Rail and Maritime Metrics

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Project ID: TA034

Overview

Timeline

- Start date: Jan 2019
- End date: Open
- Percent complete: NA

Budget

- FY19 DOE Funding: $500 K
- Planned DOE FY20 Funding: $1000K
- Total DOE Project Value: $1500 K

Barriers (MT)

A. Inadequate Standards
E. Financing mechanisms (Lack of cost and performance data)
F. Inadequate experience
G. Lack of knowledge regarding the use of hydrogen

Partners/Interactions

- Caterpillar
- Cummins
- Wabtec
- Sandia National Laboratory

- This project evaluates and identifies opportunities for heavy-duty fuel cells (100 kW – 100 MW) in rail and maritime sectors and market introduction of H_2 at large scale (H2@Scale)

Objectives and Relevance

Rail metrics for line-haul freight locomotives, regional commuter passenger locomotives, and yard switchers

- Conduct system level analysis of fuel cell powertrains
- Model and analyze on-board gaseous and liquid hydrogen storage including tender cars
- Analyze hydrogen refueling infrastructure for rails
- Conduct total-cost-of-ownership analysis (TCO) and compare to the incumbent diesel technology
- Consistent with H2@Scale program objectives, identify early opportunities for hydrogen and fuel cells in locomotive applications and applications with most impact

Maritime metrics for harbor tugboats, auto/passenger ferries, and feeder container ships

- Conduct system level analysis of fuel cell powertrains
- Model and analyze on-board liquid hydrogen storage and on-board reforming options
- Analyze hydrogen refueling infrastructure for maritime applications
- Conduct total-cost-of-ownership (TCO) analysis and compare to the incumbent diesel technology
- Consistent with H2@Scale program objectives, identify early opportunities for hydrogen and fuel cells in maritime applications and applications with most impact

Rail and Maritime Metrics: Milestones

Rail Metrics		
Complete analysis of a dedicated liquid hydrogen infrastructure to refuel freight and passenger trains, and construct scenarios in which hydrogen can be produced at costs competitive with diesel.	12/31/2019	Quarterly Progress Measure (Regular)
Conduct simulations to determine hydrogen consumption on specific routes for freight and passenger trains and potential advantages of energy harvesting systems. Update TCO analyses for favorable routes.	3/31/2020	Annual Milestone (Regular)
Interface with other projects to determine the cost and performance of fuel cell systems and tender car for liquid hydrogen storage. Consider the costs of ruggedizing fuel cells to accommodate rail specific operations and tender car for safety in side collisions.	6/30/2020	Annual Milestone (Regular)
Complete TCO analyses of freight, passenger and yard switchers including the costs for refurbishing maintenance facilities and penalties incurred in switching to Tier IV diesel engines and emission standards. Compare costs with LNG as fuel option.	9/30/2020	Annual Milestone (Regular)
Complete analysis of a dedicated liquid hydrogen infrastructure to refuel container ships and construct scenarios in which hydrogen can be produced and bunkered at costs competitive with marine diesel.	12/31/2019	Quarterly Progress Measure (Regular)
Maritime Metrics		
Complete conceptual design and TCO analysis of ammonia as a fuel for maritime applications, considering off-site production and alternative propulsion systems based on ammonia combustion engine and solid oxide fuel cell options.	3/31/2020	Annual Milestone (Regular)
Complete TCO analysis of hydrogen infrastructure dedicated to support all port applications including ships, rubber tired gantry (RTG) cranes, reach stackers, yard tractors, and cold ironing.	6/30/2020	Annual Milestone (Regular)
Complete TCO analysis of hydrogen infrastructure dedicated to support all port applications including ships, rubber tired gantry (RTG) cranes, reach stackers, yard tractors, and cold ironing.	6/30/2020	Annual Milestone (Regular)
Complete TCO analysis of fuel cell container ships, ferries and tug boats with dedicated liquid hydrogen infrastructure and inputs from other projects on maritime fuel cells and liquid hydrogen storage for maritime applications.	9/30/2020	Annual Milestone (Regular)

Collaborations and Interactions

Rail LH_2 Refueling and Siting Issues	Sandia National Laboratory
Rail LH_2 Tender Car	Chart Industries, Inc
Federal Railroad Administration (FRA/USDOT)	Rail Safety - LH_2 and Fuel Cells
Fuel Cells and H_2 for Rails	2019 H2@Rail Workshop, Michigan State University, Lansing, MI, March 26 - 27, 2019
Fuel Cells and H_2 for Maritime Applications	2019 H2@Ports Workshop, Marines' Memorial Club & Hotel, San Francisco, CA September 10 - 12, 2019

Rail Metrics: Total Cost of Ownership (TCO)

Freight, Regional Passenger and Yard Switcher Locomotives ($/kWh)

- Lifetime cost of locomotive, maintenance/refurbishment and fuel levelized over total service hours (kWh)
- TCO for 30-y locomotive service life
  - ✓ Engine lifetime: 10 y for freight and regional, 15 y for yard switcher
  - ✓ $2.25/gal diesel fuel (R-1 Railroad Annual Reports for 2018, www.stb.gov)
  - ✓ 10% internal rate of return

	Freight	Regional	Switcher
Engine (BHP)	4,430	3,023	2,115
Fuel Tank Capacity (gal)	5,000	5,000	2,000
Locomotive Operating Hours (MWh/year)	3,300	2,340	535
Fuel Consumption (gal/year)	230,000	186,000	46,000
Average Specific Fuel Consumption (g/kWh)	222	225	279
Total Locomotive Cost ($)	3,000,000	6,900,000	2,100,000
Maintenance Cost ($/year)	125,000	150,000	75,000
Overhaul Lifetime Cost ($)	524,000	633,000	175,000
Fuel Cost ($/kWh)	0.16	0.16	0.19
Levelized Cost ($/kWh)	0.30	0.50	0.76

- Freight locomotives: Fuel accounts for ~53% of TCO. Besides engine reliability and availability, locomotive, maintenance & engine overhaul, and fuel costs are extremely important.
- Regional locomotives: Fuel accounts for 32% of TCO. Locomotive, maintenance, and fuel costs are important.
- Switcher locomotives: Fuel accounts for 25% of TCO. Locomotive, maintenance, and fuel costs are important.

Fuel Cell System Cost

System costs projected using 90-kW_e automotive style stacks, 2 stacks/module, 2 modules for 360-kW_e heavy-duty vehicles (HDV)*

Current PEM systems (\$285/kW_e)

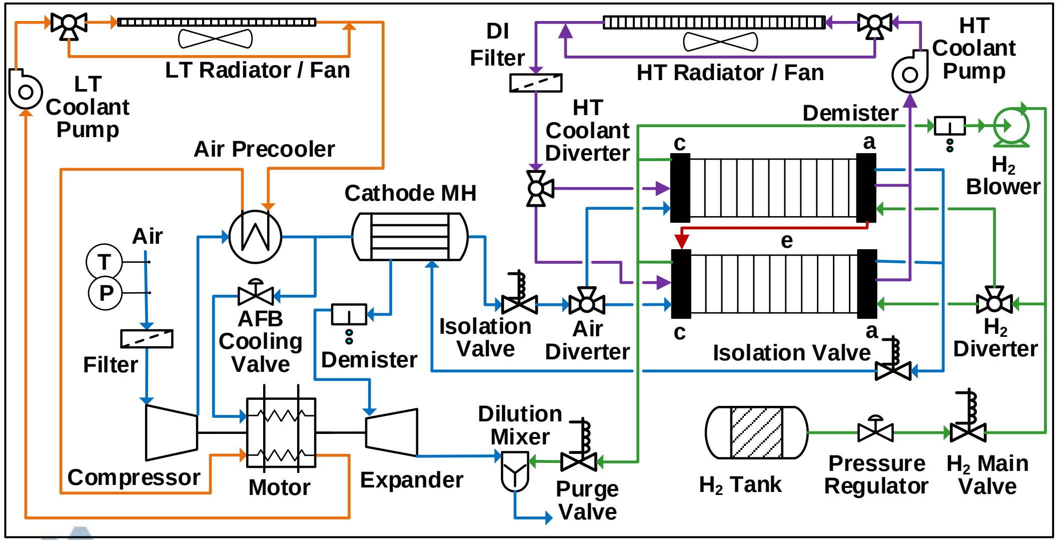
- Pt or Pt alloy cathode electrodes with 0.35 mg/cm^2 Pt loading, 400-kW_e gross power, assembled at low production volumes (100 HDV systems/year)

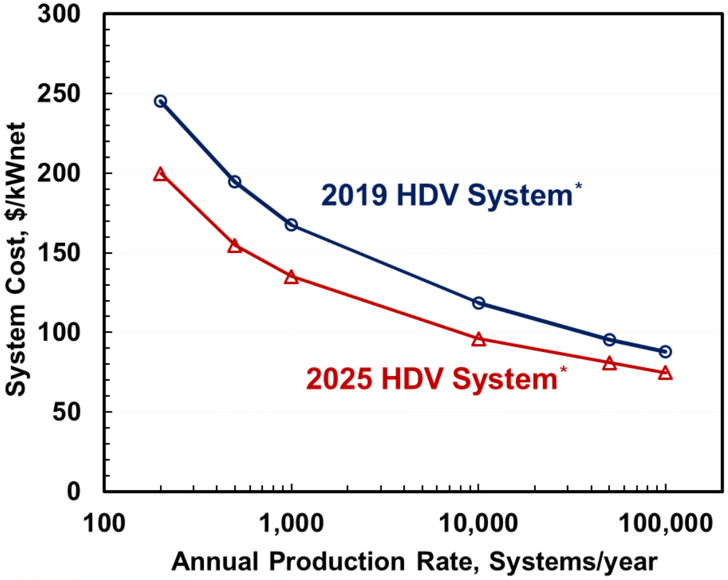
Interim PEM systems (\$130/kW_e)

- Same configuration as current systems, cost savings due to higher production volumes (5,000 HDV systems/year)

Ultimate PEM systems (\$60/kW_e)

- Cost savings from higher production volumes (>100,000 HDV systems/year) and technology advancements (higher activity catalysts with lower Pt loading, improved air management system)





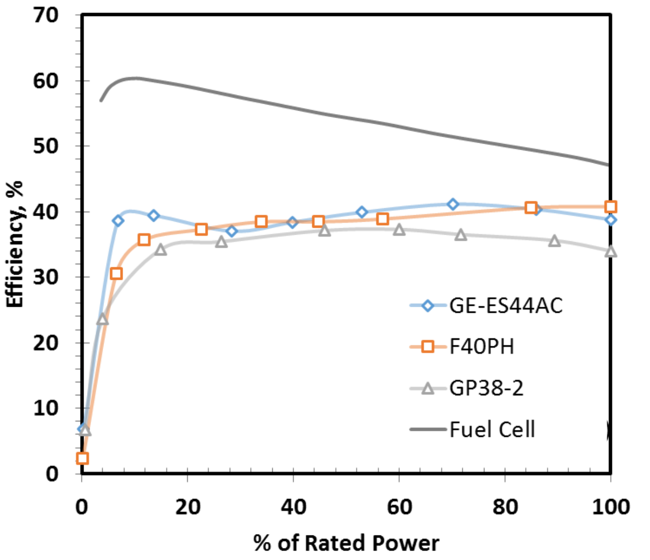
*Strategic Analysis, Fuel Cell System Analysis, Fuel Cell Tech Team Meeting, 20 February 2019

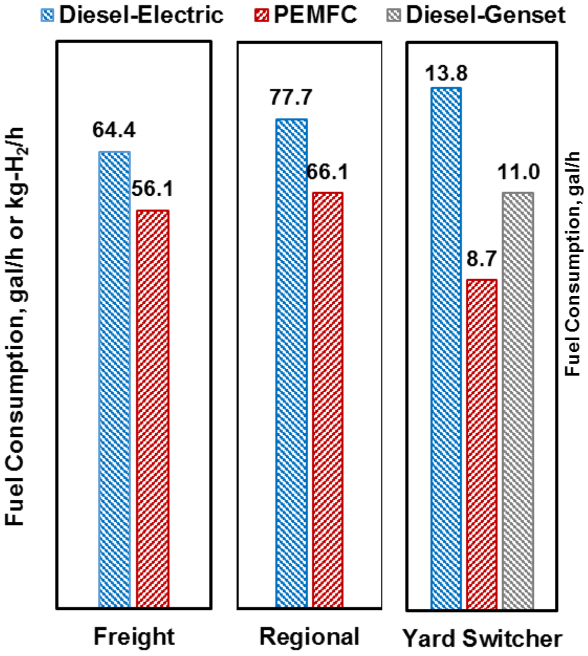
Drive Cycle Efficiency

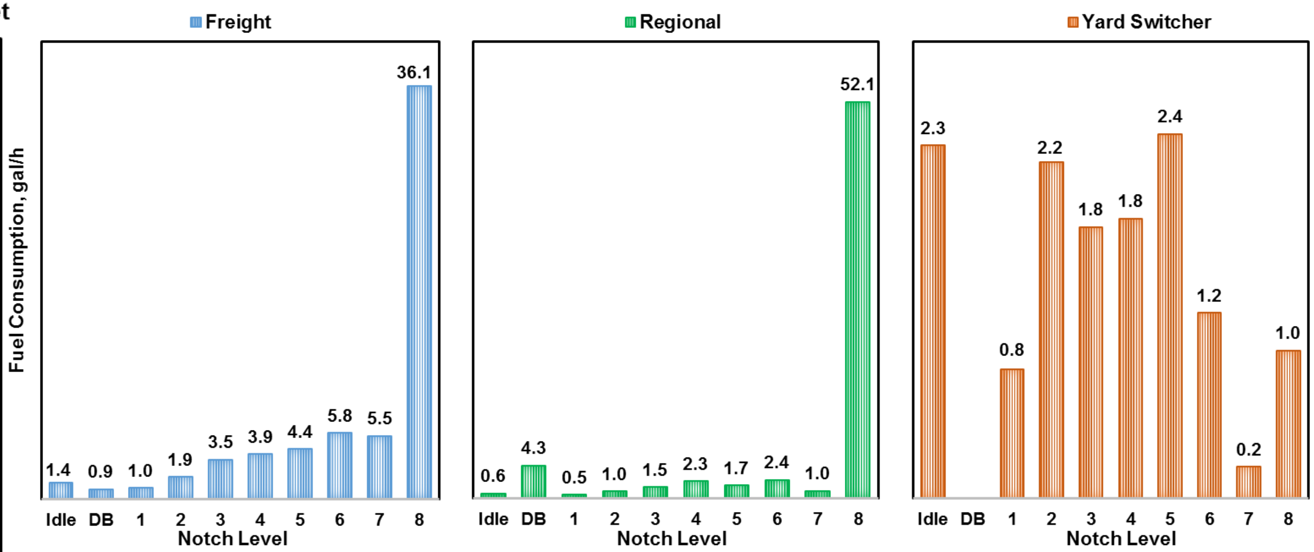
Drive Cycle Efficiency (DCE) on EPA Duty Cycles

DCE: Ratio of kWh produced to kWh in fuel consumed on drive cycle

- Freight: Significant fuel consumption at high notch levels where diesel is most efficient. DCE: 38% diesel, 49.5% FCS
- Regional: Frequent start-stops, actual cycle depends on service route. DCE: 37.5% diesel, 51% FCS
- Yard Switcher: Significant fuel consumption at idle and low notch levels where FCS has distinct advantages. DCE: 30% diesel, 53% FCS







- **Duty Cycle Regional - Piedmont passenger service by Amtrak. Graver, B. and Frey, C. (2015). Comparison of Over-the-Rail and Rail Yard Measurements of Diesel Locomotives. Environ. Sci. Technol., 49, 13031−13039**
- **Duty Cycle Freight/Switcher: EPA**

Hydrogen Storage System Cost

Cryo-Compressed Hydrogen (CcH_2) Storage System for Freight and Regional Locomotives

Freight Locomotives: One tender car needed, 4850 kg-H_2 stored at 500 bar, 70 K

- 93 m^3 and ~48.5 tonne required storage volume and weight for ~10 wt% gravimetric and 50 g/L volumetric capacities

Regional Locomotives: Tender car not needed, if 1 refueling/day, 500-kg stored H_2

Liquid H_2 tender in lieu of CcH_2 tender also needs to be investigated

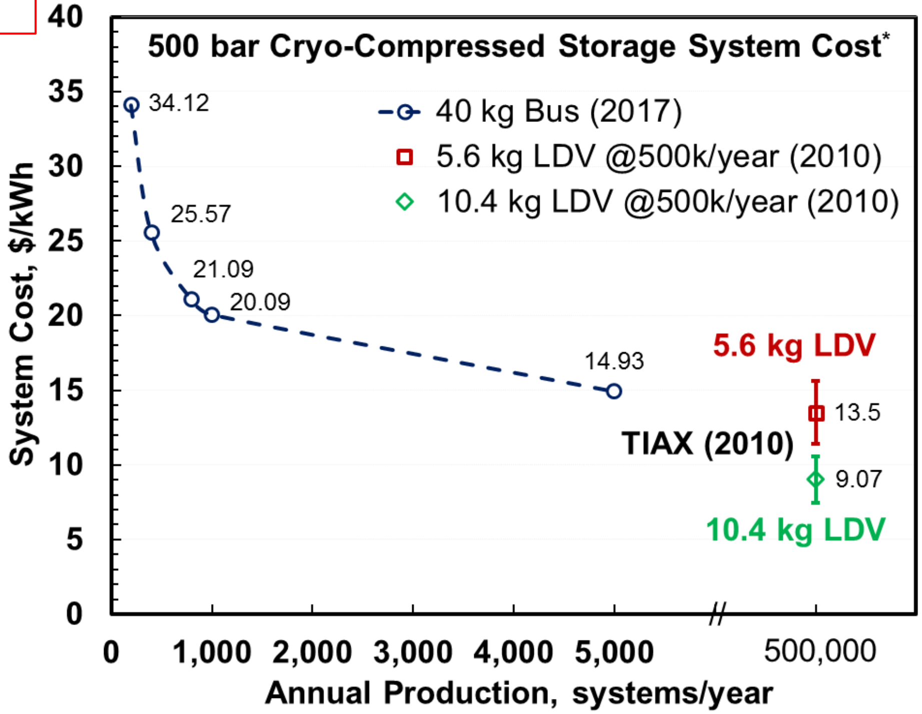
350-bar Compressed Hydrogen (cH_2) Storage System for Switcher Locomotives

Tender car not needed for 100 kg-H_2 stored at 350 bar, room temperature

- 5 m^3 required storage volume for 6-7 wt% gravimetric and ~19 g/L volumetric capacities

Projected CcH_2 Storage System Costs

- **Current PEM:** \$1130/kg-H_2 (200 HDV systems/year)
- **Interim PEM:** \$500/kgkg-H_2 (5000 HDV systems/year)
- **Ultimate PEM:** \$266/kg (DOE target)



Dispensed Hydrogen Cost

- AC Transit, CA: 13 buses, 2 stations, liquid H_2 delivery / electrolysis
- Sunline, CA: 10 buses, on-site SMR, new station electrolysis based
- OCTA, CA: 1 bus, H_2 purchased from local retail stations
- SARTA, OH: 7 buses, liquid H_2 delivery
- Fuel cost: \$9/kg-H_2 (current), \$7/kg-H_2 (interim), \$4/kg-H_2 (ultimate)

Agency	AC Transit[1]	SunLine[2]	OCTA[3]	SARTA[4]
Data period	2/13-7/17	3/12-10/18	3/16-12/18	2/18-12/18
Number of months	54	80	34	11
Average H2 cost, $/kg	8.39	10.17	13.95	5.14
Maximum H2 cost, $/kg	10.26	26.02	16.99	5.88
Minimum H2 cost, $/kg	6.49	2.53	12.99	5.00
Overall FCEB fuel cost, $/mile	1.41	1.82	1.47	1.03
Baseline technology	Diesel	CNG	CNG	CNG/diesel hybrid
Average fuel cost, $/gal or gge	2.43	0.96	1.15	1.89 / 2.30
Overall baseline fuel cost, $/mile	0.57	0.32	0.32	0.45 / 0.51

Overall cost Comparison to baseline

Fuel cost is based on data provided by agencies, not all are equal comparisons

[1] Delivered cost
[2] Includes station O&M
[3] Retail cost from local public stations
[4] Delivered cost

Leslie Eudy, Summary of Fuel/Energy Costs for NREL Evaluation Projects, NREL ZEB Technology Showcase and Symposium, February 6, 2019

Fuel Cell System Maintenance Cost

Average long term or life-cycle maintenance costs

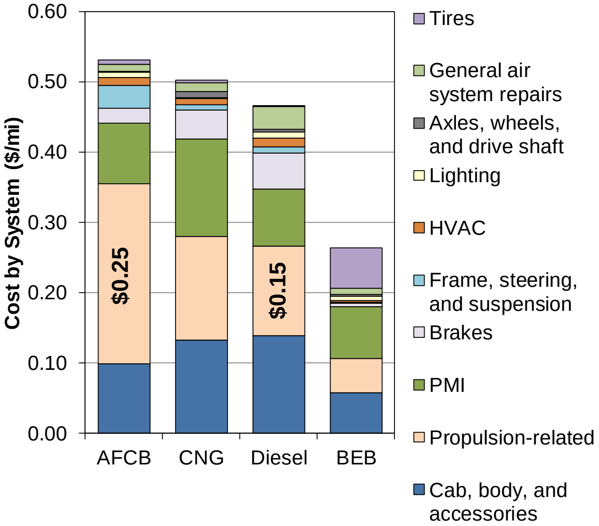
- Diesel electric locomotives: 1-1.5 $/mile (Prices and costs in the railway sector, J.P. Baumgartner, 2001, LITep)
- Diesel electric locomotives: $125,000/year (California Air Resources Board)
- Diesel electric locomotives: 30-40% maintenance cost due to engine (Ephraim, M. Maintenance and Capital Costs of Locomotives, Electro-Motive Division, GM)

FCS vs. diesel engine relative maintenance cost from FCEB data: 1.67 (current)

- Majority of issues with FCS are due to balance of plant and not stack: air handling, blowers, cooling pumps, plumbing

Summary of FCEB Data through February 2018

	2017 Fleet Average	2018 Fleet Max	2018 Fleet Average	2016 Target	Ultimate Target	Target Met
Bus lifetime (years)	4.7	7.5	5.5	12	12	
Bus lifetime (miles)	118,989	189,168	128,656	500,000	500,000	
Powerplant lifetime[a] (hours)	13,801	27,330	13,041	18,000	25,000	2016
Bus availability (%)	76	90	71	85	90	
Roadcall frequency[b] (bus)	4,710	4,715	4,516	3,500	4,000	Ultimate
Roadcall frequency (fuel cell system)	20,705	23,741	18,026	15,000	20,000	Ultimate
Maintenance cost ($/mi)	1.03	0.56	0.53	0.75	0.40	
Fuel economy (mpdge)[c]	6.51	7.82	7.01	8	8	
Range (miles)[d]	247	357	300	300	300	



Leslie Eudy, Technology Validation: Fuel Cell Bus Evaluations. DOE Hydrogen and Fuel Cells Program, 2018 Annual Merit Review and Peer Evaluation Meeting

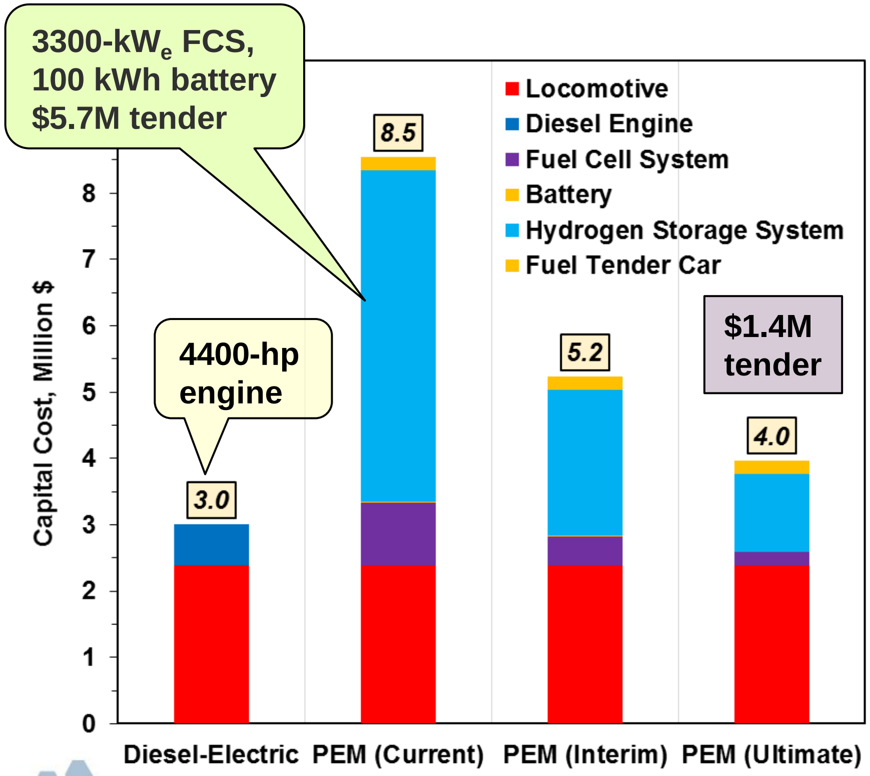
Total Cost of Ownership – Fuel Cell Freight Locomotives

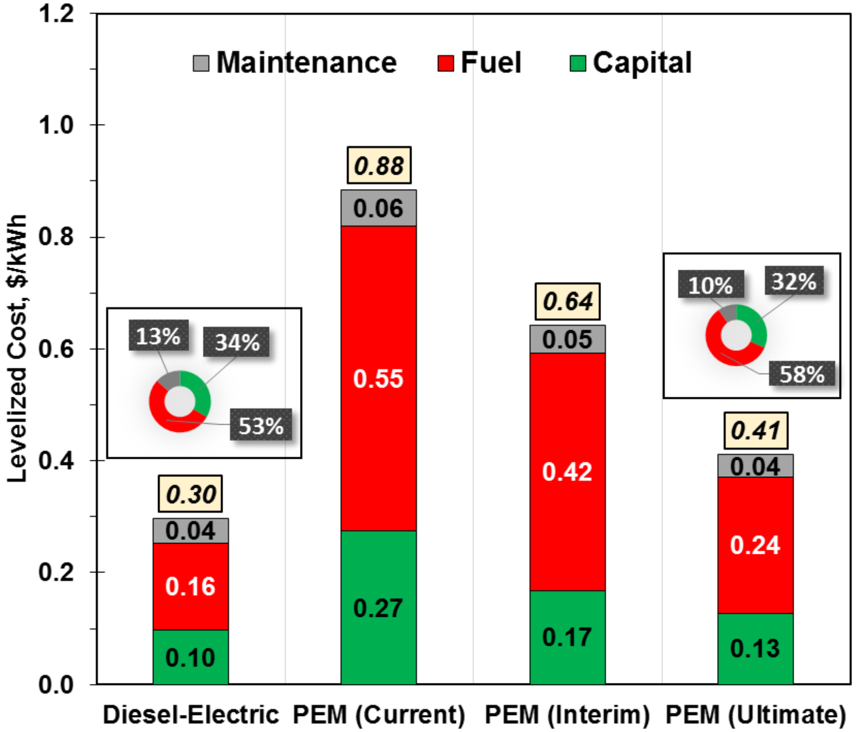
A challenging application for fuel cells because ~75% of fuel is consumed in freights at notches 6, 7 and 8 where diesel engines are most efficient

- Projected gain in FCS drive cycle efficiency relative to diesel engine: 30%
- **Break-even delivered hydrogen cost relative to $2.25/gal diesel: $2.20/kg**

Other factors that may favor fuel cells

- Stricter emission standards for diesel locomotives
- More expensive diesel fuel: EIA projects increase of 21% by 2030 and 27% by 2035
- Carbon credits and if hydrogen is produced from renewables

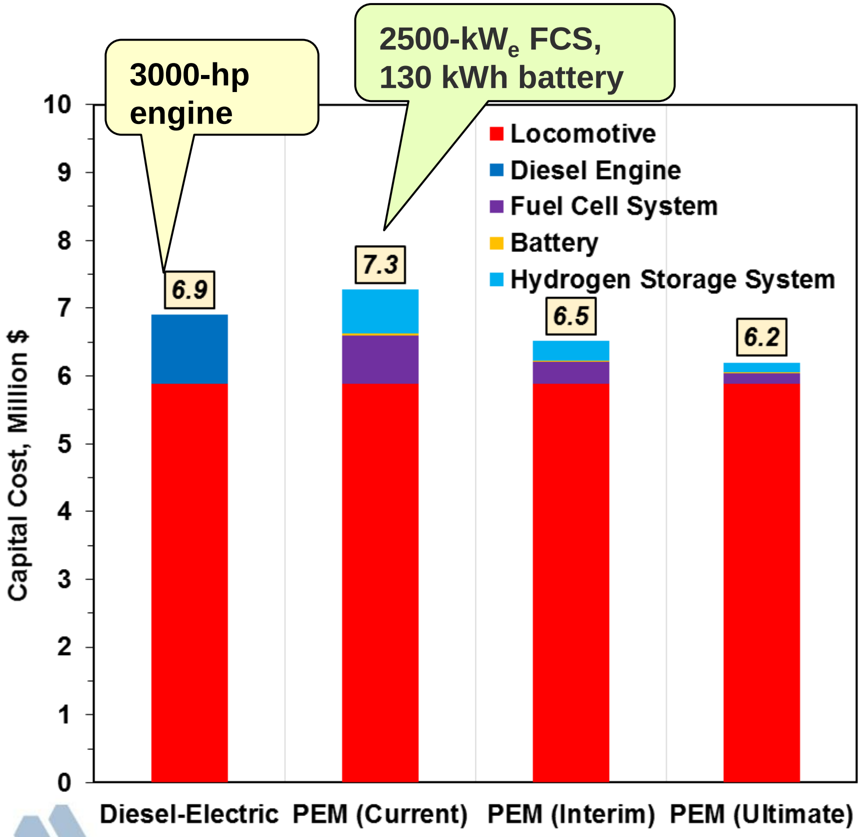


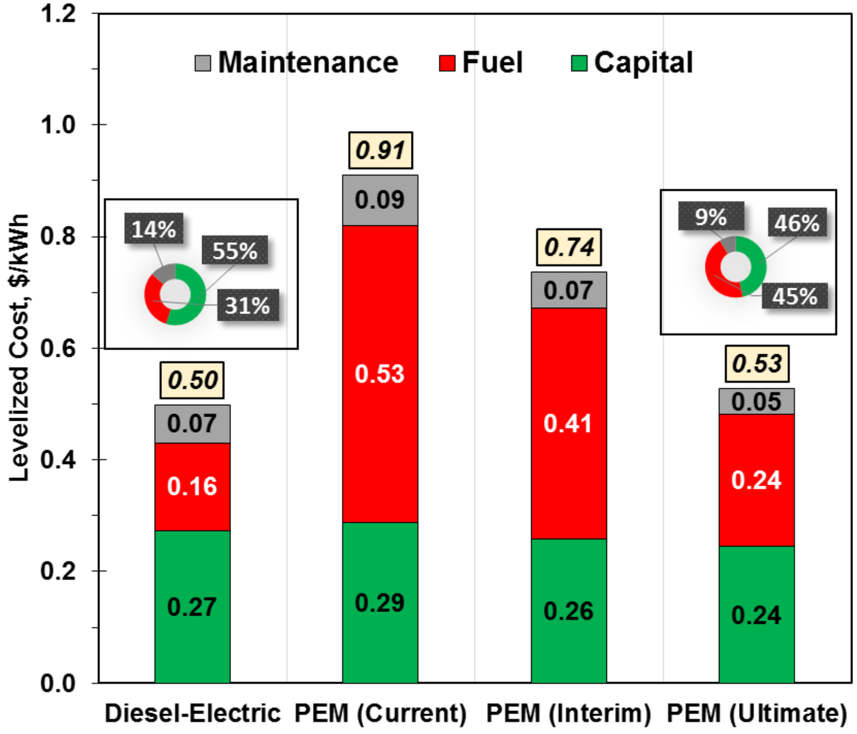


Total Cost of Ownership
Fuel Cell Regional-Passenger Locomotives

Preliminary TCO of fuel cells more suitable for regionals than freights

- Higher projected gain in FCS drive cycle efficiency relative to diesel engine because the metropolitan duty cycle includes frequent stops and low speeds: 37%
- With 1 refueling/day, only 500-kg H_2 storage is required and can be accommodated without a tender car if H_2 stored as cryo-compressed gas. May also be feasible to eliminate the tender car with 350-bar cH_2 storage system.
- **Break-even delivered hydrogen cost relative to \$2.25/gal diesel: \$3.50/kg**

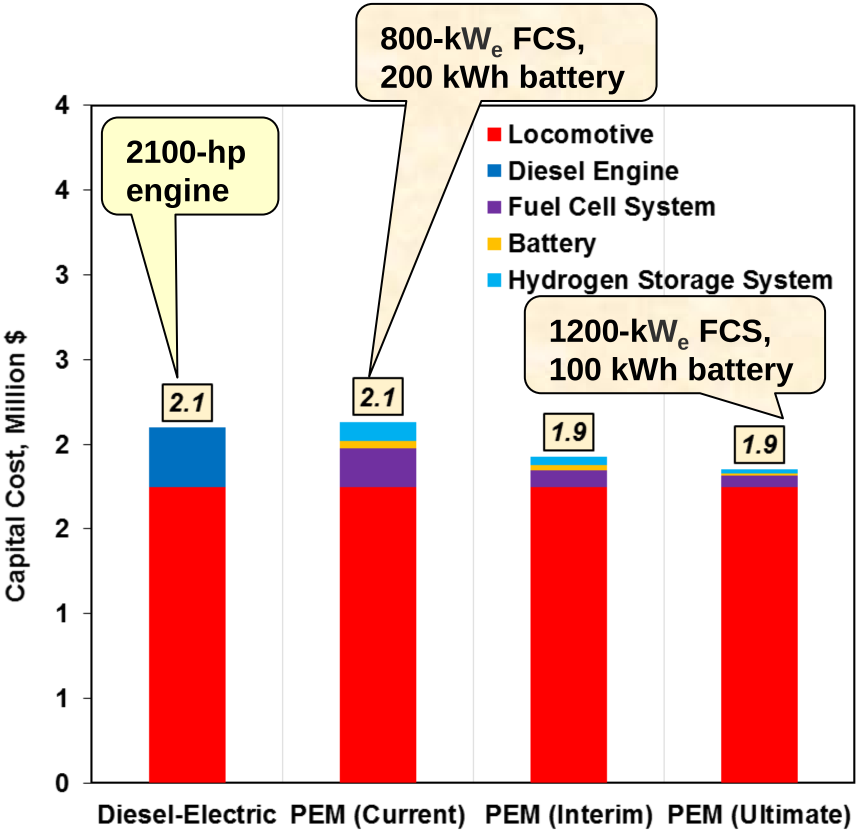




Total Cost of Ownership
Fuel Cell Yard-Switcher Locomotives

Preliminary TCO of fuel cells more favorable for yard switchers than freights or regionals

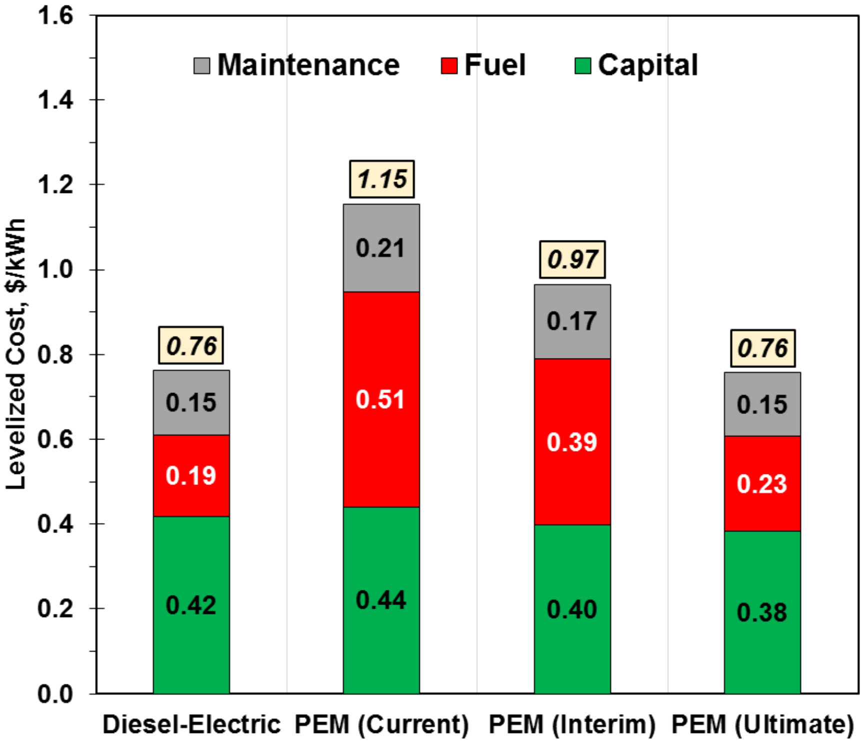
- On EPA duty cycles for switchers, 76% higher FCS drive cycle efficiency relative to diesel engine
- On TCO basis, fuel cells can be cost competitive if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at $4/kg
- **Break-even delivered hydrogen cost relative to $2.25/gal diesel: $4.00/kg**



2100-hp engine

800-kW$_e$ FCS, 200 kWh battery

1200-kW$_e$ FCS, 100 kWh battery



Rail Metrics: Summary and Outlook

Task 1: Summary and Future Work

Preliminary TCO of fuel cells more favorable for yard switchers than freights and regionals

- Future targets favor a 1200-kW_e fuel-cell dominant hybrid with 120 kWh battery
- 76% higher drive cycle efficiency than diesels on EPA duty cycles
- On TCO basis, fuel cells can be cost competitive if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at $4/kg

Break-even delivered hydrogen cost relative to $2.25/gal diesel

- Freight locomotives: $2.20/kg
- Regional passenger locomotives: $3.50/kg
- Yard switcher locomotives: $4.00/kg

Hydrogen storage for locomotives

- Fuel tender car with liquid hydrogen refueled CcH_2 storage system for freight locomotives: 4,800 kg stored H_2, 80 kg/min refueling rate for 1-h refueling time
- CcH_2 or 350-bar cH_2 storage for regional locomotives, 500 kg stored H_2
- 350-bar cH_2 storage for yard switcher locomotives, 100 kg stored H_2

Opportunities for further development

- Higher efficiency fuel cell systems taking advantages of lower projected costs and modularity
- Higher durability MEAs: advanced materials, system controls, optimized operating conditions
- Availability and reliability of FCS BOP components including air management
- May be desirable to develop single stacks >250 kW_e
- Methods for meeting and exceeding the critical target of $4/kg-$H_2$ at pump

Maritime Metrics: 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

Task 2: Approach

Photo courtesy of Wärtsilä

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

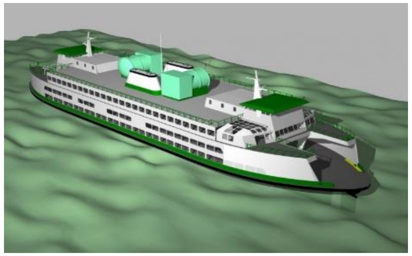


Photo courtesy of Washington State Ferries

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 (2X95 m^3 LNG – conceptual)
- Propulsion: 4.5 MW main, 1.2 MW auxiliary

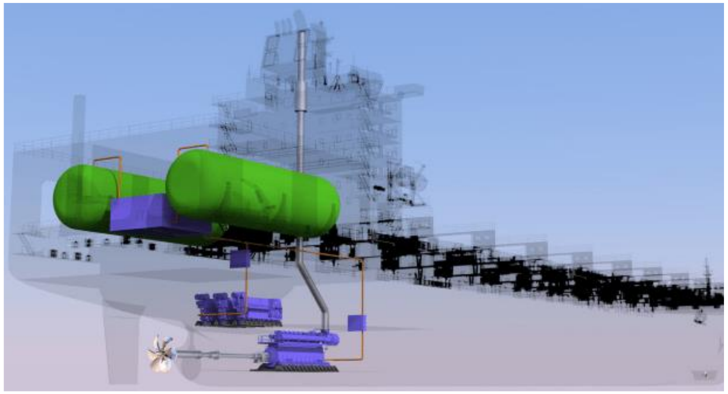


Photo courtesy of General Dynamics NASSCO

Isla Bella LNG Container Ship[3]

- Main Dimensions: 233(L)X32(W)X10(D)m
- Performance: 3100-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

Photo Credit: Carnival Corp.

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	**3100**
Roundtrip Distance, nm	**2200**
Roundtrip Duration, h	**168**
Sail time, h	**116**
Average Speed, h	**19**
Service Life, y	**25**

Isla Bella LNG Container Ship

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Photo Credit: TOTE Maritime

	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
Secondary Diesel, g/kWh	197	169	

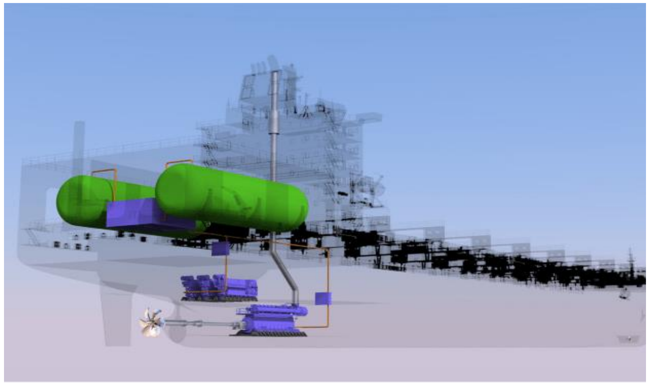


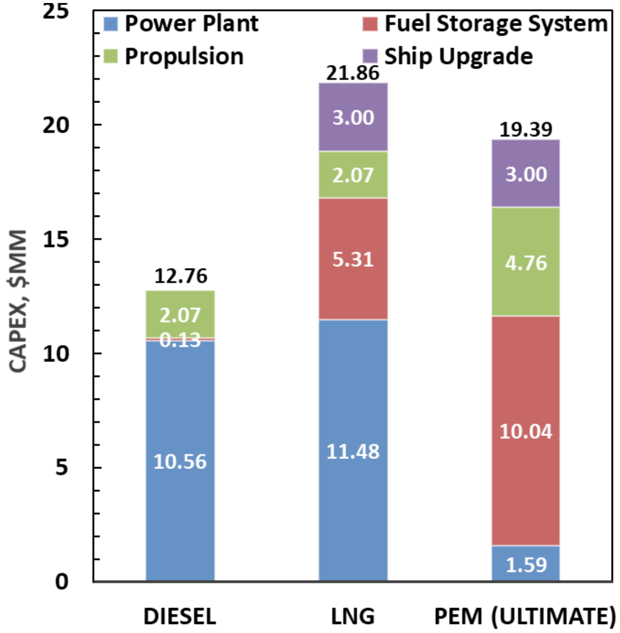
Photo courtesy of General Dynamics NASSCO

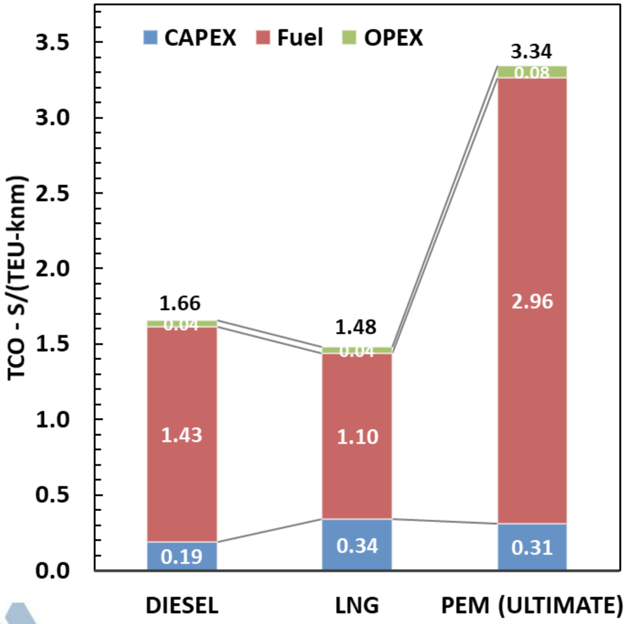
FCS Container Ship

- 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

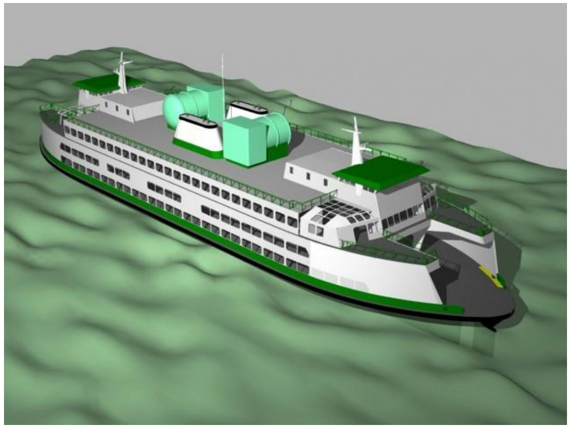
- FCS has lower initial cost: room to increase efficiency and durability at higher cost
  - ➢ OPEX includes current/interim/ultimate stack replacement cost after 25/30/35 kh
- LH_2 storage system cost > propulsion system cost > FCS cost
- TCO dominated by fuel cost: LNG option slightly cheaper than diesel 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	?	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	

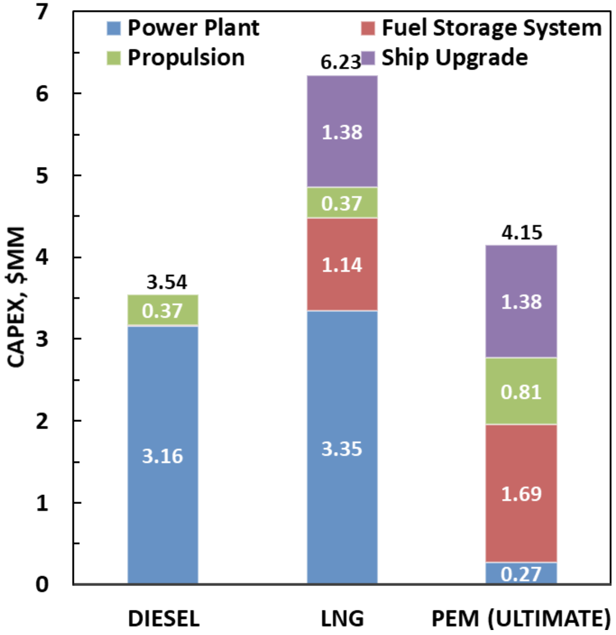


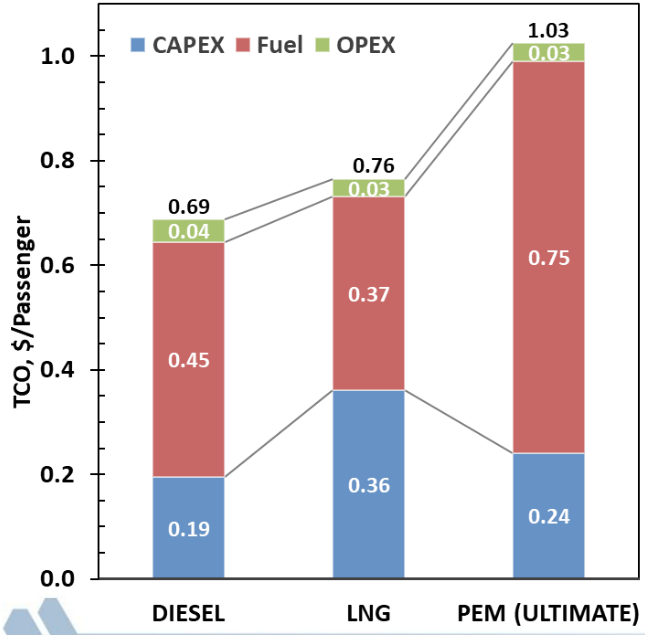
An illustration of LNG tanks on Issaquah class ferry. Image courtesy Washington State Ferries

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

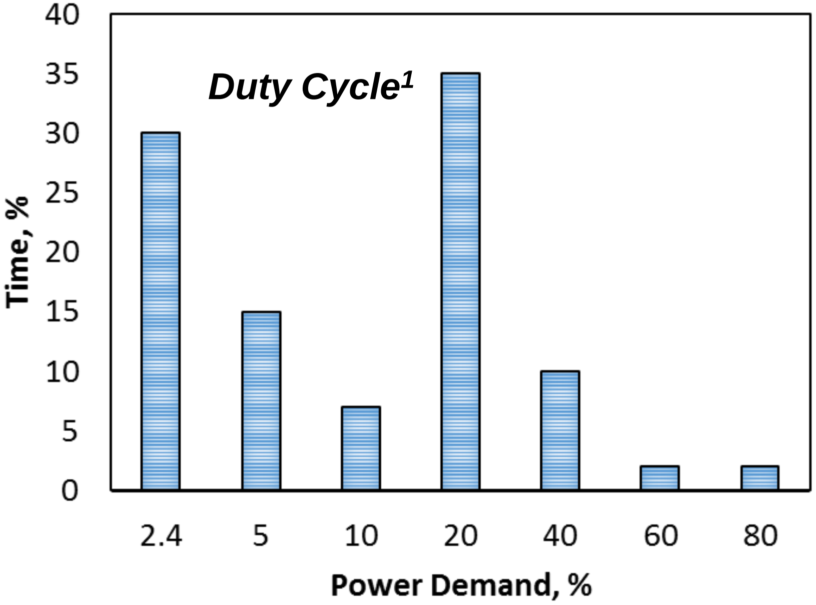
- FCS has lower initial cost: room to increase efficiency and durability at higher cost
  - ➢ OPEX includes current/interim/ultimate stack replacement cost after 25/30/35 kh
- LH_2 storage system cost > propulsion system cost > FCS cost
- TCO sensitive to fuel cost: LNG option comparable to diesel and 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
Secondary Diesel, 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

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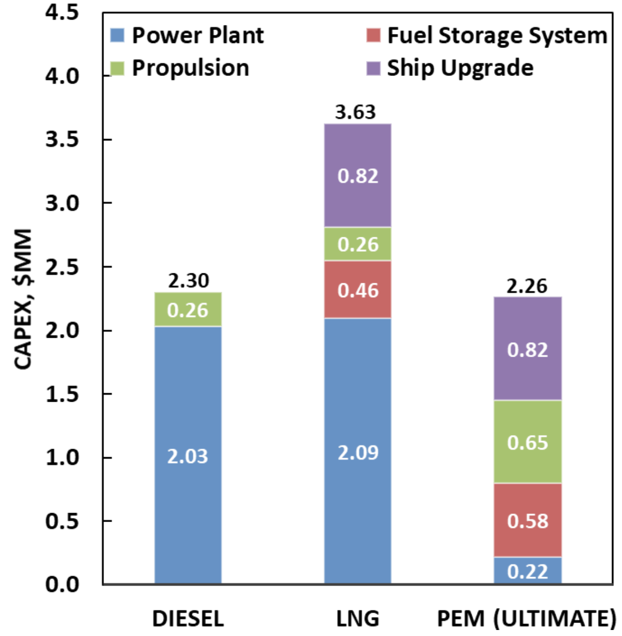
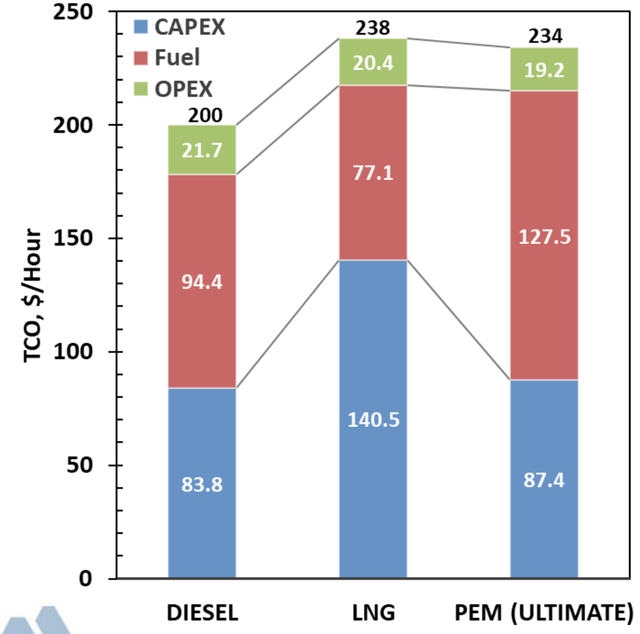
[1] Boyd, E. and Macperson, D. Using Detailed Vessel Operating Data to Identify Energy-Saving Strategies, ITS 2014, Germany

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

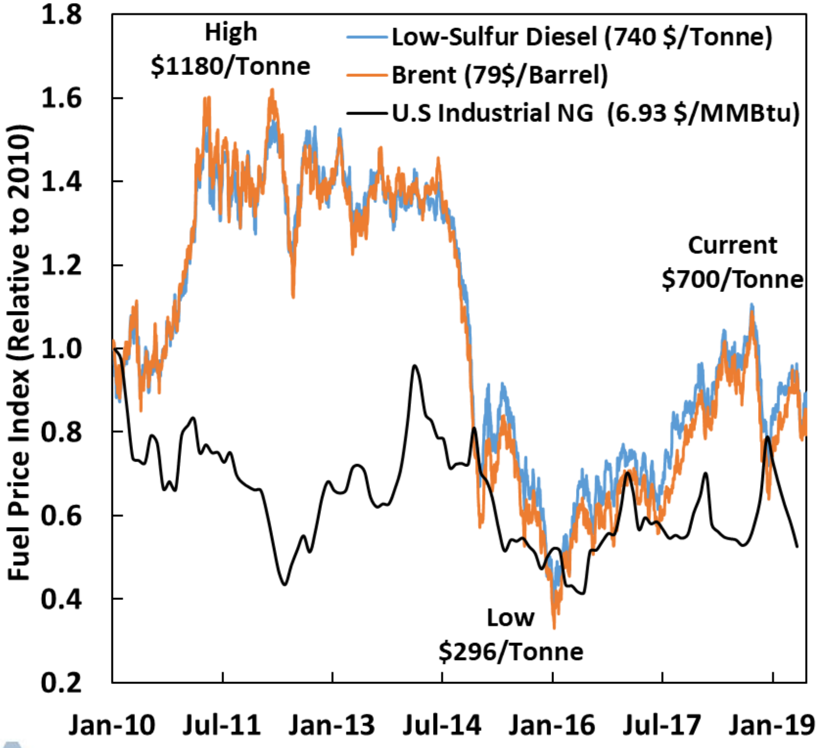
Break-Even Cost of Bunkered LH_2

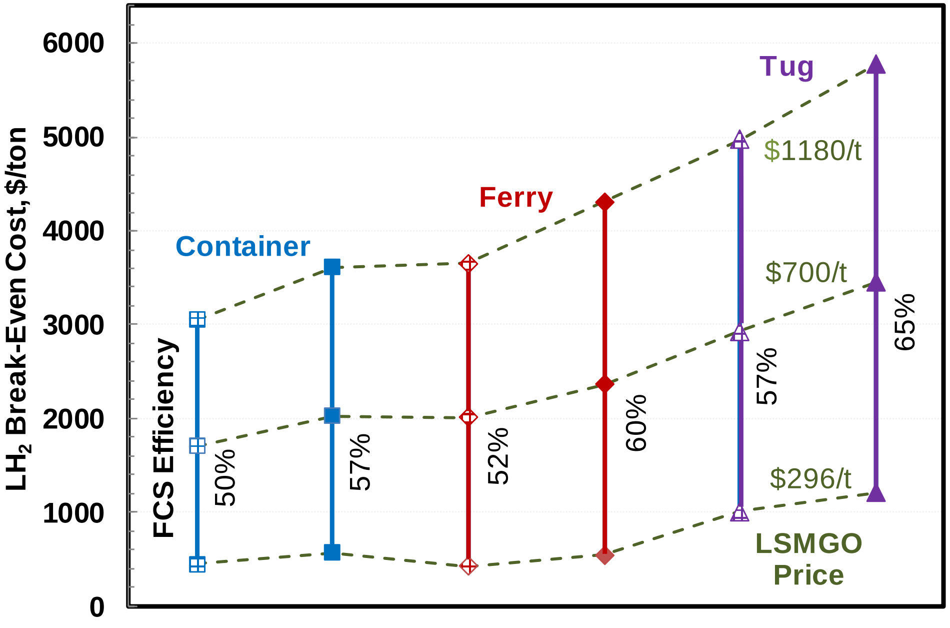
LSMGO Price

- 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 \$296/t (low), \$700/t (current), and \$1180/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

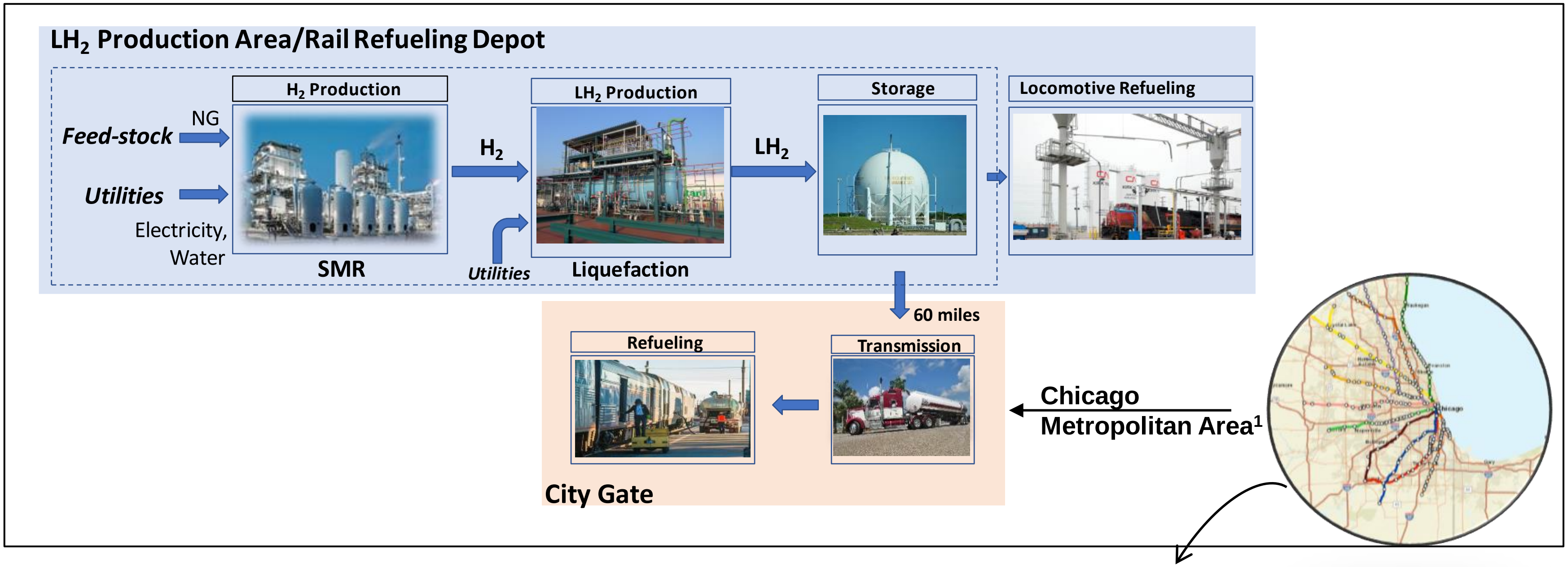
- Fuel cells for maritime auxiliary power
- Higher efficiency fuel cell systems taking advantages of lower projected costs
- Higher durability MEAs: advanced materials, system controls, optimized operating conditions
- Availability and reliability of FCS BOP components including air management
- Methods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

Backup Slides
H_2 Refueling Infrastructure

Rail Refueling Infrastructure

Consider two refueling infrastructure cases, commuter and freight locomotives

- Metra/BNSF/UP at four sites requiring a total 60 TPD of hydrogen
- *Refueling occurs directly by truck during a 10 hour refueling time window*[1].
- *Liquid hydrogen delivered from a plant located 60 miles from the city gate.*
- Large locomotive refueling depot (350 TPD H_2) with capacity to refuel 72 locomotives daily



District	Operator	Fueling Location	Fuel Usage (gal/year)	Lines Serviced	No. of Locomotives	H2 Equivalent Usage (kg/day)
Milwaukee	Metra	Western Avenue	6,235,935	MDN, MDW, NCS	38	14,522
Rock Island	Metra	49th street	2,692,684	RI	20	6,271
BNSF	BNSF	14th street	5,741,447	BNSF, SWS	30	13,370
UP	UP	M19	3,620,785	UPW, UPN, UPNW	51	8,432
		Ogilvie	7,170,932			16,699
		Total	*25,461,783*		*139*	*59,295*

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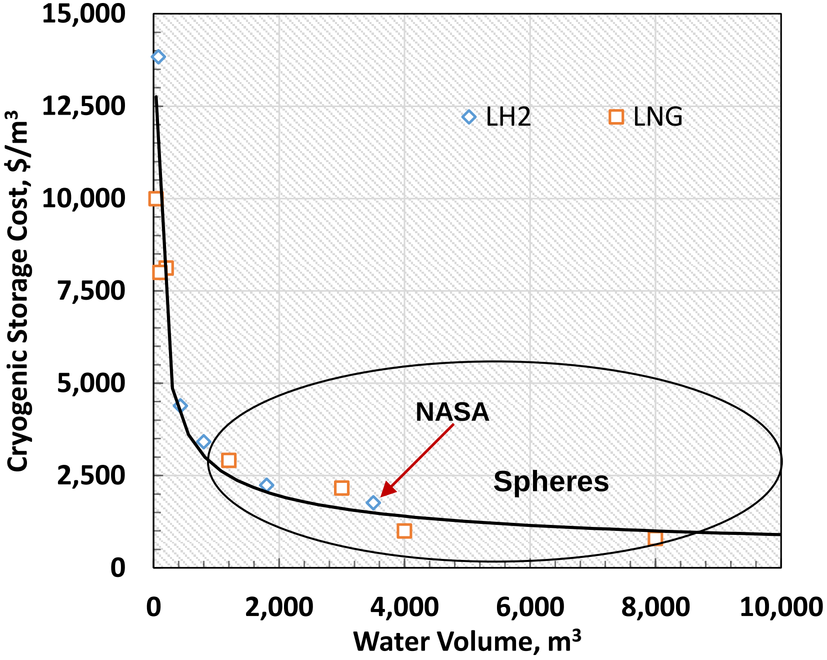
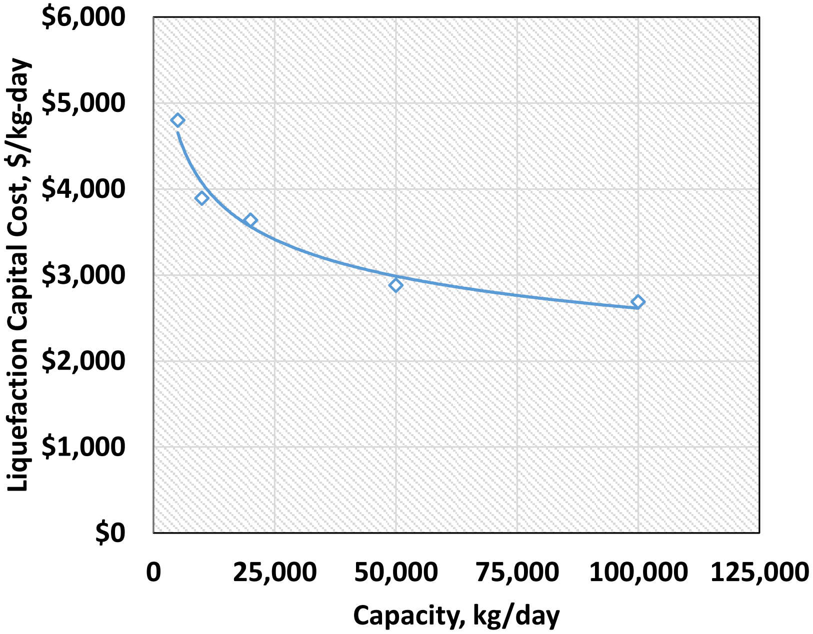
[1] ***Locomotive Alternative Energy Fuel Study, LTK Engineering Services, 2019***

Rail Refueling Infrastructure – Cost factors





Projected LH_2 System Costs

Current Technology

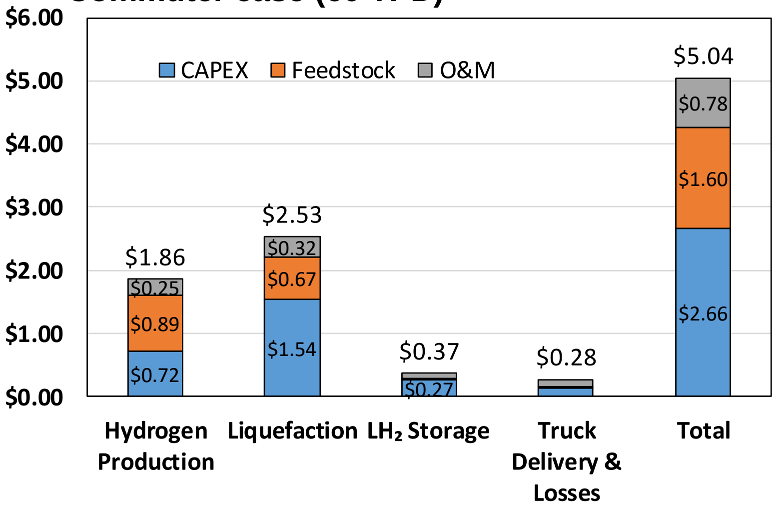
- LN_2 pre-cooled Claude cycle
- Max liquefier unit: 100,000 kg/day
- Electricity consumption: 10 kWh/kg-H_2
- H_2 losses due to compressor seal: 0.5%
- Storage: Spherical layout, vacuum insulated with glass-bubbles
- LH_2 storage: 10 days for plant outages

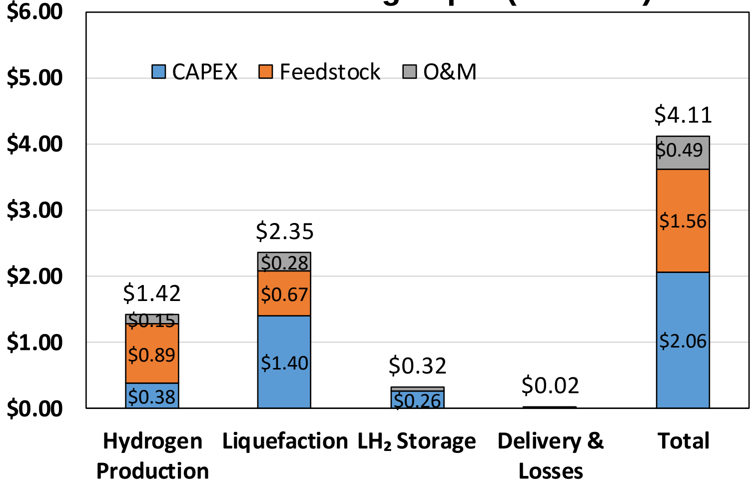
Projected LH_2 Delivery Costs

Current Technology

- Cryogenic tank-truck, 4,000 kg usable H_2
- Cost of tank and cab: $900,000
- Pump rate: 25 kg/min
- Fuel consumption: 5 miles/gal
- H_2 losses during unloading: 0.35%
- Cost of diesel fuel: $3/gal

Rail Refueling Infrastructure – Bunkered cost of hydrogen


Commuter case (60 TPD)

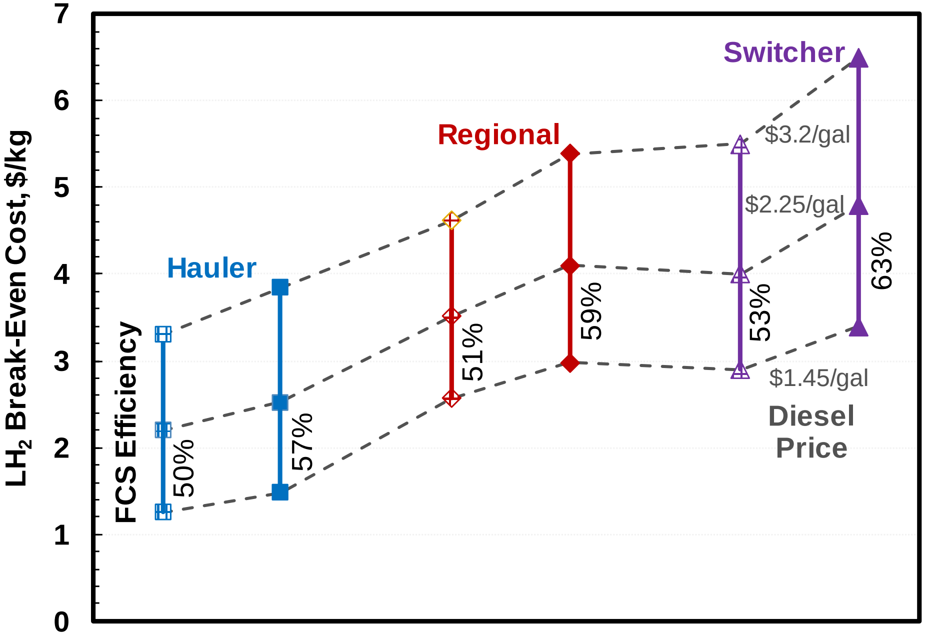

Locomotive refueling depot (350 TPD)

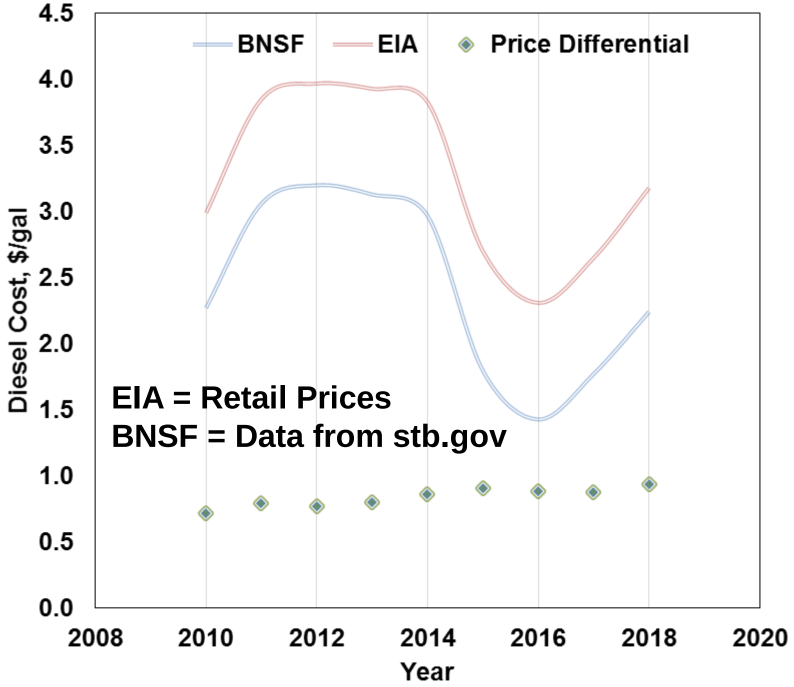
LH_2 can meet hydrogen fuel cost targets today for a large capacity refueling depot

- H_2 production by **NG SMR**: Cost of NG ($5.5/mmBTU), cost of electricity ($0.067/kWh)[1]
- Large refueling depot assumed H_2 production, liquefaction and dispensing can be co-located in the railyard of refueling depot. No need for LH_2 distribution.
  - Incurs the lowest H_2 production cost due to economy of scale (~$4/kg)
  - Boil-off losses during dispensing and storage recaptured. Total H_2 losses: ¢1/kg-H_2
  - Modest LH_2 delivery cost (pump and terminal only 3% of total storage cost)
- 60 TPD commuter refueling scenario incurs a LH2 bunkered cost of $5.04/kg-$H_2$
  - Distribution cost amount to $0.25/kg-$H_2$. (Total of 13 trucks needed for daily refueling
  - Boil-off losses during dispensing are not recoverable: Total H_2 losses: ¢3/kg-H_2
  - LH_2 production cost >$4/kg-$H_2$ due to lower plant capacity

[1] **NG and electricity prices based on EIA 2018 average for entire year in Illinois**

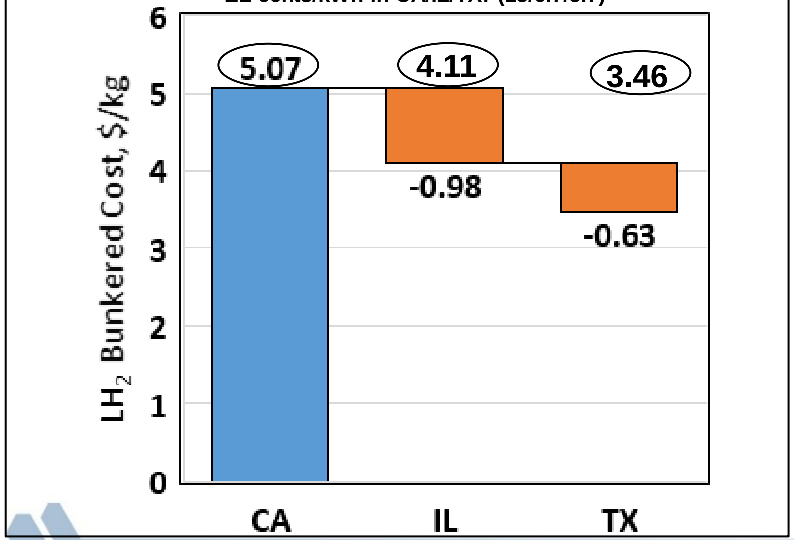
Diesel Fuel Costs and H_2 Fuel Break-Even





EIA = Retail Prices
BNSF = Data from stb.gov

NG \$/mmBTU in CA/IL/TX: (7.12/5.55/2.65)
EL cents/kWh in CA/IL/TX: (13/6.7/5.7)



LH_2 price sensitive depending on location and cost of feedstock (\$3.46/kg-\$5.07/kg)

Diesel Fuel: Rail companies pay ~\$0.9/gal less than retail prices (federal tax exempt, purchase agreements at large quantities)[1]

Diesel fuel price 2010-2018: \$1.45/gal-\$3.2/gal

- Hauler: Difficult to compete with H_2 at current low diesel fuel prices (\$2.25/gal).
- Diesel fuel at \$3.2/gal. LH_2 competitive at \$3.95/kg and 57% FC efficiency

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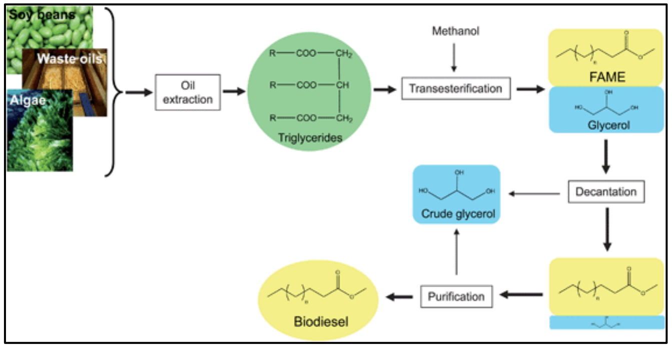
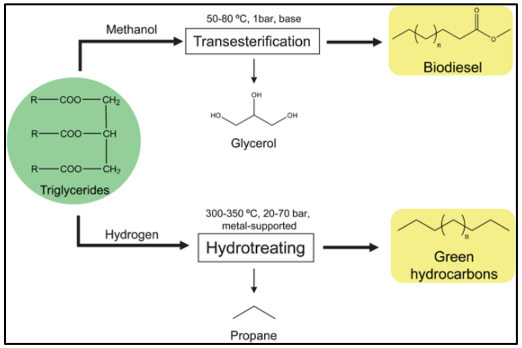
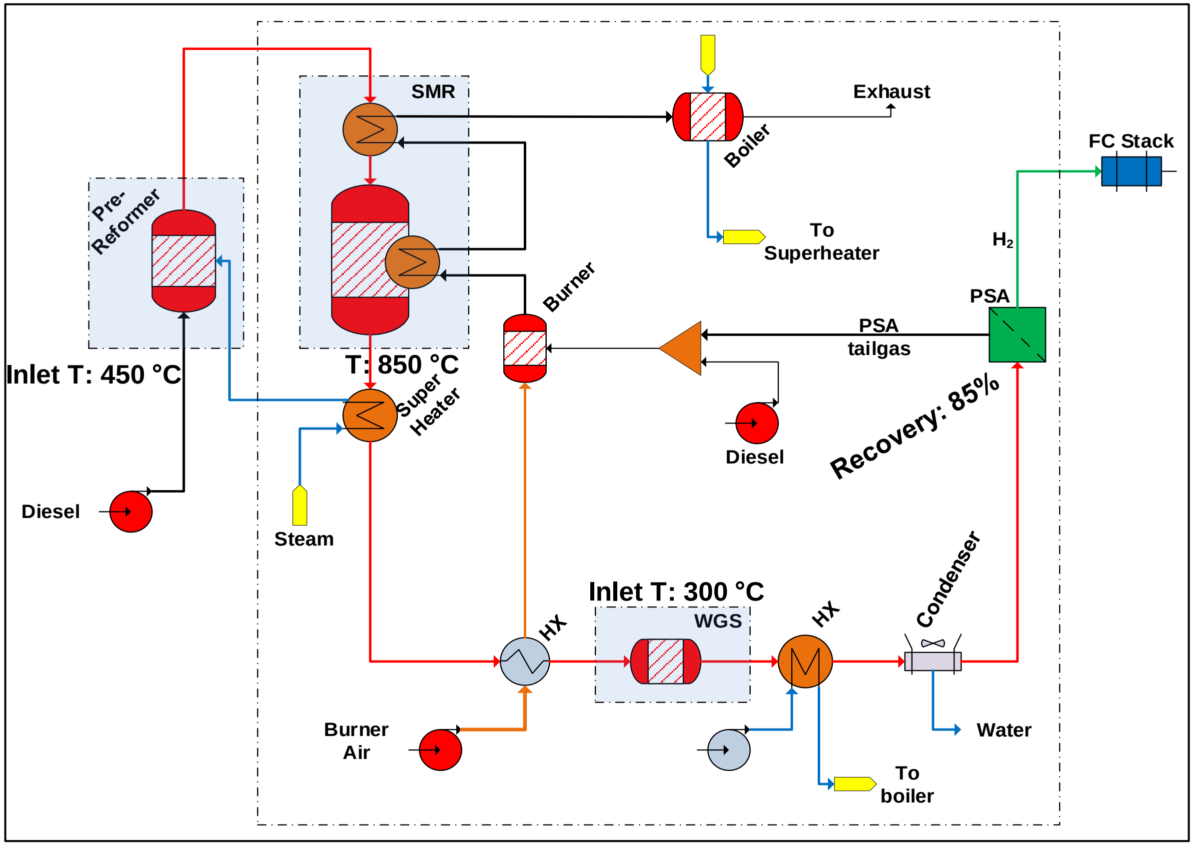
[1] Historical diesel fuel costs collected for BNSF through waybill data stb.gov

Backup Slides
Hydrogen Fuel Cells in Maritime Applications
Bio-Diesel and Ammonia Options

Container Ship – Biodiesel Reformer Option A







- Option A: Conventional SR plant with PSA for H_2 purification
- Pre-reformer converts HC to a methane rich stream – Plant identical to methane steam reforming (SMR)
- Diesel fuel represented as hexadecane (hydro-processed biodiesel)[1]
- H_2 needed during sail-time: 34,000 kg-H_2/day
- H_2 needed at port (Aux Power) 1,000 kg/day
- Need to either store H_2 for aux. power at port or have a dedicated reformer
- Size of plant:
  - 10% of SOA central SMR
  - Efficiency (Fuel to H_2): 74.8%

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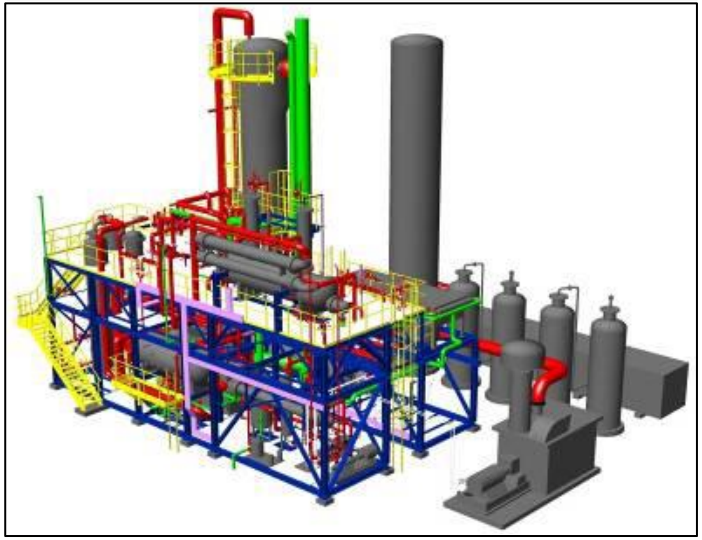
[1] Hydrotreating produces straight chain paraffinic hydrocarbons that are free of aromatics, oxygen and sulfur and have high cetane numbers.

Modular Steam Reformers

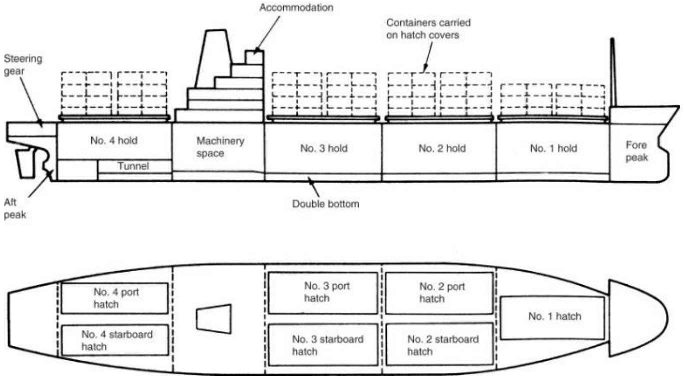
HyGear (Linde) 330 Nm^3/h

Topsoe HTCR 6,000 Nm^3/h

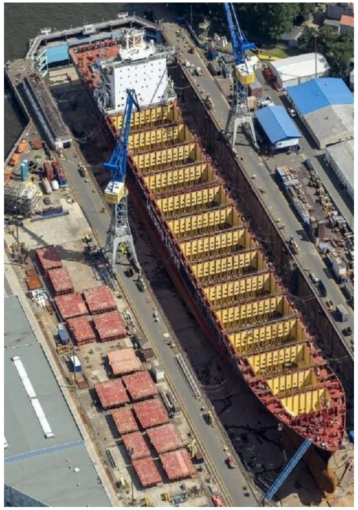


Manufacturer	Capacity (Nm^3/h)	Capacity (kg/d)	L (m)	W (m)	H (m)	Weight (kg)
HyGear	50	108	4	2.5	2.6	7,500
HyGear	100	216	6	2.5	2.6	12,500
Osaka Gas	100	216	5.8	2.6	2.8	11,000
H2Gen	268	578	7.7	2.4	2.7	11,800
HyGear (Linde)	330	712	14	3	4	
Tospsoe	6,000	12,946	25	18	20	
H_2 needed at Sail		34,000				
Main Engine			15	9.5	12.2	539,000

~60% of volume below deck used for container stowage
~48 HyGear 330 Units needed: Lost cargo ~18%
3 Topsoe 6,000 Units needed: Lost cargo ~25%

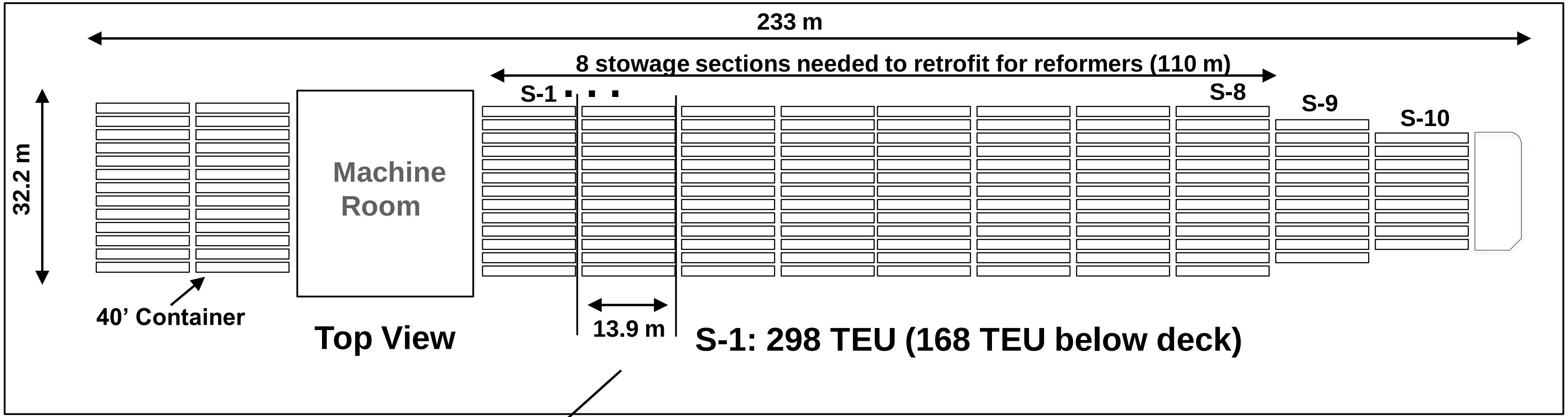


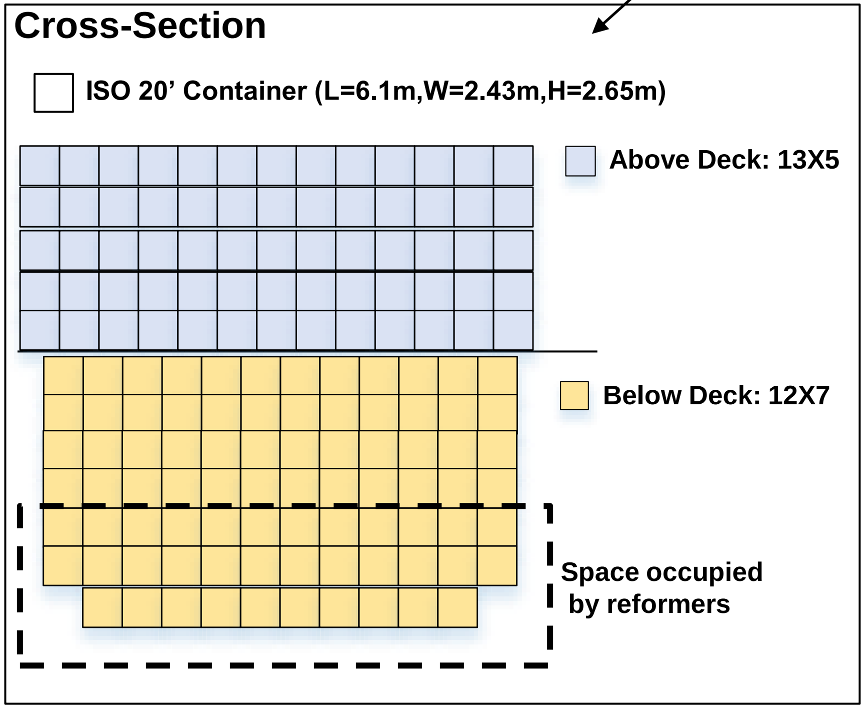
Stowage below Deck



ISO Container (ft)	L (m)	W (m)	H (m)
20	6.1	2.43	2.6
40	12.2	2.43	2.6
53	16.1	2.43	2.6

Default Container Ship – 3,100 TEU



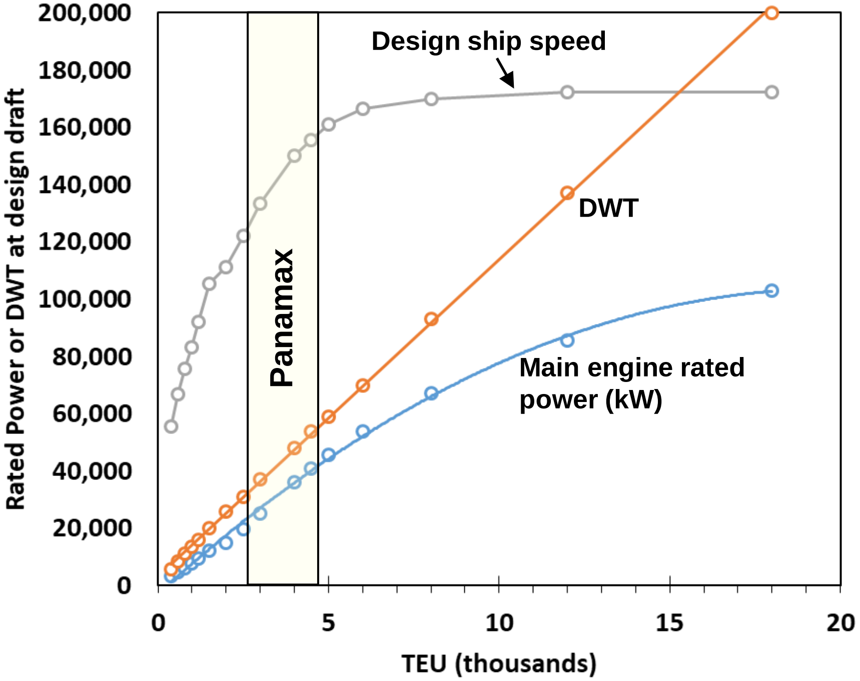


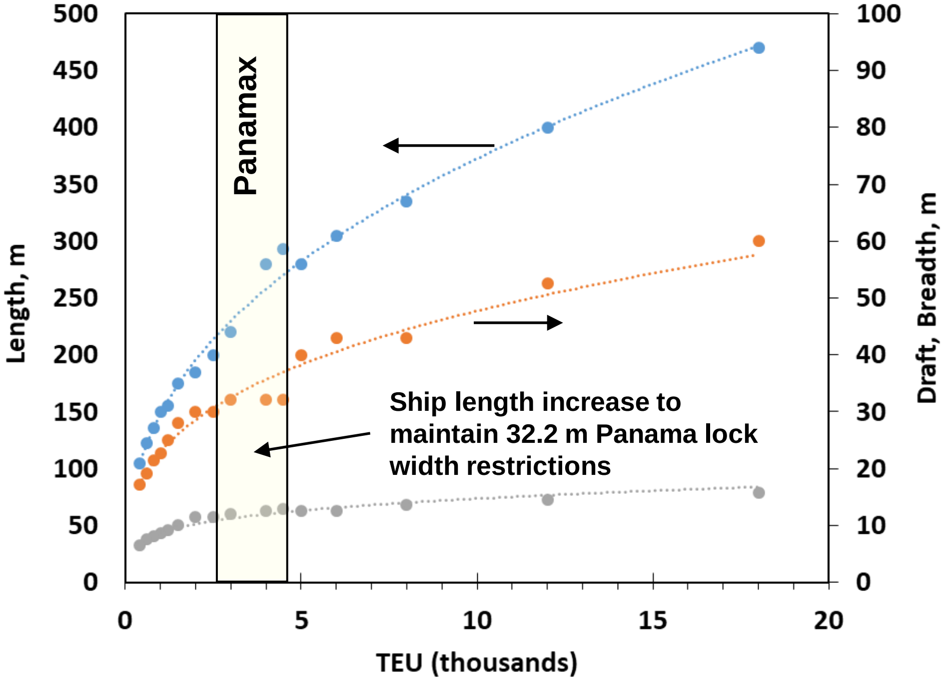
Reformer Option

- Hydroprime® 330 (712 kg-H_2/day)
- Number of units: 47
- 1.5 m space between reformers, 6X8 parallel strings required (4.5mX13.7m)
- Three container rows in height needed to accommodate vent stack and piping to machine room

- Number of total TEU's lost: 576 (~18.5%)
- Two stowage sections are additionally required to allow full utilization of cargo (27.8 m)
- Size of new ship: 3,700 TEU equivalent

Container Vessel Specifications

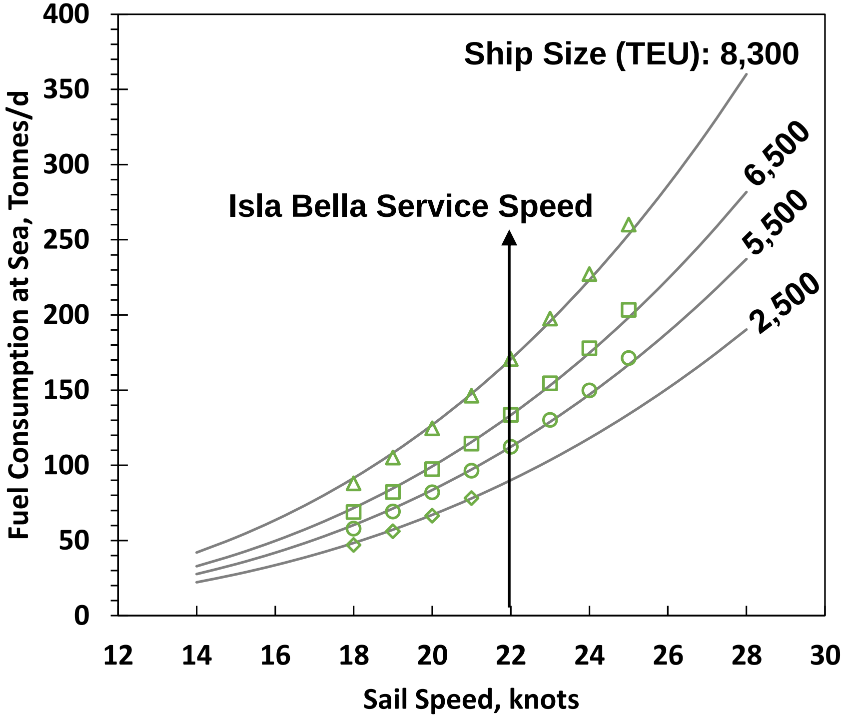


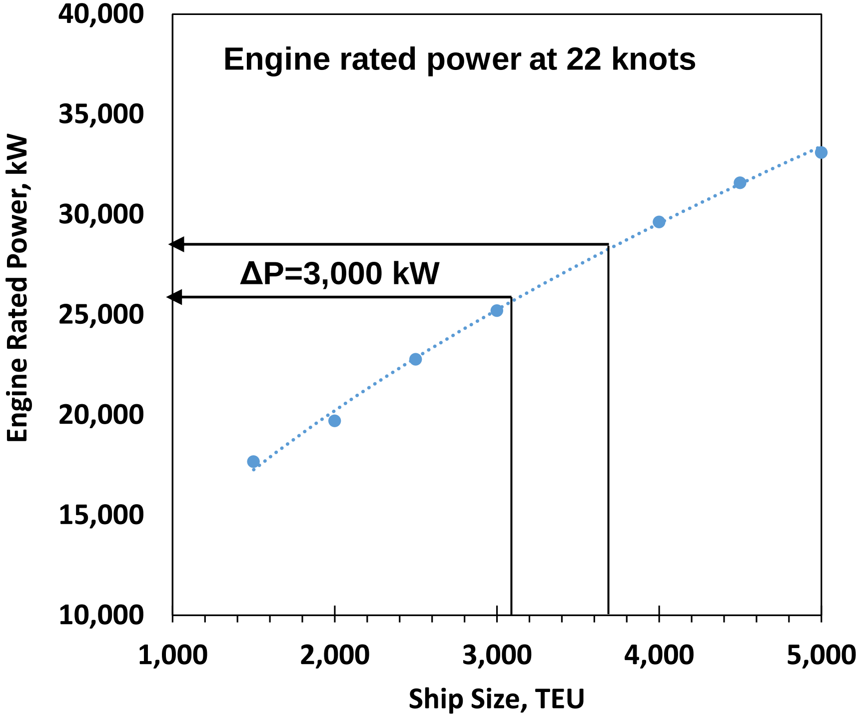


- Hull dimensions, are chosen according to resistance criteria and safety conditions, i.e. stability, unsinkability and integrity of a hull.
- Stable values of hull length, breadth and draft for various TEU carrying capacities result from restrictions in sailing areas (for the Panama Canal, where locks are used in vessel transport, the restrictions stem from block measurements: L = 290 m, B = 32 m, D = 12 m).
- Length/Draft ratio fairly constant at 2.68 as breadth remains fixed to 32 m. It would be feasible to increase the ship's length by 28 m while maintaining Panama lock restrictions.
- Increasing hull dimensions will also increase power demand (and fuel consumption) at rated speed requirements.

DWT = Dead-weight tonne (water displacement)

Container Vessel Engine Requirements: 3,100 to 3,700 TEU Equivalent



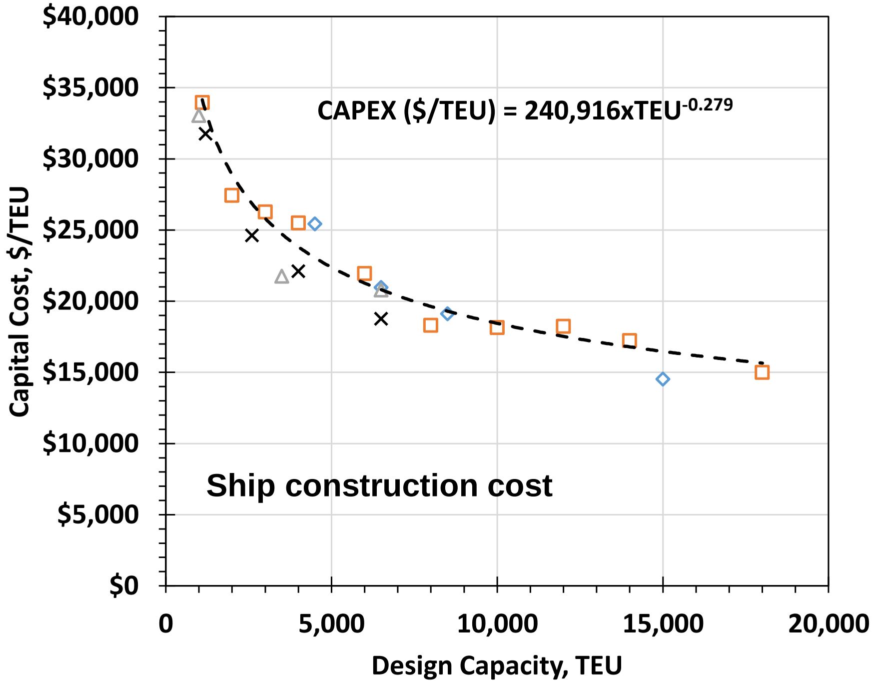


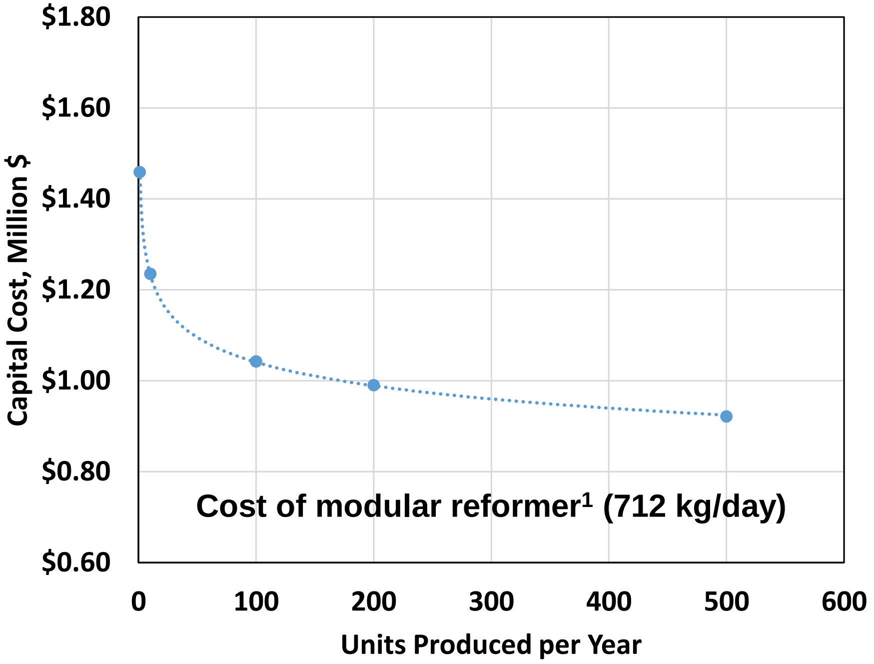
- Specific Fuel consumption (SFC) affected by hull size and sail speed:

$$SFC(v) = SFC(v_0)x\left(\frac{v}{v_0}\right)^3$$

- Rated engine power as function of ship size estimated from data and corrected to the design speed of Isla Bella (22 knots)
- Ship size increase from 3,100 TEU to 3,700 TEU increases engine rated power by 3 Mw (25.2 MW to 28.2 MW)
- An additional of 5 reformers are needed increasing the total number to 52
- 5 reformers placed in the machine room to avoid additional ship increase and power

Cost Factors for on-board Diesel Reforming

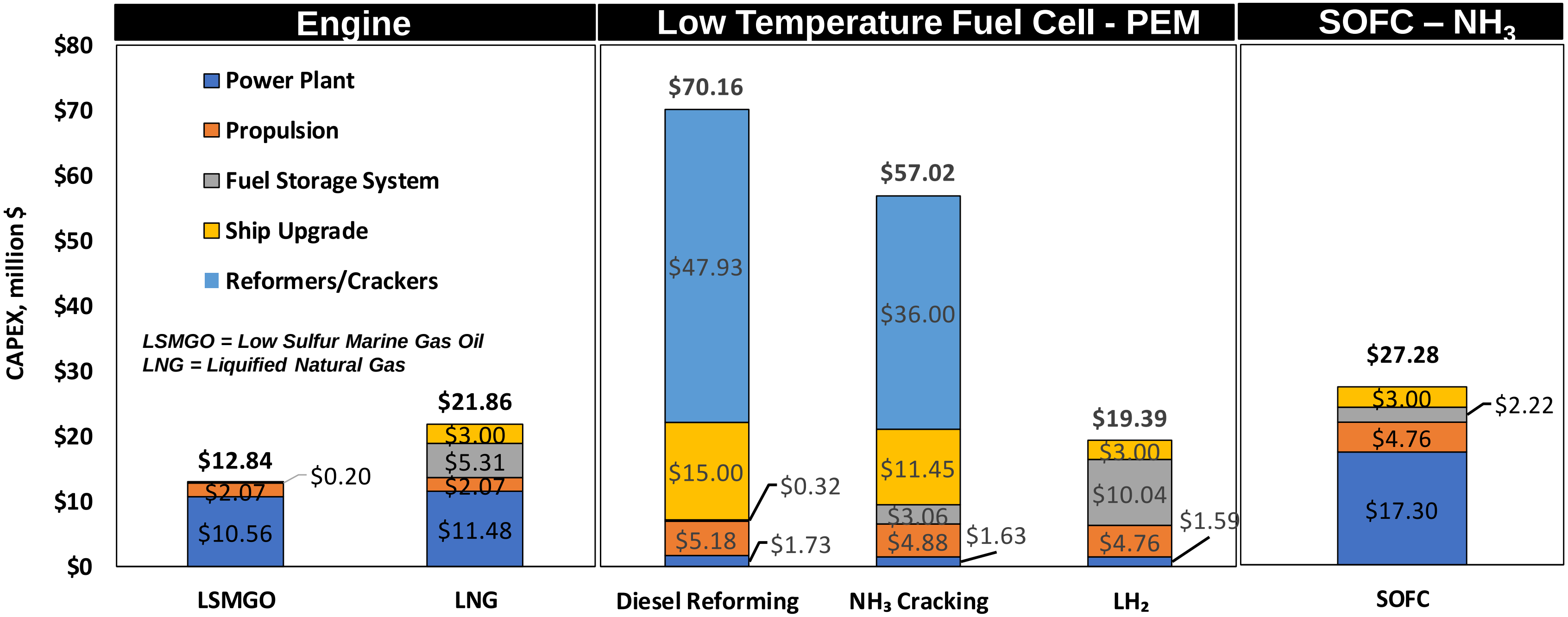




- Ship construction cost estimated from different sources in the literature as function of ship size (TEU).
- Ship enlargement (excluding engine) will add $10.8 million (3,100 to 3,700 TEU)
- Modular reformer/PSA system cost based on H_2Gen cost estimates including pre-reformer
- Cost of reformer (712 kg/d) estimated to $0.92 million if mass produced in quantities of 500 units, reformer capital cost
- O&M cost for each reformer (712 kg/d): $65,000/year

[1] *C.E. Thomas et al. (2009). Low-Cost Hydrogen Distributed Production System Development. DE-FG36-05GO15026*

Capital Cost of Propulsion/Fuel Type Options Investigated



Capital Costs

- **Engines**: LSMGO (low sulfur marine gas oil) capex dominated by engine costs. LNG version slightly more expensive but fuel storage costs increase due to 2X900 m^3 LNG storage tanks.
- **PEM**: Fuel cells incur the lowest contribution of the overall CAPEX. Only ultimate cost targets for fuel cell are considered in this analysis ($60/kW).
  - Bio-diesel reformers and ammonia crackers dominate capital cost. In addition, ship upgrade[1] costs are the highest due to the need to enlarge the ship as to maintain similar cargo capacity as the incumbent technology (engine).
  - **SOFC**: Capex dominated by SOFC stacks and BOP, $719/kW at ***high*** production volumes.
- **Fuel storage costs**: LH_2>LNG>Ammonia>LSMGO

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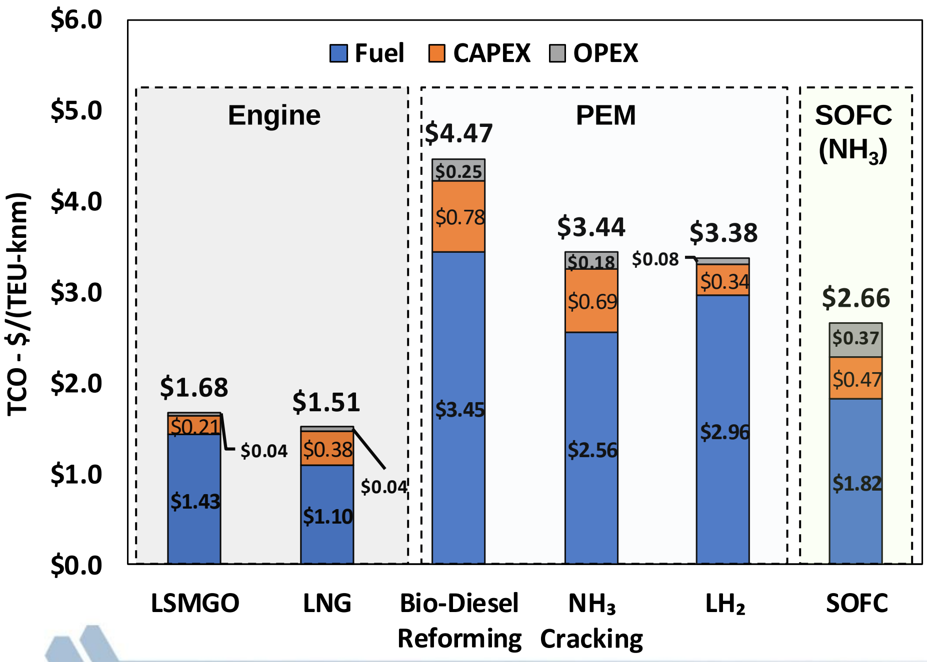
[1] Ship upgrade costs include hull enlargement (as needed), double wall pipes, and ventilation/fire-proofing spaces of gas-production

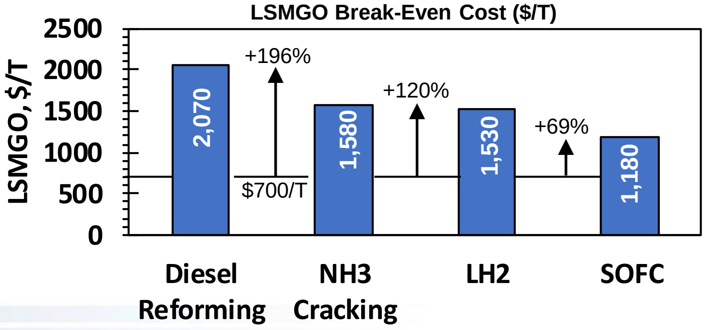
Container Ship Summary – TCO

Parameter	Engine (LSMGO)	Engine (LNG)	PEM (Reforming)	PEM (LH$_2$)	PEM (Cracker)	SOFC
Fuel	LSMGO	LNG	Bio-Diesel (FAME)	H$_2$	NH$_3$	NH$_3$
Cargo Capacity (TEU)	3,100	3,040	3,100	2,980	2,980	3,005
Cargo Utilization (%)	100	98	100	96	96	97
Peak Power Requirement (MW)	25.2	25.2	28.8	25.2	27.1	26.2
Fuel Efficiency (%)	49	49.6	37.7	50	40.7	52
Fuel Consumption at Sail (TPD)	96	78	155	34	278	201
Fuel LHV (MJ/kg)	42.8	48.6	38.8	120	19	19
Fuel Density (kg/m^3)	960	428	878	70.8	690	690
Fuel Cost ($/Tonne)	700	616	1,050	4,000	420	420
Fuel Cost ($/kJ)	16.36	12.67	27.06	33.33	22.11	22.11

TEU = Twenty Foot Equivalent Container; TPD = Tonnes/day; FAME = Fatty Acid Methyl Ester



- Container ship: TCO dominated by fuel cost - difficult match for fuel cells at current LSMGO price ($700/T)
- Engines have similar efficiency as fuel cells
- SOFC/Ammonia case incurs the lowest TCO among fuel cell alternatives.



Technology Transfer Activities

Not applicable to this project.

Publications and Presentations

Presentation at the 2019 H2@Rail Workshop, Michigan State University, Lansing, MI, March 26 - 27, 2019

R. Ahluwalia, D. Papadias, J-K Peng, T. Krause, S. Chan, and P. Devlin, "Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives – Preliminary Results"

Presentation at the 2019 H2@Ports Workshop, Marines' Memorial Club & Hotel, San Francisco, CA September 10 - 12, 2019

D. Papadias, R. Ahluwalia, E. Connelly, and P. Devlin, "Total Cost of Ownership (TCO) Analysis for Hydrogen Fuel Cells in Maritime Applications – Preliminary Results"

Institutional Talk at Office of Energy Efficiency and Renewable Energy (EERE), Jun 18, 2019

D. D. Papadias, J-K Peng, and R. Ahluwalia, "H2@Scale and H2@Rail: Hydrogen Carriers, Hydrogen Storage and Locomotive Total Cost of Ownership"

Response to Reviewers' Comments

This is a new project. It was not reviewed last year.

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