ANSI/CSA America FC1-2004 Stationary Fuel Cell Power Systems

Example of synergies on the regulatory side



Fuel cell room ventilation inlet location in conflict with IGF 13.3.5

May be applicable for other fuels, but referring to NFPA-2 and CGA 5-5 for guidance on hydrogen

Economics

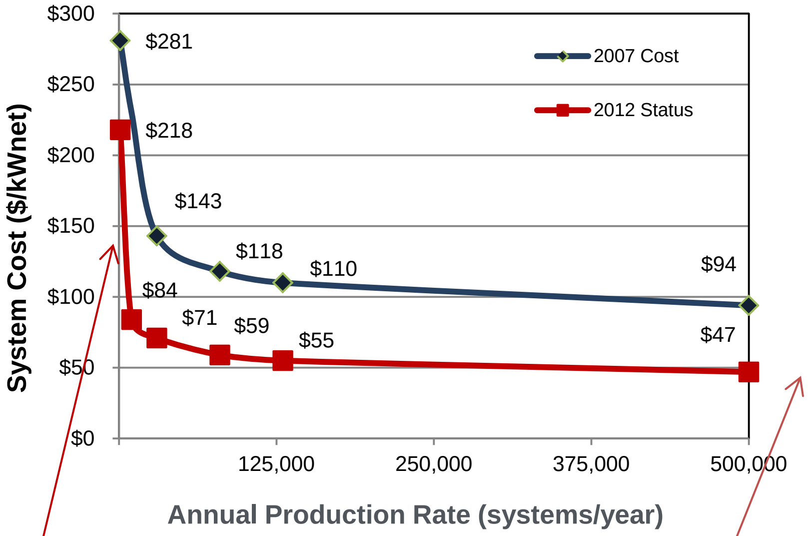
Factors being considered in the economic analysis: *Ferry*

- Ferry design and build cost
  - Similar to high speed aluminum diesel vessels, with increase due to higher cost of LH_2 and fuel cell systems.
  - Determined by designer and builder
- Ferry operating cost
  - Estimated from existing operations including any difference between diesel engine and fuel cell O&M.
- Ferry revenue
  - Estimated from existing route/fare structures in the SF Bay

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

Cost of Automotive PEM Fuel Cells*

Projected Costs at Different Manufacturing Rates



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**

Factors being considered in the economic analysis: *Hydrogen Fuel*

- Hydrogen station design and build cost
- Hydrogen fuel cost

Existing dockside hydrogen station in Hamburg, Germany

Variables:

- Type of hydrogen (conventional or renewable)
- Hydrogen supply arrangement
  - Project builds and maintains the station, pays for LH_2 deliveries
  - Hydrogen Purchase Agreement: third party owns and operates the station, delivers LH_2 into ferry tanks with an “all-in” cost.

Factors being considered in the economic analysis: *Grants, Loans, and other financial assistance*

- Federal grants for public transit agencies
- The Federal Ship Financing Program (Title XI)
- State (CA) grants for clean emissions, off-road passenger transport
- State (CA) grants for hydrogen infrastructure development
- State (CA) loans for clean energy project
- Private sector funding

Summary: Feasibility Study Status

- Technical design package has been submitted to USCG and ABS; Expect approval mid-March.
- In parallel, working on economic feasibility analysis
- Final report planned for mid-April

Feasibility Chart

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

Learning about vehicles through the ferry project, and vice-versa…


Tom and Joe B. with Michael Dray at the CSULA station


Tom with Tim Lipman at UC Berkeley R&D station


Redwood City Community Development Manager Gary Lepori with the fuel cell light tower

"I was very fond of the vehicle and would have kept it permanently if they allowed me to. Fueling at the AC transit station was easy and efficient… I would definitely buy one of the Fuel Cell powered cars if and when they become available as long as the fueling infrastructure expanded a little more than it is currently."

-- Red and White Fleet employee Jeff Unverferth about his experience in the UC Berkeley fuel cell vehicle driver research program

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