Total Cost of Ownership (TCO) Analysis for Hydrogen Fuel Cells in Maritime Applications – Preliminary Results

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Fuel Cells and Hydrogen in Maritime Applications

Hydrogen fuel cells can play an important role in curbing the emissions of regulated and unregulated pollutants in maritime applications

- Sustainable marine transportation
- Future restrictions on marine diesel oil
- Tighter standards on emissions of sulfur oxides and NO_x

Hydrogen fuel cells must also compete with low-sulfur marine gas oil (LSMGO) and liquefied natural gas (LNG) combustion engines on the basis of total cost of ownership (TCO)

- TCO defined to include the cost of fuel; levelized cost of propulsion/auxiliary engines, propulsion system, and fuel storage system; and the cost of annual maintenance, lifetime overhaul, and consumables
- 10% internal rate of return (IRR) applied to the initial capital investment
- To avoid uncertainties due to price volatilities, inflation not applied to fuel cost

Hydrogen fuel cells are an emerging technology*

DOE-FCTO Targets	Current	Interim	Ultimate	References
FCS for heavy duty trucks, $/kW	285	130	60	[22]
FCS lifetime, h	25,000	30,000	35,000	[22]
Delivered hydrogen cost, $/kg	9	7	4	[22]
	Container	Ferry	Tug	
LH_2 storage system, Million $	10	1.7	0.59	[8,13-19]
Annual FCS maintenance, $	607,000	78,000	65,000	[23]

All results in this report are based on FCTO targets for fuel cell trucks. Future work will develop specific requirements and evaluate potentials for fuel cells for maritime applications.

Maritime Fuels: LSMGO, LNG and LH_2

We are using LSMGO as the reference fuel for maritime applications considered in this study.

- Harbor tugs and ferries operate in Emissions Control Areas (ECA) that effectively limit sulfur content in fuel to <0.1% as in low-sulfur marine gas oil (LSMGO).
- From 2020, IMO regulations will cut sulfur dioxide emissions by 86%, reducing worldwide (container ships) sulfur content in fuel from 3.5% (IFO) to 0.5% (MGO).
  - Ships operating in international waters must install scrubbers if burning IFO, or switch to MGO. The scrubber option is not evaluated in this study.
  - Ships using MGO must switch to LSMGO (or install scrubbers) after entering the ECA zone.
  - Small difference in price of MGO and LSMGO

Fuel Characteristics

- On LHV basis, 1 gallon of LSMGO is equivalent (MGE) to 3.0 kg-NG, or 1.215 kg-H_2
  1 MGE = 7.0 L-LNG = 17.2 L-LH_2
- On price basis, LSMGO = $0.016 $/MJ; LNG = $0.013 $/MJ; LH_2 = $0.075 $/MJ

	Density kg/m^3	LHV MJ/kg	Bunkered Price, $/ton	Comments
LSMGO	900	42.8	700	https://shipandbunker.com
LNG	428	48.6	616	MGO density range: 850 - 910 kg/m^3
LH_2	70.8	120	9,000	LH_2 cost: Eudy and Post [23]

In this report, ton (t) refers to metric ton and equals 1000 kg

TCO Analysis for Selected Maritime Applications

Photo courtesy of Wärtsilä

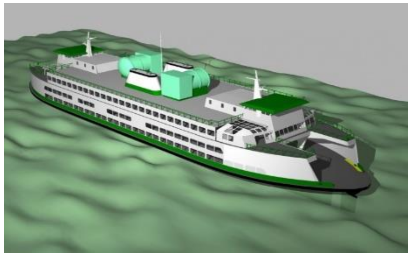


Photo courtesy of Washington State Ferries

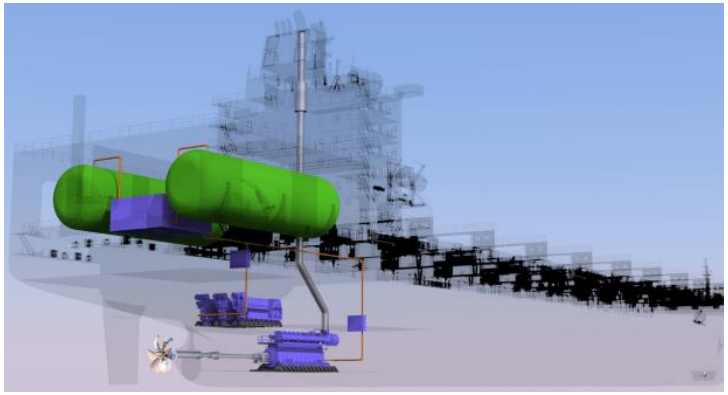


Photo courtesy of General Dynamics NASSCO

Wärtsilä LNG Tugboat[1]

- Main Dimensions: 28.8(L)X13(W)X6(D)m, 495 T
- Performance: 55-T pull, 12 nm/h service speed
- Dual Fuel Tank: 25-m^3 LNG, 50-m^3 fuel oil
- Propulsion: 2x9L DF:3330 kW, WST-18 thruster

M/V Issaquah: Auto/Passenger Ferry[2]

- Main Dimensions: 100(L)X24(W)X5.1(D)m
- Performance: 1200 passengers, 124 Vehicles
- Fuel Tank: Diesel (2X43 m^3 LNG – conceptual)
- Propulsion: 4.5 MW main, 1.2 MW auxiliary

Isla Bella LNG Container Ship[3]

- Main Dimensions: 233(L)X32(W)X10(D)m
- Performance: 2100-TEU (36,571 T), 1100 nm
- Dual Fuel Tank: 2x900-m^3 LNG (475,000 gallon)
- Engine: 26-MW main, 3 x1.74-MW auxiliary

AIDAnova LNG Cruise Ship[4]

- Main Dimensions: 337(L)X42(W)X9(D)m, 180 kT
- Performance: 5,200 passengers, 1,500 crew
- Fuel Tank: 3,600 m^3 LNG for 14-days operation
- Genset: 62 MW (37 MW propulsion)

Each application includes gensets or auxiliary power: cold ironing at ports not considered.

Container Ship – Engine and Fuel Systems

Container Ship	
Max Slot Capacity, TEU	**2100**
Roundtrip Distance, nm	**2200**
Roundtript Duration, h	**168**
Sail time, h	**116**
Average Speed, h	**19**
Service Life, y	**25**

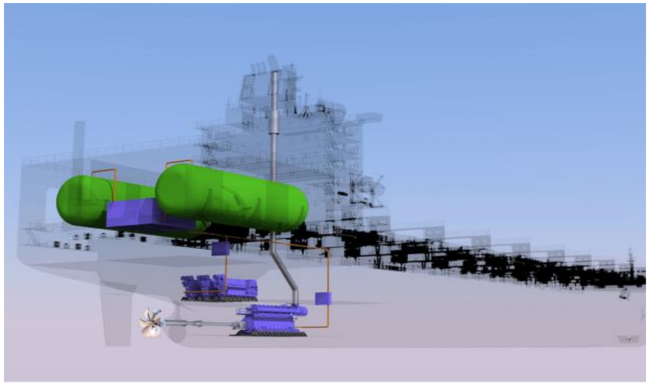


Photo courtesy of General Dynamics NASSCO

Isla Bella LNG Container Ship

- Main Dimensions: 233(L)X32(W)X10(D)m
- Performance: 2100-TEU (36,571 T)
- Engine: 25-MW main, 3x1.74-MW auxiliary
- Dual Fuel Tank: 2x900-m^3 LNG (475,000 gallon)

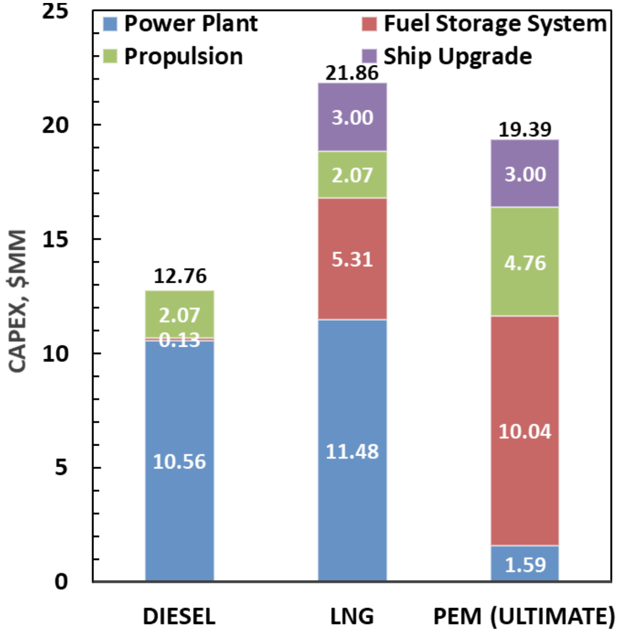
	LSMGO	LNG	LH_2-FC
Engine			
Propulsion, MW	25.0	25.0	26.5
Auxiliary Genset, MW	5.7	5.7	
Fuel Storage			
Main Fuel, t	467	342	163
Secondary Diesel, t		39	
Main Fuel, m^3	2,500	1,800	3,300
Secondary Diesel, m^3		300	
Fuel Consumption			
Main Fuel, g/kWh	172	146	60
Genset Fuel, g/kWh	197	169	

FCS Container Ship

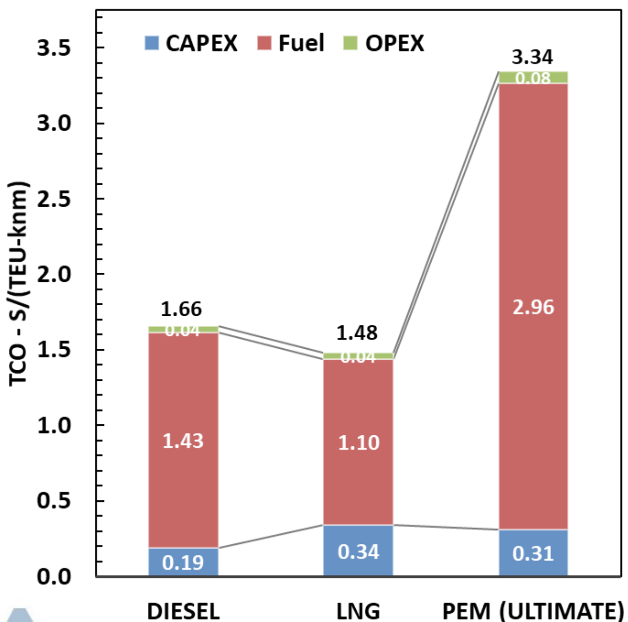
- A 26-MW FCS replaces 25-MW propulsion engine and 3 x 1.74 MW auxiliary genset
- Container ship refueled with LH_2 once per round trip, 4 x 820 m^3 tanks. LNG tanks have excess capacity. LSMGO refueled once a month.
- On LHV basis, comparable efficiencies of LSMGO (48.9%), LNG (49.6%) and LH_2 (50%) fuel options

TEU: twenty-foot equivalent units; nm: nautical mile

Container Ship – TCO



	LSMGO	LNG	LH_2-FC
CAPEX			
Propulsion, $/kW	280	350	60
Auxiliary Genset ($/kW)	380	505	
No_x Emission Control ($/kW)	50		
Gearbox/Electric Motor, $/kW	70	70	120
Power Conditioning, $/kW	60	60	60
Fuel Storage System, $/$m^3$	50	2,830	2,960
Ship Upgrade, k$		3,000	3,000
OPEX			
Main Fuel, $/ton	700	620	4000
Secondary Diesel, $/kg		700	
Maintenance, k$/yr	290	460	607
Comsumables, k$/yr	170		
Lifetime Overhaul, k$			200



FCS Container Ship

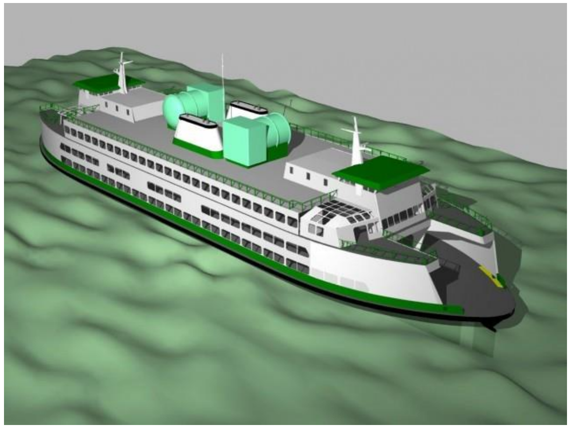
- FCS has lower initial cost: room to increase efficiency and durability at higher cost
  - ➢ OPEX includes current/interim/ultimate stack replacement cost after 25/30/35 kh
- LH_2 storage system cost > propulsion system cost > FCS cost
- TCO dominated by fuel cost: LNG option slightly cheaper than diesel and much cheaper than LH_2
- LH_2 break-even cost at 57% efficiency: 2030 $/ton
- LNG fuel cost factors per MMBTU basis: $4 NG, $5 liquefaction, $4 transport and bunkering

Only ultimate cost targets for FCS ($60/kW) and H_2 ($4,000/ton) included in this report

Ferry – Engine and Fuel Systems

Washington State Ferries (WSF) - Issaquah Class RoPax				
Number of Passengers	1200			
Number of Cars	124			
Route	Seattle-Bremerton, 13.5 nm			
	Time, min	**Engine Power, kW**	**# of Engines**	**Total Power, kW**
Transit	50	1,721	2	3442
Maneuvering	10	391	2	782
Docked	20	379	1	379
Auxiliary	80	202	2	404

	LSMGO	LNG	LH_2-FC
Engine			
Propulsion, MW	4.5	4.5	4.5
Auxiliary Genset, MW	1.2	1.2	
Fuel Storage			
Main Fuel, t	192	37	14
Secondary Diesel, t		48	
Main Fuel, m^3	200	86	190
Secondary Diesel, m^3		50	
Fuel Consumption			
Main Fuel, g/kWh	197	178	58
Secondary Diesel, g/kWh	215	205	

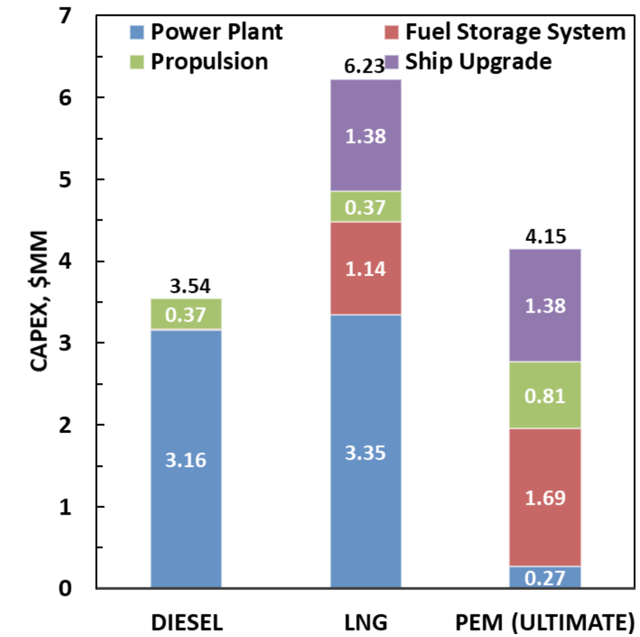


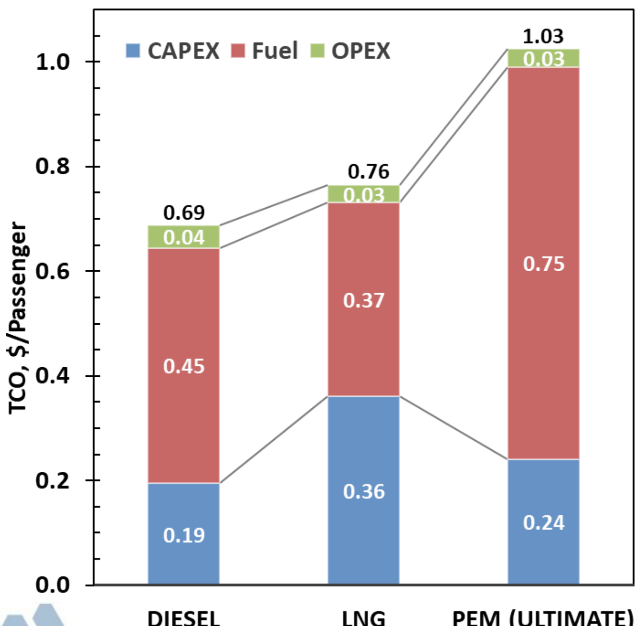
An illustration of LNG tanks on Issaquah class ferry. Image courtesy Washington State Ferries

FCS Ferry

- A 4.5-MW FCS replaces 2 x 2.25-MW propulsion engines and 3 x 300-kW auxiliary gensets
- Ferry refueled with LH_2 (or LNG) once every 5 d. LSMGO tank has excess capacity.
  - 2 x 43 m^3 LNG tanks vs. 2 x 95 m^3 LH_2 tanks
  - Above-deck location, tank size may not be a critical issue
- On LHV basis, LH_2-FCS has higher efficiency on ferry duty cycle: 52% vs. 43% for LSMGO and LNG systems

Ferry – TCO





	LSMGO	LNG	LH_2-FC
CAPEX			
Propulsion, $/kW	480	600	60
Auxiliary Genset, $/kW	540	718	
No_x Emission Control, $/kW	96		
Gearbox/Electric Motor, $/kW	70	70	120
Power Conditioning, $/kW	60	60	60
Fuel Storage System, $/m^3	50	12,606	8,540
Ship Upgrade, k$		1,375	1,375
OPEX			
Main Fuel, $/ton	700	620	4000
Secondary Diesel, $/ton		700	
Maintenance, k$/yr	83	105	78
Comsumables, k$/yr	53		
Lifetime Overhaul, k$			33

FCS Ferry

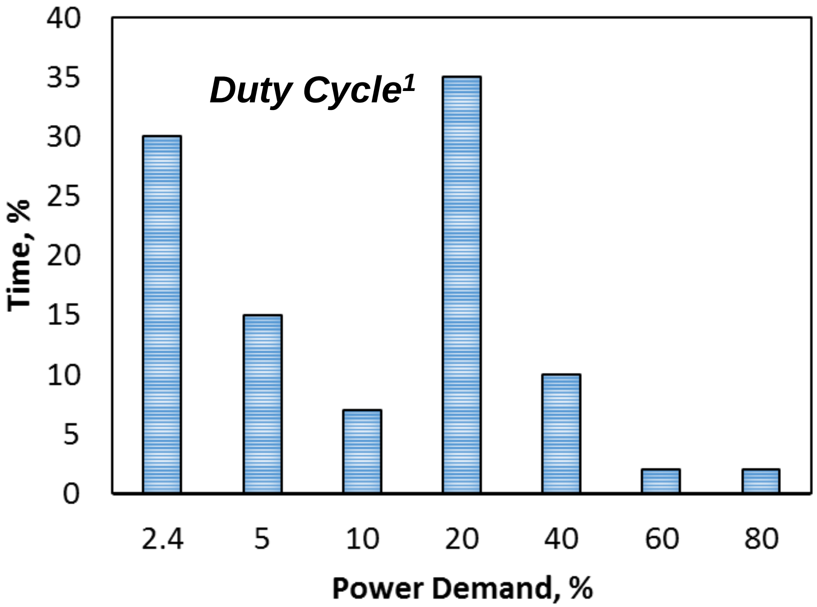
- FCS has lower initial cost: room to increase efficiency and durability at higher cost
  - ➢ OPEX includes current/interim/ultimate stack replacement cost after 25/30/35 kh
- LH_2 storage system cost > propulsion system cost > FCS cost
- TCO sensitive to fuel cost: LNG option comparable to diesel and much cheaper than LH_2
- LH_2 break-even cost at 60% efficiency: 2360 $/ton
  - ➢ FCS may compete with LSMGO and LNG options at slightly below ultimate H_2 cost target

Harbor Tug – Engine and Fuel Systems

LNG: 25 m^3 tank, below deck

Image courtesy of Wärtsilä

	LSMGO	LNG	LH_2-FC
Engine			
Propulsion, MW	3.6	3.6	4.5
Auxiliary Genset, kW	200	200	
Fuel Storage			
Main Fuel, t	48	10	3
Secondary Diesel, t		10	
Main Fuel, m^3	50	25	41
Secondary Diesel, m^3		10	
Fuel Consumption			
Main Fuel, g/kWh	221	195	53
Genset Fuel, g/kWh	235	205	



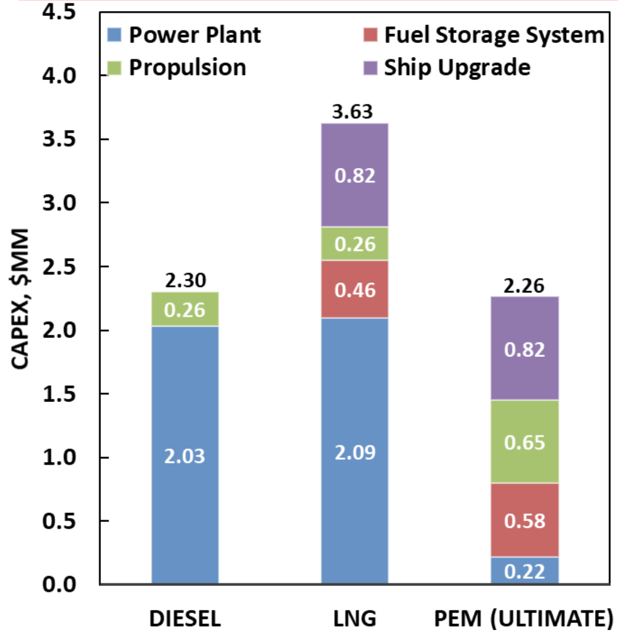
FCS Harbor Tug

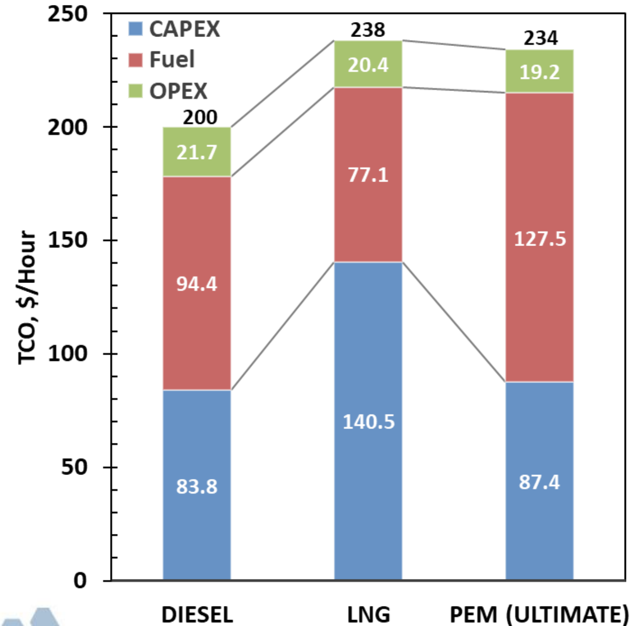
A 4.5-MW FCS replaces 2 x 1.8-MW propulsion engines and 2 x 100-kW auxiliary gensets

- Ferry refueled with LH_2 (or LNG) once every 4 d. LSMGO tank has excess capacity.
  - 25 m^3 LNG tank vs. 41 m^3 LH_2 tank
  - Below deck location, tank size may not be a critical issue
- On LHV basis, LH_2-FCS has higher efficiency on tug duty cycle: 57% vs. 38% for LSMGO and LNG systems

[1]Boyd, E. and Macperson, D. Using Detailed Vessel Operating Data to Identify Energy-Saving Strategies, ITS 2014, Germany

Harbor Tug – TCO





	ULS-MDO	LNG	LH_2-FC
CAPEX			
Propulsion, $/kW	426	535	60
Auxiliary Genset, $/kW	662	880	
No_x Emission Control, $/kW	97		
Gearbox/Electric Motor, $/kW	70	70	120
Power Conditioning, $/kW	60	60	60
Fuel Storage System, $/m^3	50	16,400	13,000
Ship Upgrade, k$		875	875
OPEX			
Main Fuel, $/ton	700	620	4000
Secondary Diesel, $/ton		700	
Maintenance, k$/yr	89	100	65
Comsummables, k$/yr	53		
Lifetime Overhaul, k$			26

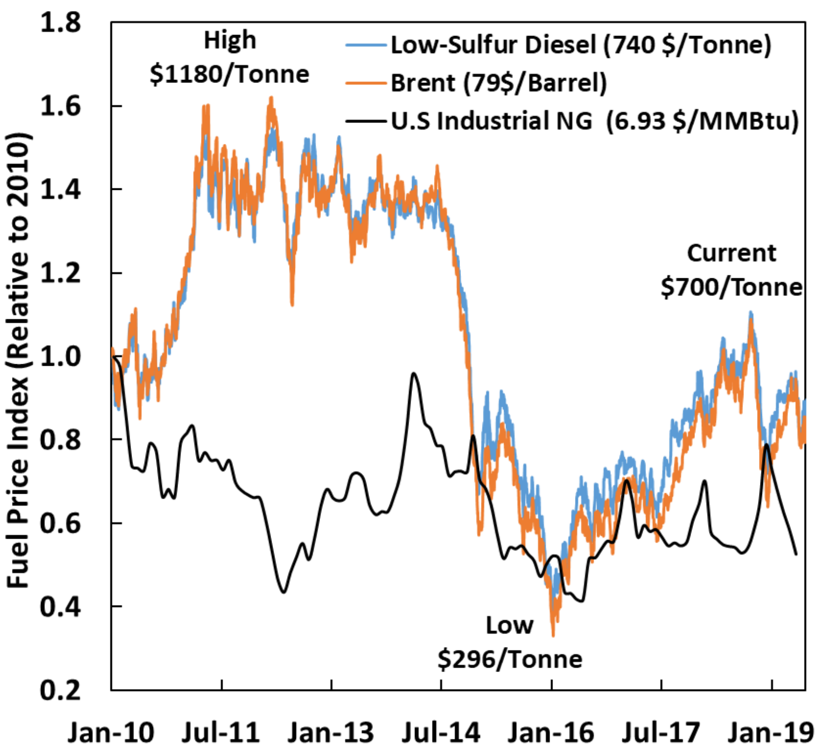
FCS Harbor Tug

- FCS has lower initial cost: room to increase efficiency and durability at higher cost
  - OPEX includes current/interim/ultimate stack replacement cost after 25/30/35 kh
- Propulsion system cost > LH_2 storage system cost > FCS cost
- TCO nearly equally sensitive to CAPEX and fuel costs
- On TCO basis, FCS competes with LSMGO and LNG engines at $4000/ton LH_2 cost
  - Break-even cost at 65% duty cycle efficiency: 3450 $/kg

Break-Even Cost of Bunkered LH_2

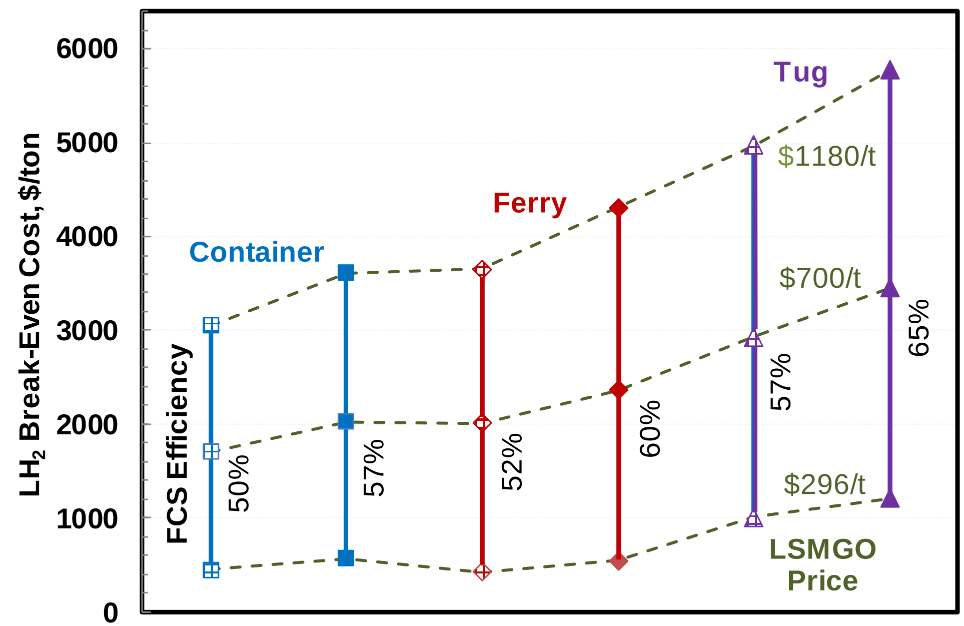
LSMGO Price

- LSMGO price follows the Brent index more closely than natural gas (NG)
- LSMGO price is volatile
  - ➢ Over the last 9 years, it has varied between \$245/t (low), \$700/t (current), and \$1185/t (high).



Break-Even Cost of Bunkered LH_2

- Break-even cost of bunkered LH_2 (\$/ton) as function of LSMGO price (low/current/high) and FCS efficiency
  - ➢ Container: 450 (low) – 1710 (current) – 3610 (high)
  - ➢ Ferry: 430 (low) – 2010 (current) – 4310 (high)
  - ➢ Harbor Tug: 1010 (low) – 2930 (current) – 5770 (high)



Prospects of Hydrogen Fuel Cells in Maritime Applications

Prospects of fuel cells depend on the types of maritime application

- Container ship: TCO dominated by fuel cost - difficult match for fuel cells at current LSMGO price ($700/t) and the ultimate target for hydrogen fuel cost ($4,000/t)
- Ferry boat: TCO sensitive to fuel cost - a modest $0.30 increase in ticket price needed for cost parity with LNG option
- Harbor tug: TCO equally sensitive to capex and fuel costs - fuel cells are competitive with LSMGO and LNG engines at slightly below the ultimate cost target

Higher efficiency fuel cells raise the break-even cost of bunkered hydrogen relative to $700/t LSMGO price

- Container ship: $2030/ton
- Ferry boat: $2360/ton
- Harbor tug: $3450/ton

Hydrogen storage for maritime applications

- Storing H_2 as liquid is the method of choice

Opportunities for further development

- Fuel cells for maritime auxiliary power
- Higher efficiency fuel cell systems taking advantages of lower projected costs
- Higher durability MEAs: advanced materials, system controls, optimized operating conditions
- Availability and reliability of FCS BOP components including air management
- Methods of meeting and exceeding the critical FCTO target of $4/kg-$H_2$ for light-duty vehicles and medium-duty and heavy-duty trucks

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Preliminary Total Cost of Ownership (TCO) Analysis Results

1. Container Ship

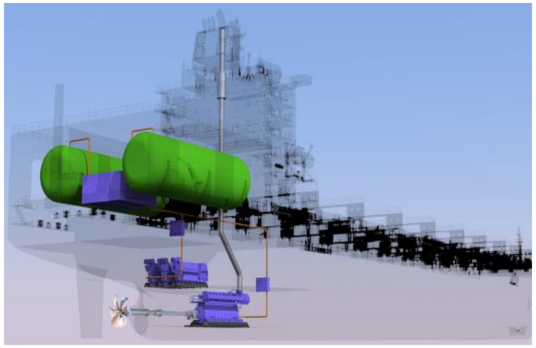
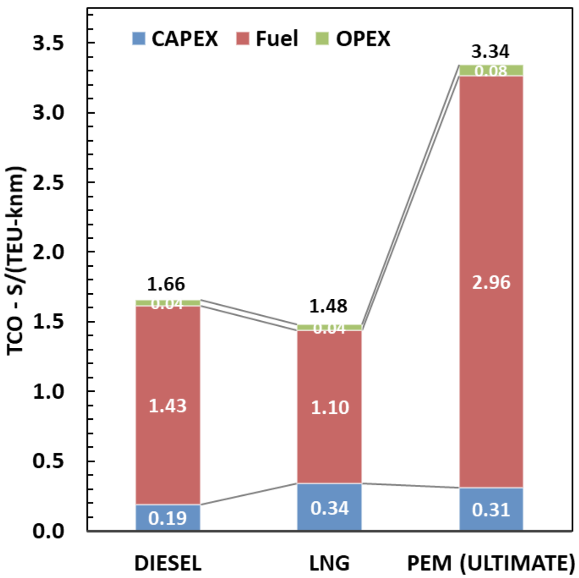


Image courtesy of General Dynamics NASSCO



2. Ferry

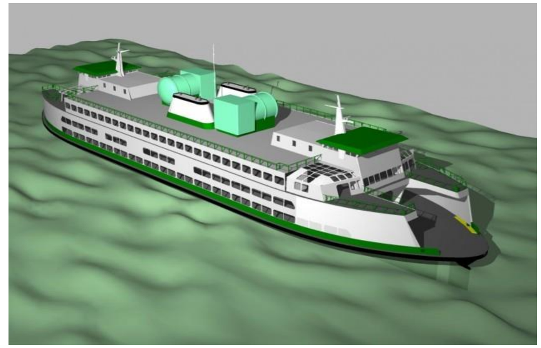
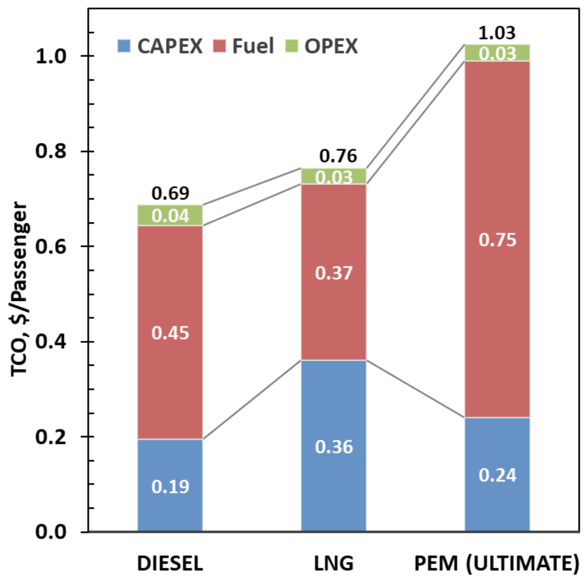
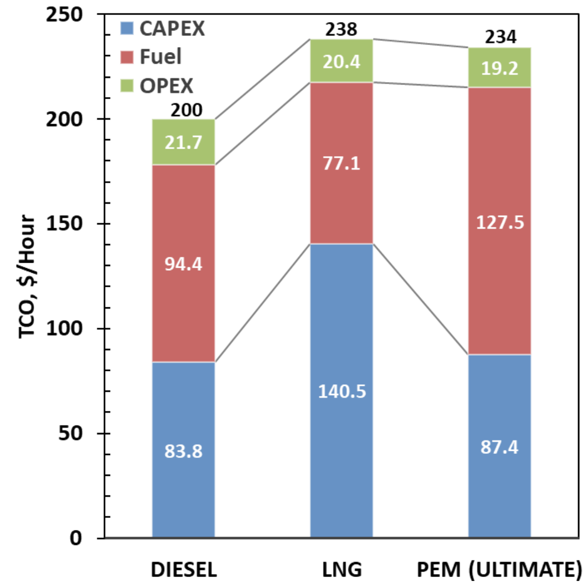


Image courtesy of Washington State Ferries



3. Harbor Tug

Image courtesy of Wärtsilä



Fuel cells with LH_2 storage could compete with low sulfur diesel and LNG ferries and tugs (if cost targets are met)