Issues Encountered During the San Francisco Bay Area Renewable Energy Electric Vessel with Zero Emissions (SF-BREEZE) Feasibility Study

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Zero Emission Hydrogen Vessel Workshop

Washington, DC

February 26, 2016

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2016-XXXX.

Concept behind the study

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 & 80% base utilization

Example existing dockside hydrogen station in Hamburg, Germany

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

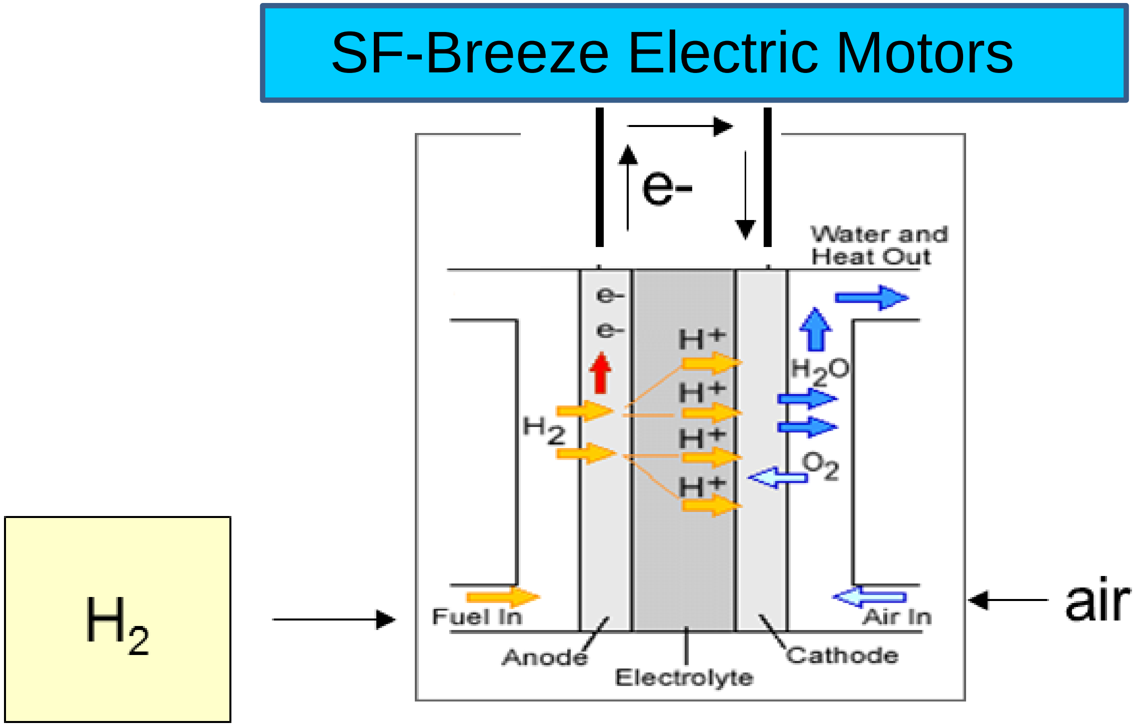
	Ferry	Hydrogen Station
Technical	?	?
Regulatory	?	?
Economic	?	?

Funded by US DOT / Maritime Administration

Primary Issues

1. "New" technology acceptance
2. Hydrogen safety
3. Influence of LNG
4. Fueling facilities: landside infrastructure and supply logistics
5. Weight and volume and effect of endurance and speed
6. Getting real emissions benefits (well-to-waves), i.e.: renewable H2
7. Cost

How a Fuel Cell Works



Hydrogen Fuel Cell

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

Going In:

H_2 and air

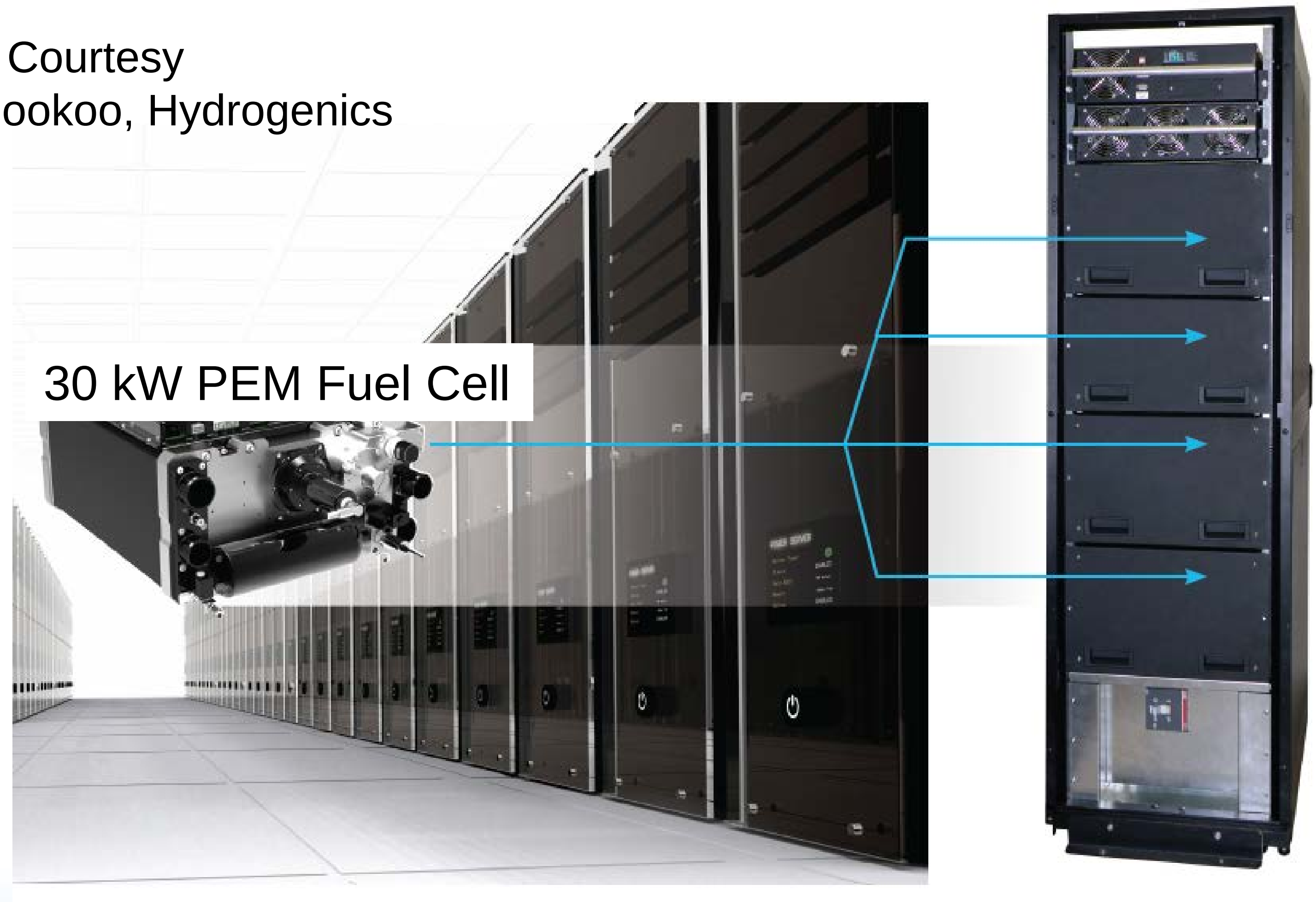
Going Out:

Electricity
Waste Heat
Warm humidified air

In the SF-Breeze, the "electrolyte" is a "proton exchange membrane", hence the name "PEM" Fuel Cell.

Modular PEM Fuel Cell Power Systems

Photos Courtesy
Ryan Sookoo, Hydrogenics



H x D x W (in.)
78.2 x 42.1 x 30.0

Weight = 1764 lbs

Note: The fuel cells want room temperature H_2, but the best way to store hydrogen on the SF-Breeze is as liquid hydrogen (LH_2) which is very cold (-253 C!), or ***Cryogenic.***

LH_2 Has Been Used for Decades

A typical trailer can deliver 4000 kg at a time.

LH_2 tanks are double walled vacuum insulated tanks with 304 stainless steel liner

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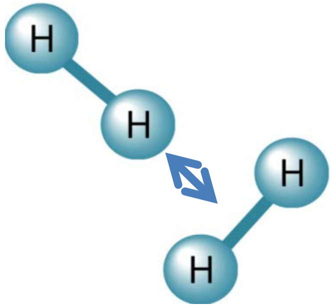
Hydrogen 101

H_2 molecules barely interact at all



- **Evaporates very fast** (4,000 gallons in ~7 seconds)
- **Extremely buoyant** (goes straight up at ~40 mph)

Can ignite to a flame in the right mixture *but very hard to get that mixture!*

Hydrogen safety is centered around avoidance of creating a flammable mixture and removal of ignition sources where flammable mixtures may be present.

Safety Analyses

Pool fire times

The Nature of Fires: LH_2 vs. LNG

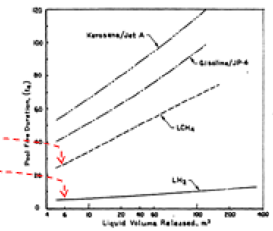
NASA funded a model study of the fire safety aspects of LH_2 and LNG as part of their program in alternative-fuel aircraft in the 1980s.

$6\ m^3$ = 6,000 L = 1587 gallons = 426 kg of LH_2

Pool Burn Times :

LNG = 25 s

LH_2 = 5 s



COMPARISON OF THE FIRE DURATIONS FOR POOL FIRES RESULTING FROM THE INSTANTANEOUS RELEASE OF THE FOUR FUELS

LH_2 pool fires burn out faster than LNG pool fires primarily due to the much lower heat of vaporization of LH_2. But both fuels, if spilled, would burn themselves out rapidly.

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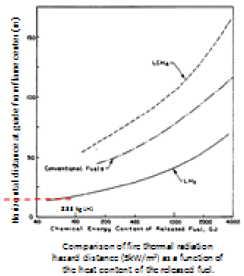
LH_2 Fires Pose Less Safety Risk Than LNG Fires

Results from the NASA-funded study:

Note: $5\ kW/m^2$ is the threshold for skin thermal injury.

Approach limit for LNG fire = ~54m

Approach limit for LH_2 fire ~ 18m



You can be 3X closer to a H_2 fire than a NG fire for the same safety factor.

Fire safety

Note: the flame temperatures of H_2 and CH_4 are similar, but the H_2 flame is less "emissive" because no carbon is produced in the combustion

LH_2 fires are radiatively much less hazardous than LNG fires for two reasons: First, they don't contain carbon, and so radiate less power than NG flames. Second, since the product of H_2 combustion is H_2O, the flame radiation is strongly absorbed by H_2O in the air.

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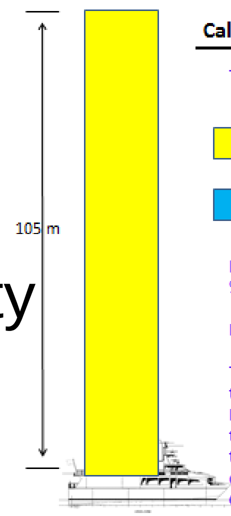
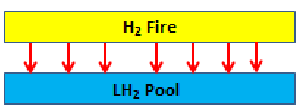
Deck integrity



Calculate Radiant Energy Intercepted by the Deck,

Total thermal energy radiated = 24040 MJ



Radiation is the dominant heat transfer mechanism from fire to pool

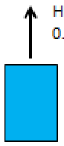
Entire Area of Flame = 5298 m^2
% Bottom circular area = 0.033

Radiation directed downward = 0.033 x 24040 MJ = 801 MJ

This energy has to vaporize the LH_2 liquid to a vapor. At the estimated 29 K tank operation temperature, ΔH_{vap} = 323.9 kJ/kg. Thus 388 MJ of the radiant energy is spent evaporating the fuel. Even if the LH_2 cools the Al deck with 388 MJ, we have to reheat the Al, still expending that energy. Therefore, total energy left over = 801 – 388 MJ = 413 MJ (radiant energy directed towards the deck).

Estimating Dilution at Boil-off Venting

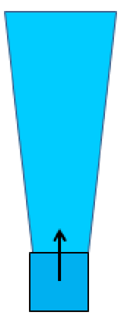
Consider the 2" diameter vent pipe pointing straight up.



H_2 venting, 1%/day = 0.139 grams/second total, 0.0694 g/second out of one pipe.

In one second the H_2 has risen 5 meters = 500 cm

Assuming completely quiescent air, the % volume in the 5 meters above the vent is at 3.5 % after 1 second, below the LFL for H_2. Any boat movement or wind reduces the hydrogen/air concentration much further.



(dimensions not to scale)

Diffusion velocities laterally are much slower than buoyant velocities, and are ~ 0.02 m/sec = 0.04 miles per hour at normal temperature and pressure. So Diffusion broadens the cone a bit, but its rising a lot faster than broadening.

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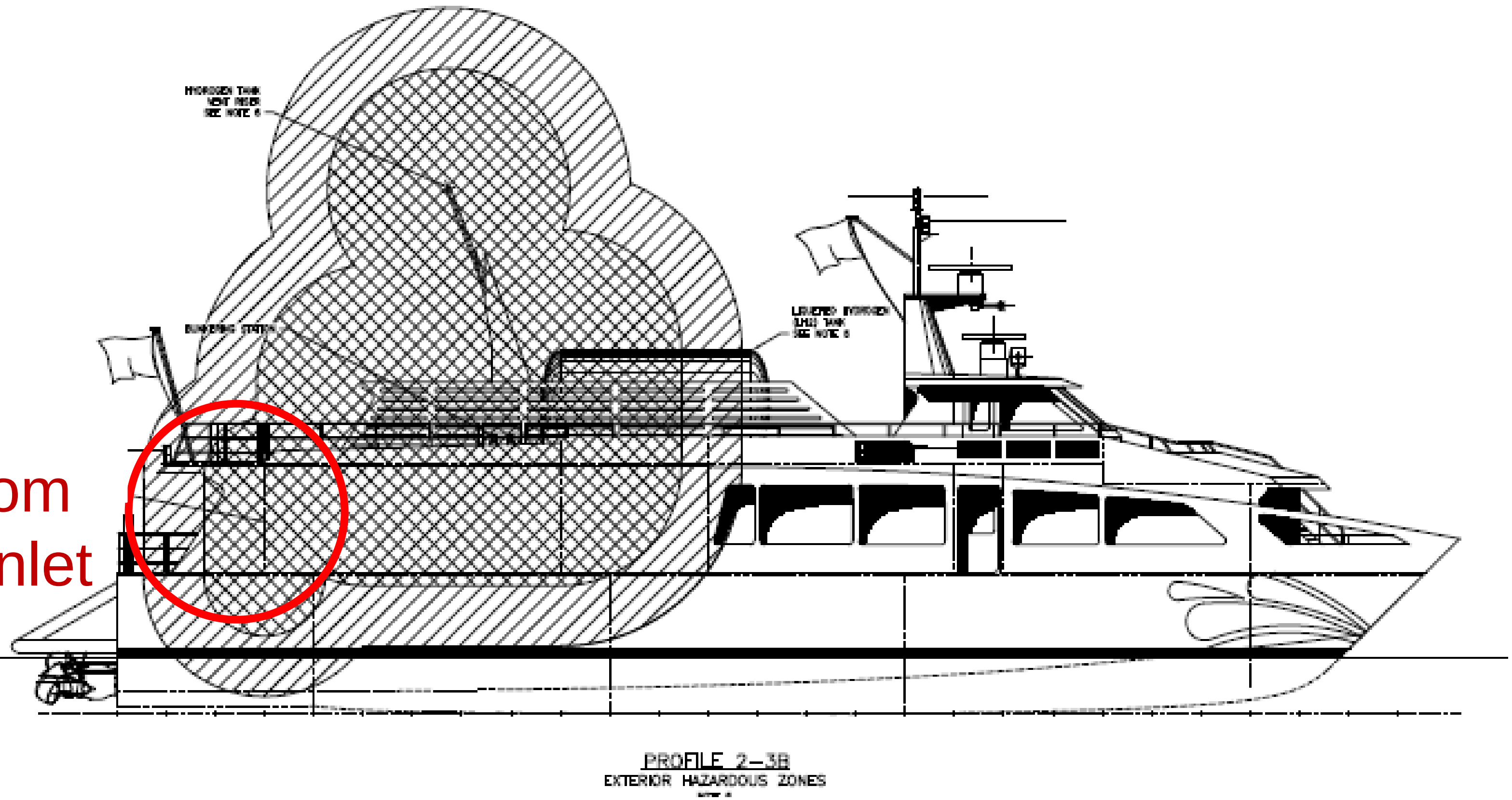
LH_2 boil off safety

Decades of studies on H_2 and LH_2 flames, fires, and safety

Example: Hazardous Zones



Fuel cell room ventilation inlet location in conflict with IGF 13.3.5

Based on the buoyant and evaporative properties of hydrogen, it isn't practical for the hazardous zones from equipment on the upper deck to extend down to the main deck.

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Recent developments in LNG shipping are helping – In general, LNG and liquid hydrogen (LH_2) are similar

IMO INTERNATIONAL MARITIME ORGANIZATION

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MARITIME SAFETY COMMITTEE
95th session
Agenda item 22

MSC 95/22/Add.1
19 June 2015
Original: ENGLISH

REPORT OF THE MARITIME SAFETY COMMITTEE ON ITS NINETY-FIFTH SESSION

Attached is annex 1 (Resolution MSC.391(95) – Adoption of the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code)) to the report of the Maritime Safety Committee on its ninety-fifth session (MSC 95/22).

IMO IGF Code

U.S. Department of Homeland Security
United States Coast Guard

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United States Coast Guard

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Washington, DC 20593-7509
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Phone: (202) 372-1413
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16715
CG-OES Policy Letter
No. 02-15
FEB 19 2015

From: R.E. Bailey, CAPT
COMDT (CG-OES)

To: Distribution

Subj: GUIDANCE RELATED TO VESSELS AND WATERFRONT FACILITIES CONDUCTING LIQUEFIED NATURAL GAS (LNG) MARINE FUEL TRANSFER (BUNKERING) OPERATIONS

USCG Policy Letters

ABS

GUIDE FOR

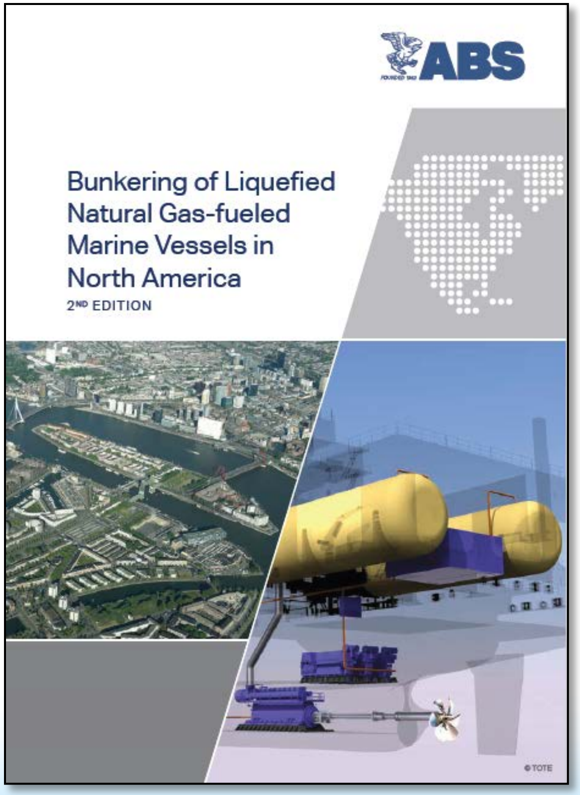
PROPULSION AND AUXILIARY SYSTEMS FOR GAS FUELED SHIPS

ABS Guidance

… and many others!

For bunkering (fueling), guidance notes for LNG are used along with LH_2 supplier expertise

1. ABS, "LNG Bunkering: Technical and Operational Advisory".
2. ABS, "Bunkering of Liquefied Natural Gas-fueled Marine Vessels in North America".
3. USCG, "Guidance Related to Vessels and Waterfront Facilities Conducting Liquefied Natural Gas (LNG) Marine Fuel Transfer (Bunkering) Operations".
4. USCG, "Guidelines for Liquefied Natural Gas Fuel Transfer Operations and Training of Personnel on Vessels Using Natural Gas as Fuel"
5. 46 CFR 154 - Safety Standards for Self-Propelled Vessels Carrying Bulk Liquefied Gases



The goal of everyone involved is to establish regulations that make sense for this and future LH_2 vessels

USCG MSC and Design and Eng. Stds.

USCG Sector San Francisco

USCG Liquid Gas Carrier NCOE

American Bureau of Shipping

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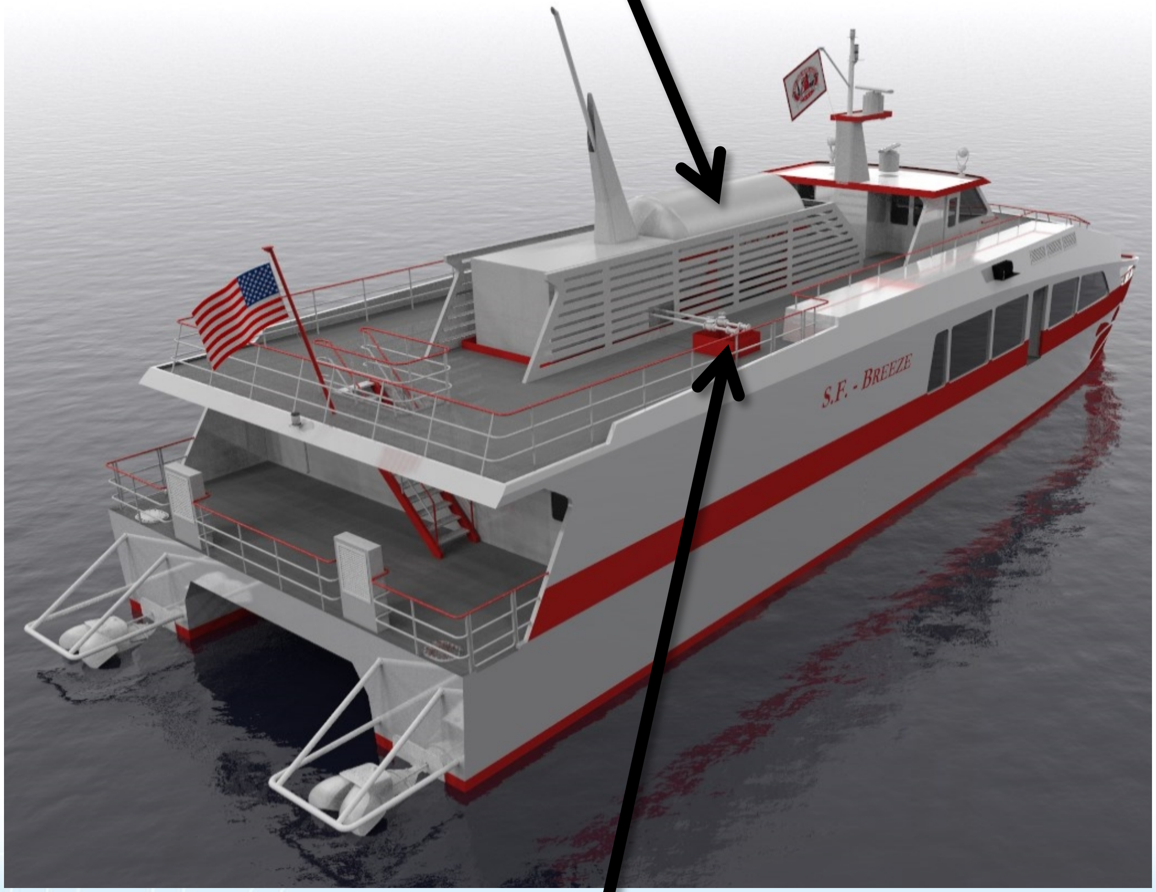
Ferry Fueling Characteristics

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*

Process will be similar to LNG bunkering

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

(2) Piping and connecting the fueling arm

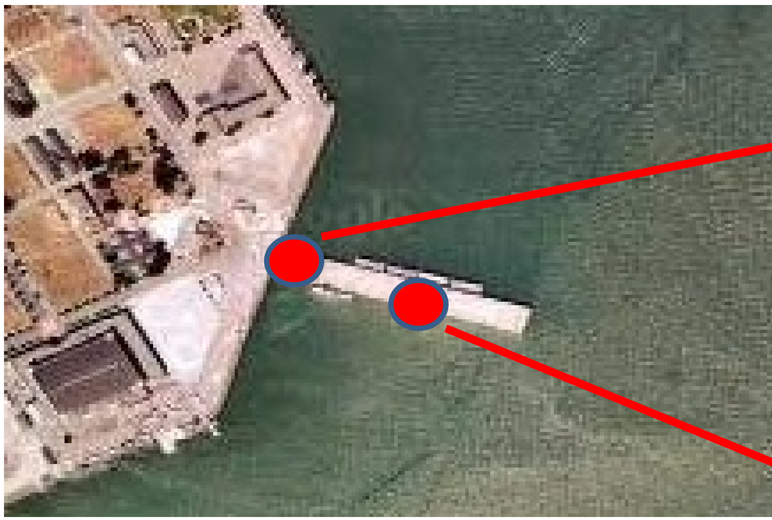
(3) Transferring the fuel

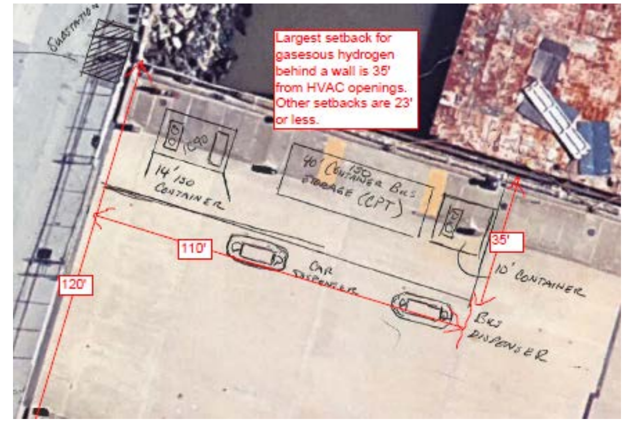
(4) Underway

See complete video at: youtu.be/oZWuTWtp5Rs

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

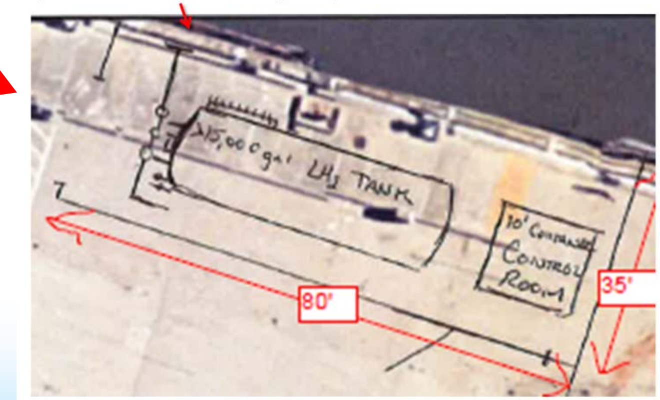
Layout of the fueling facility is flexible and can be adapted to the site.





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.

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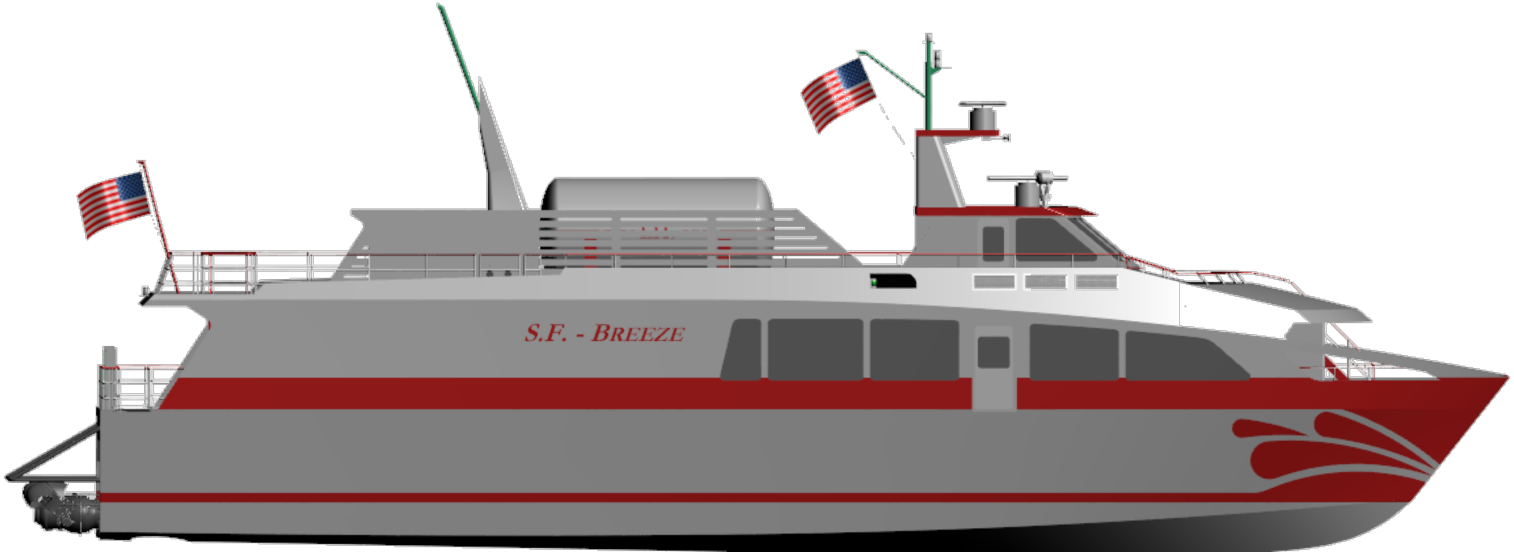
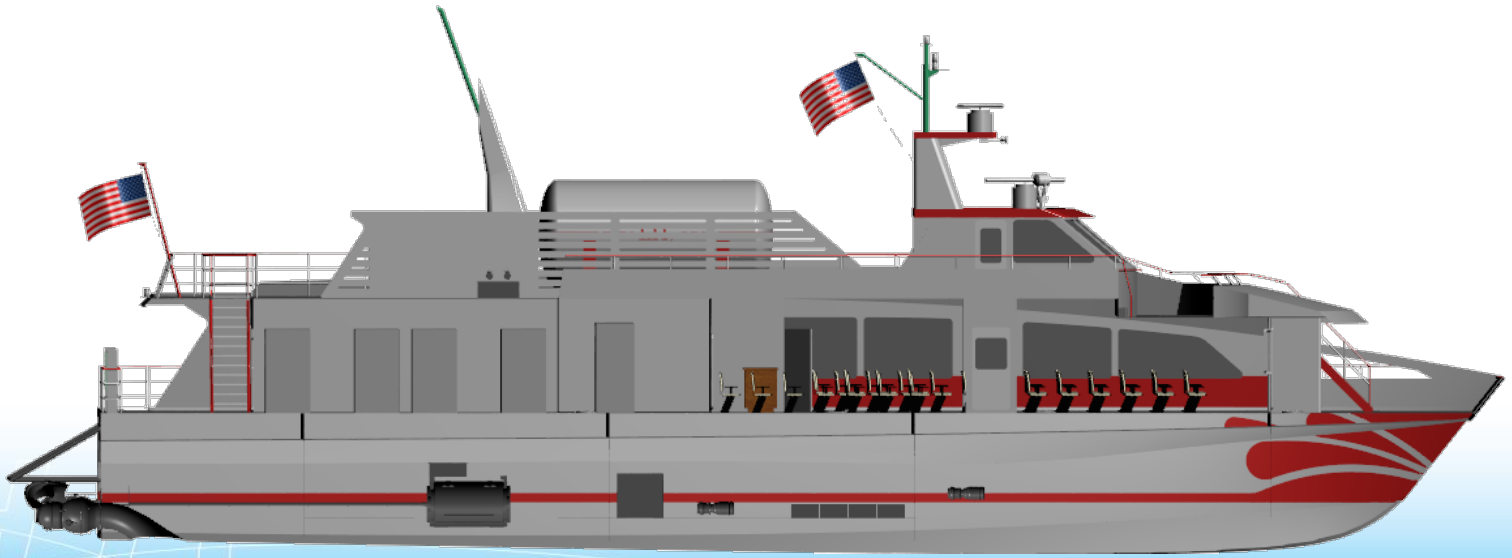
Current Design





The SF-BREEZE is heavier: Requires more power, carries less passengers, and carries less fuel

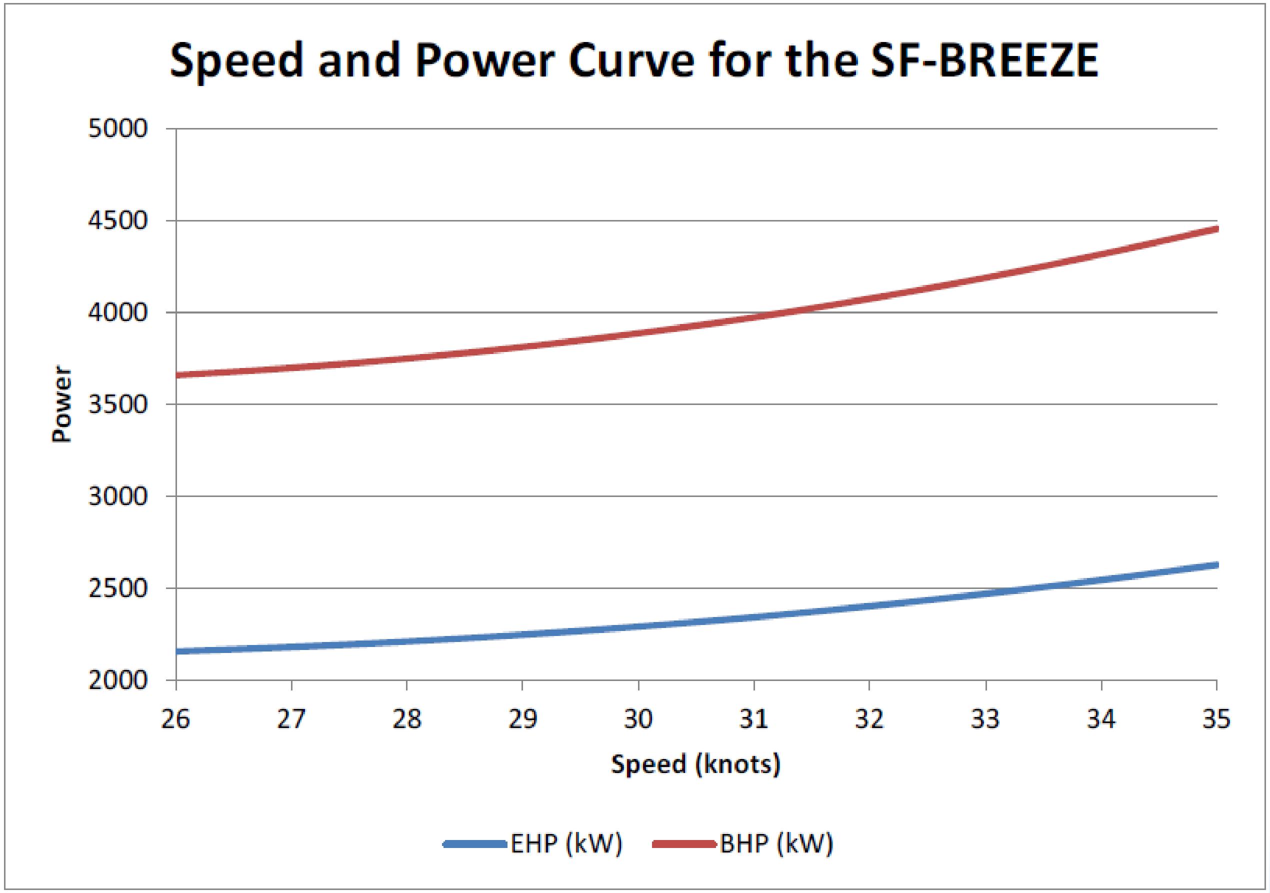
SF-BREEZE

150 Passengers
Propulsion Power at 35 kts = 4.4 MW
PEM Fuel Cells (120 kW racks)
Fuel Cell Efficiency = 51% at full power
LH_2 from fossil NG or renewable
Fuel sized for half-day with 20% margin

Vallejo

300 Passengers
Propulsion Power at 35 kts = 3.4 MW
Two MTU 16V4000 Diesel Engines
Conventional Diesel Fuel
Engine efficiency = 41.9% at full power
Fuel sized for full day with 100% margin

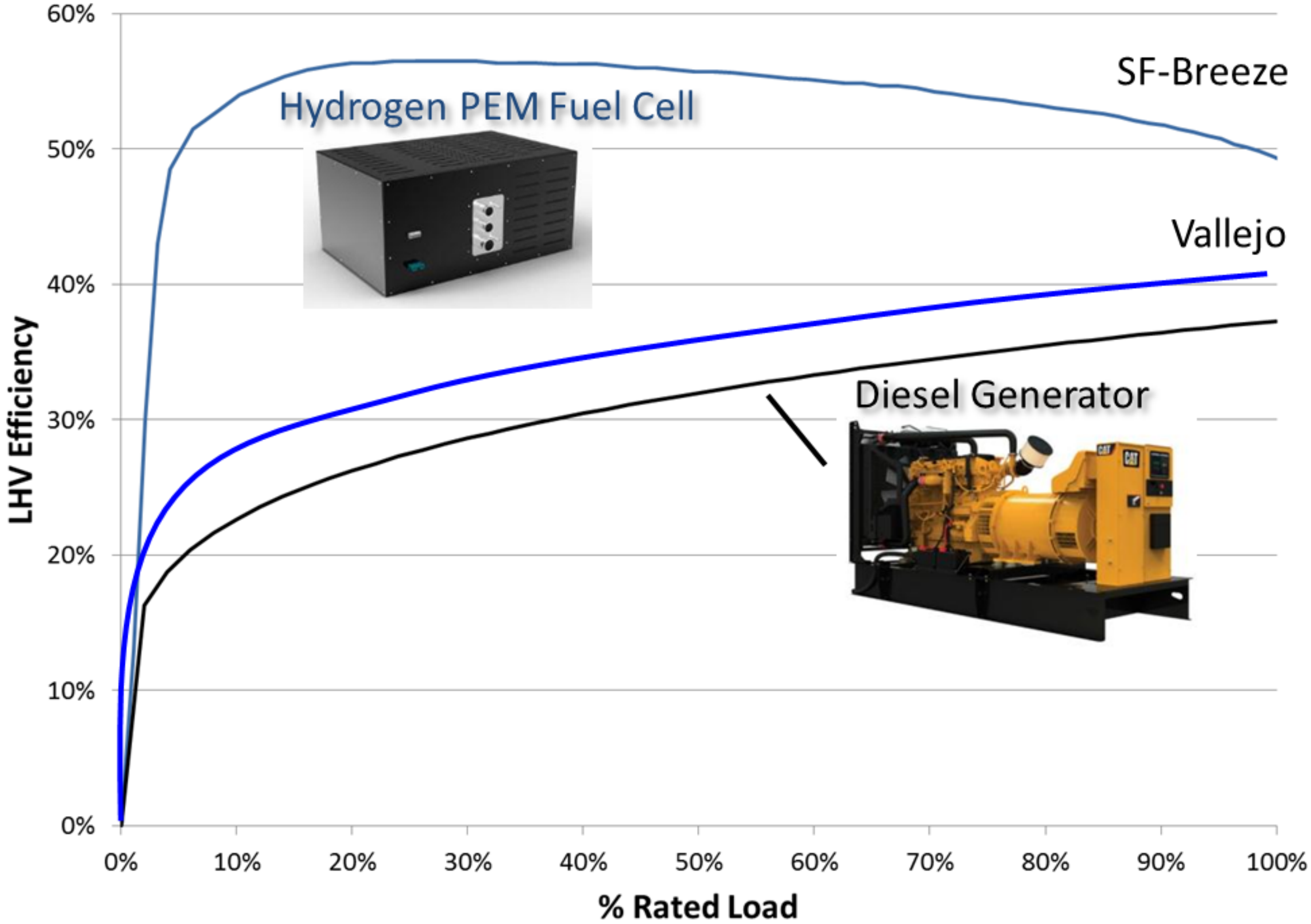
What is the "sweet spot" for zero emission hydrogen vessels? Maybe bigger and slower…



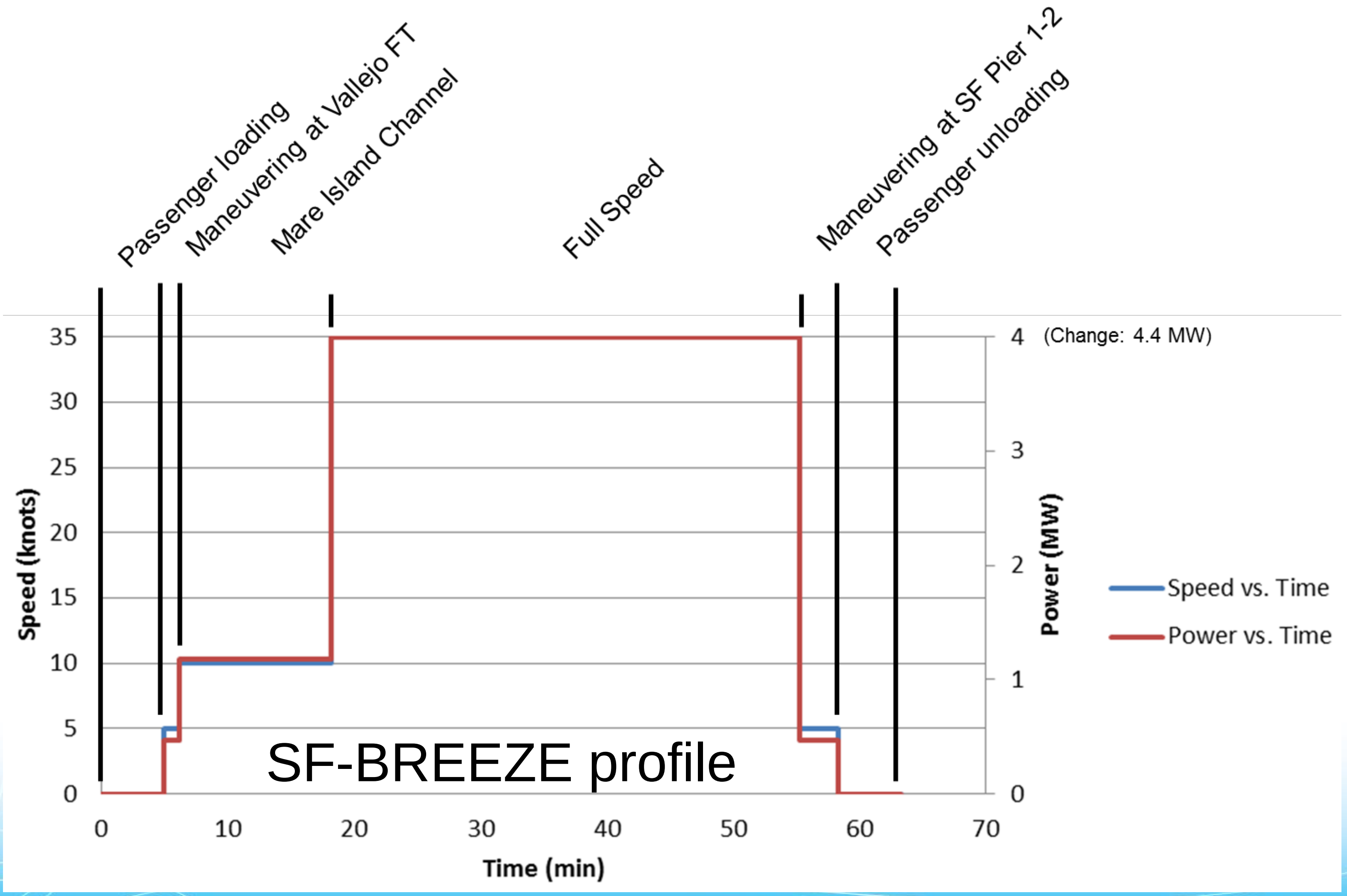
…and/or reduce fuel cell weight and volume.

Fuel cells like part load, diesels do not.

Higher efficiency = Less fuel burned



Perhaps hydrogen fuel cell vessels are better suited for applications with more part-load operation.



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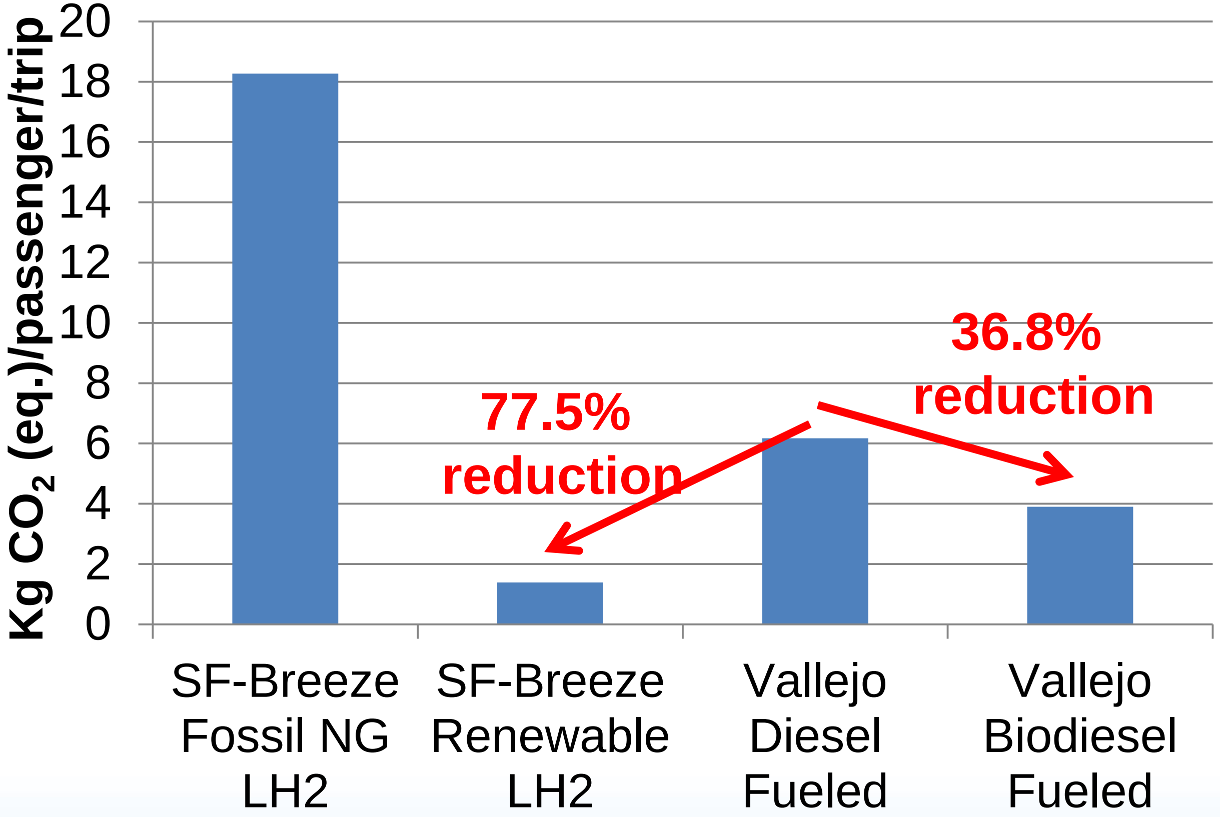
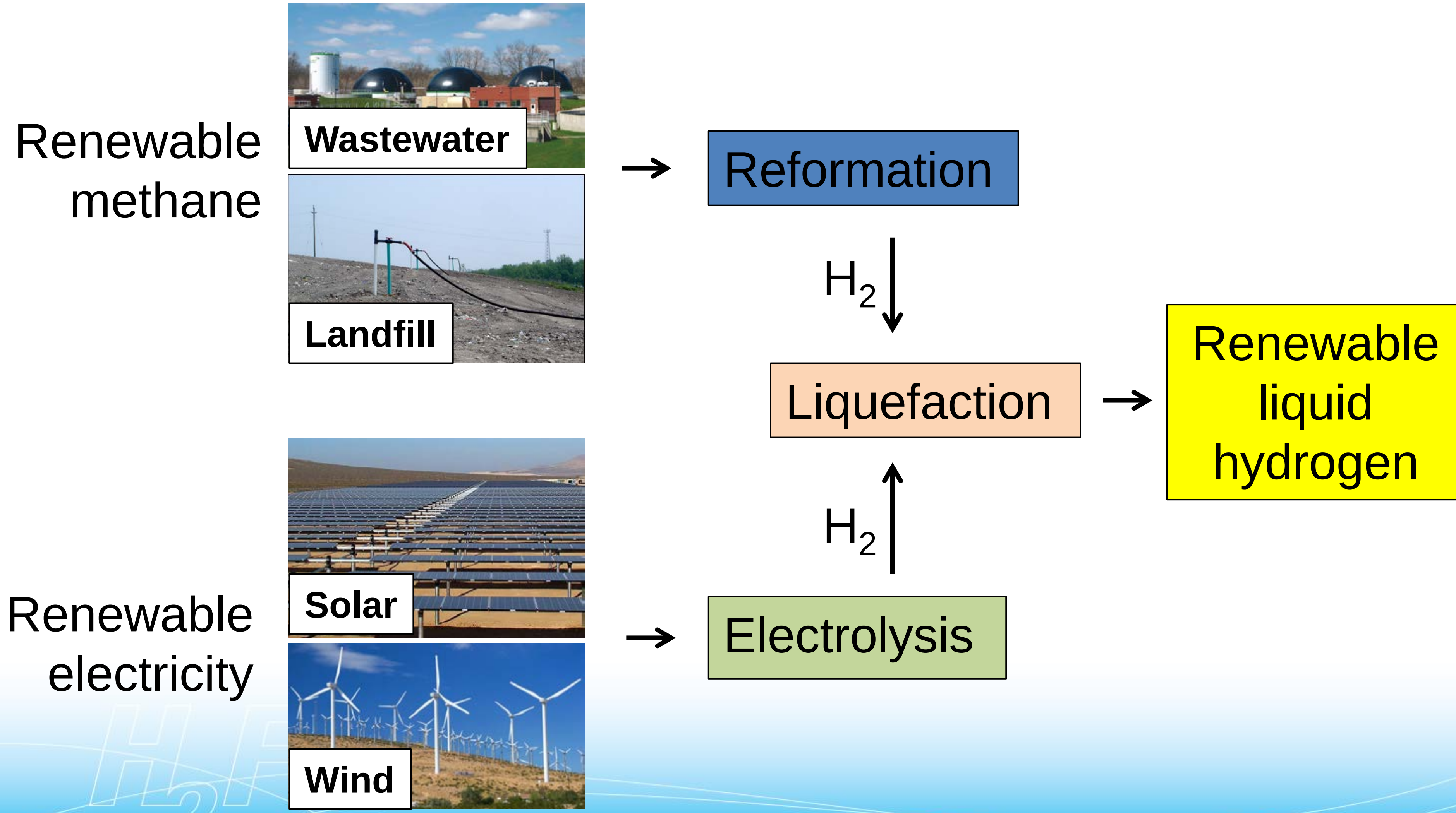
On a per-passenger basis, dramatic reductions in GHG emissions are achievable with the SF-BREEZE, but it requires the use of renewable LH_2



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.



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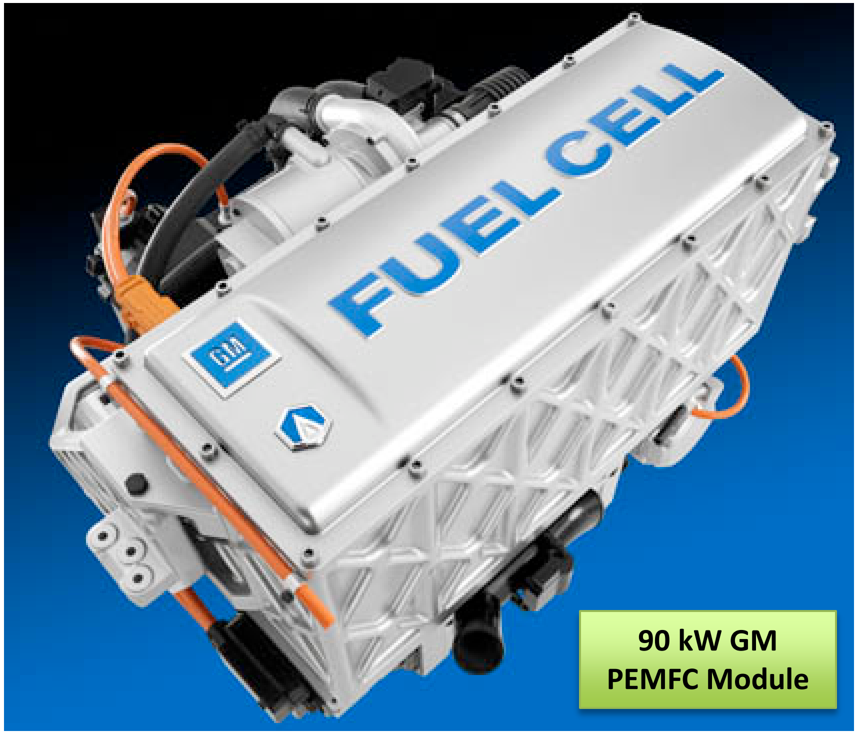
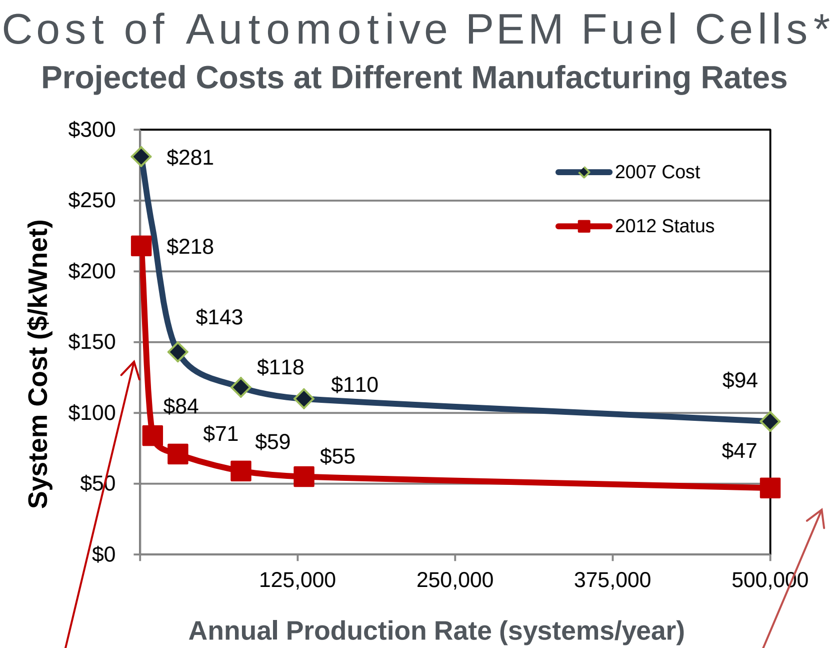
The H_2+FC system has a higher capital and higher per-unit fuel cost than the diesel engine system

- Fuel cell capital
- Fuel expense difference
  - Affected by operating profile
  - Renewable hydrogen appears difficult to predict
- Need to quantify operating benefits
  - Maintenance
  - Monetization of pollution/health effects

Fuel cell cost is high but can come down if the automotive market is successful.





**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**