Rail and Maritime Metrics

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Project ID: TA034

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
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 H₂ 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

<table>
<thead>
<tr>
<th>Description</th>
<th>Date</th>
<th>Milestone Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td>12/31/2019</td>
<td>Quarterly Progress Measure (Regular)</td>
</tr>
<tr>
<td>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.</td>
<td>3/31/2020</td>
<td>Annual Milestone (Regular)</td>
</tr>
<tr>
<td>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.</td>
<td>6/30/2020</td>
<td>Annual Milestone (Regular)</td>
</tr>
<tr>
<td>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.</td>
<td>9/30/2020</td>
<td>Annual Milestone (Regular)</td>
</tr>
<tr>
<td>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.</td>
<td>12/31/2019</td>
<td>Quarterly Progress Measure (Regular)</td>
</tr>
</tbody>
</table>

#### Maritime Metrics

<table>
<thead>
<tr>
<th>Description</th>
<th>Date</th>
<th>Milestone Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td>3/31/2020</td>
<td>Annual Milestone (Regular)</td>
</tr>
<tr>
<td>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.</td>
<td>6/30/2020</td>
<td>Annual Milestone (Regular)</td>
</tr>
<tr>
<td>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.</td>
<td>6/30/2020</td>
<td>Annual Milestone (Regular)</td>
</tr>
<tr>
<td>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.</td>
<td>9/30/2020</td>
<td>Annual Milestone (Regular)</td>
</tr>
<tr>
<td>Rail LH₂ Refueling and Siting Issues</td>
<td>Sandia National Laboratory</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------</td>
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<tr>
<td>Rail LH₂ Tender Car</td>
<td>Chart Industries, Inc</td>
<td></td>
</tr>
<tr>
<td>Federal Railroad Administration (FRA/USDOT)</td>
<td>Rail Safety - LH₂ and Fuel Cells</td>
<td></td>
</tr>
<tr>
<td>Fuel Cells and H₂ for Rails</td>
<td>2019 H2@Rail Workshop, Michigan State University, Lansing, MI, March 26 - 27, 2019</td>
<td></td>
</tr>
<tr>
<td>Fuel Cells and H₂ for Maritime Applications</td>
<td>2019 H2@Ports Workshop, Marines’ Memorial Club &amp; Hotel, San Francisco, CA September 10 - 12, 2019</td>
<td></td>
</tr>
</tbody>
</table>
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

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

- 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 (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**
- **Duty Cycle Freight/Switcher:** EPA
Hydrogen Storage System Cost

Cryo-Compressed Hydrogen (CcH₂) Storage System for Freight and Regional Locomotives

**Freight Locomotives:** One tender car needed, 4850 kg-H₂ stored at 500 bar, 70 K
- 93 m³ 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 H₂

**Liquid H₂ tender** in lieu of CcH₂ tender also needs to be investigated

350-bar Compressed Hydrogen (cH₂) Storage System for Switcher Locomotives

**Tender car not needed** for 100 kg-H₂ stored at 350 bar, room temperature
- 5 m³ required storage volume for 6-7 wt% gravimetric and ~19 g/L volumetric capacities

**Projected CcH₂ Storage System Costs**

- **Current PEM:** $1130/kg-H₂ (200 HDV systems/year)
- **Interim PEM:** $500/kgkg-H₂ (5000 HDV systems/year)
- **Ultimate PEM:** $266/kg (DOE target)

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500 bar Cryo-Compressed Storage System Cost*

- 34.12 40 kg Bus (2017)
- 5.6 kg LDV @500k/year (2010)
- 10.4 kg LDV @500k/year (2010)

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![Graph showing cost vs. annual production]
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)

<table>
<thead>
<tr>
<th>Agency</th>
<th>AC Transit(^1)</th>
<th>SunLine(^2)</th>
<th>OCTA(^3)</th>
<th>SARTA(^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data period</td>
<td>2/13-7/17</td>
<td>3/12-10/18</td>
<td>3/16-12/18</td>
<td>2/18-12/18</td>
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<tr>
<td>Number of months</td>
<td>54</td>
<td>80</td>
<td>34</td>
<td>11</td>
</tr>
<tr>
<td>Average H(_2) cost, $/kg</td>
<td>8.39</td>
<td>10.17</td>
<td>13.95</td>
<td>5.14</td>
</tr>
<tr>
<td>Maximum H(_2) cost, $/kg</td>
<td>10.26</td>
<td>26.02</td>
<td>16.99</td>
<td>5.88</td>
</tr>
<tr>
<td>Minimum H(_2) cost, $/kg</td>
<td>6.49</td>
<td>2.53</td>
<td>12.99</td>
<td>5.00</td>
</tr>
<tr>
<td>Overall FCEB fuel cost, $/mile</td>
<td>1.41</td>
<td>1.82</td>
<td>1.47</td>
<td>1.03</td>
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</table>

Baseline technology

<table>
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<tr>
<th>Agency</th>
<th>Diesel</th>
<th>CNG</th>
<th>CNG</th>
<th>CNG/diesel hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average fuel cost, $/gal or gge</td>
<td>2.43</td>
<td>0.96</td>
<td>1.15</td>
<td>1.89 / 2.30</td>
</tr>
<tr>
<td>Overall baseline fuel cost, $/mile</td>
<td>0.57</td>
<td>0.32</td>
<td>0.32</td>
<td>0.45 / 0.51</td>
</tr>
</tbody>
</table>

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

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

3300-kW<sub>e</sub> FCS, 100 kWh battery $5.7M tender

4400-hp engine

$1.4M tender
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 H₂ storage is required and can be accommodated without a tender car if H₂ stored as cryo-compressed gas. May also be feasible to eliminate the tender car with 350-bar cH₂ 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
Preliminary TCO of fuel cells more favorable for yard switchers than freights and regionals
- Future targets favor a 1200-kW\textsubscript{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\textsubscript{2} storage system for freight locomotives: 4,800 kg stored H\textsubscript{2}, 80 kg/min refueling rate for 1-h refueling time
- CcH\textsubscript{2} or 350-bar ch\textsubscript{2} storage for regional locomotives, 500 kg stored H\textsubscript{2}
- 350-bar ch\textsubscript{2} storage for yard switcher locomotives, 100 kg stored H\textsubscript{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\textsubscript{e}
- Methods for meeting and exceeding the critical target of $4/kg-H\textsubscript{2} at pump
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\textsubscript{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*

<table>
<thead>
<tr>
<th>DOE-FCTO Targets</th>
<th>Current</th>
<th>Interim</th>
<th>Ultimate</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCS for heavy duty trucks, $/kW</td>
<td>285</td>
<td>130</td>
<td>60</td>
<td>[22]</td>
</tr>
<tr>
<td>FCS lifetime, h</td>
<td>25,000</td>
<td>30,000</td>
<td>35,000</td>
<td>[22]</td>
</tr>
<tr>
<td>Delivered hydrogen cost, $/kg</td>
<td>9</td>
<td>7</td>
<td>4</td>
<td>[22]</td>
</tr>
<tr>
<td>LH\textsubscript{2} storage system, Million $</td>
<td>Container</td>
<td>Ferry</td>
<td>Tug</td>
<td>[8,13-19]</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.7</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>Annual FCS maintenance, $</td>
<td>607,000</td>
<td>78,000</td>
<td>65,000</td>
<td>[23]</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>LHV</th>
<th>Bunkered</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/m$^3$</td>
<td>MJ/kg</td>
<td>Price, $/ton</td>
<td></td>
</tr>
<tr>
<td>LSMGO</td>
<td>900</td>
<td>42.8</td>
<td>700</td>
<td><a href="https://shipandbunker.com">https://shipandbunker.com</a></td>
</tr>
<tr>
<td>LNG</td>
<td>428</td>
<td>48.6</td>
<td>616</td>
<td>MGO density range: 850 - 910 kg/m$^3$</td>
</tr>
<tr>
<td>LH$_2$</td>
<td>70.8</td>
<td>120</td>
<td>9,000</td>
<td>LH$_2$ cost: Eudy and Post [23]</td>
</tr>
</tbody>
</table>

In this report, ton (t) refers to metric ton and equals 1000 kg
Wärtsilä LNG Tugboat
- 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-m³ LNG, 50-m³ fuel oil
- Propulsion: 2x9L DF:3330 kW, WST-18 thruster

M/V Issaquah: Auto/Passenger Ferry
- Main Dimensions: 100(L)X24(W)X5.1(D)m
- Performance: 1200 passengers, 124 Vehicles
- Fuel Tank: Diesel (2X95 m³ LNG – conceptual)
- Propulsion: 4.5 MW main, 1.2 MW auxiliary

Isla Bella LNG Container Ship
- Main Dimensions: 233(L)X32(W)X10(D)m
- Performance: 3100-TEU (36,571 T), 1100 nm
- Dual Fuel Tank: 2x900-m³ LNG (475,000 gallon)
- Engine: 26-MW main, 3 x1.74-MW auxiliary

AIDAnova LNG Cruise Ship
- Main Dimensions: 337(L)X42(W)X9(D)m, 180 kT
- Performance: 5,200 passengers, 1,500 crew
- Fuel Tank: 3,600 m³ 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

**Isla Bella LNG Container Ship**
- Main Dimensions: 233(L)X32(W)X10(D)m
- Performance: 3100-TEU (36,571 T)
- Engine: 26-MW main, 3x1.74-MW auxiliary
- Dual Fuel Tank: 2x900-m³ LNG (475,000 gallon)

<table>
<thead>
<tr>
<th>Engine</th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH₂-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion, MW</td>
<td>25.0</td>
<td>25.0</td>
<td>26.5</td>
</tr>
<tr>
<td>Auxiliary Genset, MW</td>
<td>5.7</td>
<td>5.7</td>
<td></td>
</tr>
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<table>
<thead>
<tr>
<th>Fuel Storage</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, t</td>
<td>467</td>
<td>342</td>
<td>163</td>
</tr>
<tr>
<td>Secondary Diesel, t</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Fuel, m³</td>
<td>2,500</td>
<td>1,800</td>
<td>3,300</td>
</tr>
<tr>
<td>Secondary Diesel, m³</td>
<td>300</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Fuel Consumption</th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, g/kWh</td>
<td>172</td>
<td>146</td>
<td>60</td>
</tr>
<tr>
<td>Secondary Diesel, g/kWh</td>
<td>197</td>
<td>169</td>
<td></td>
</tr>
</tbody>
</table>

**FCS Container Ship**
- A 26-MW FCS replaces 25-MW propulsion engine and 3 x 1.74 MW auxiliary genset
- Container ship refueled with LH₂ once per round trip, 4 x 820 m³ tanks. LNG tanks have excess capacity. LSMGO refueled once a month.
- On LHV basis, comparable efficiencies of LSMGO (48.9%), LNG (49.6%) and LH₂ (50%) fuel options

<table>
<thead>
<tr>
<th>Container Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Slot Capacity, TEU</td>
</tr>
<tr>
<td>Roundtrip Distance, nm</td>
</tr>
<tr>
<td>Roundtrip Duration, h</td>
</tr>
<tr>
<td>Sail time, h</td>
</tr>
<tr>
<td>Average Speed, h</td>
</tr>
<tr>
<td>Service Life, y</td>
</tr>
</tbody>
</table>

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

---

Photo Credit: TOTE Maritime

Photo courtesy of General Dynamics NASSCO
Container Ship – TCO

Only ultimate cost targets for FCS ($60/kW) and H2 ($4,000/ton) included in this report

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
- LH2 storage system cost > propulsion system cost > FCS cost
- TCO dominated by fuel cost: LNG option slightly cheaper than diesel and much cheaper than LH2
  - LH2 break-even cost at 57% efficiency: 2030 $/ton
  - LNG fuel cost factors per MMBTU basis: $4 NG, $5 liquefaction, $4 transport and bunkering
## Ferry – Engine and Fuel Systems

### Washington State Ferries (WSF) - Issaquah Class RoPax

<table>
<thead>
<tr>
<th></th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH\textsubscript{2}-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine</strong></td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Propulsion, MW</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliary Genset, MW</strong></td>
<td>1.2</td>
<td>1.2</td>
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</tbody>
</table>

### Fuel Storage

<table>
<thead>
<tr>
<th></th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH\textsubscript{2}-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, t</td>
<td>192</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>Secondary Diesel, t</td>
<td></td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Main Fuel, m\textsuperscript{3}</td>
<td>200</td>
<td>86</td>
<td>190</td>
</tr>
<tr>
<td>Secondary Diesel, m\textsuperscript{3}</td>
<td></td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

### Fuel Consumption

<table>
<thead>
<tr>
<th></th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH\textsubscript{2}-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, g/kWh</td>
<td>197</td>
<td>178</td>
<td>58</td>
</tr>
<tr>
<td>Secondary Diesel, g/kWh</td>
<td>215</td>
<td>205</td>
<td></td>
</tr>
</tbody>
</table>

### 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\textsubscript{2} (or LNG) once every 5 d. LSMGO tank has excess capacity.
  - 2 x 43 m\textsuperscript{3} LNG tanks vs. 2 x 95 m\textsuperscript{3} LH\textsubscript{2} tanks
  - Above-deck location, tank size may not be a critical issue
- On LHV basis, LH\textsubscript{2}-FCS has higher efficiency on ferry duty cycle: 52% vs. 43% for LSMGO and LNG systems.
Ferry – TCO

### CAPEX

<table>
<thead>
<tr>
<th></th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH₂-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion, $/kW</td>
<td>480</td>
<td>600</td>
<td>60</td>
</tr>
<tr>
<td>Auxiliary Genset, $/kW</td>
<td>540</td>
<td>718</td>
<td></td>
</tr>
<tr>
<td>Noₓ Emission Control, $/kW</td>
<td>96</td>
<td>70</td>
<td>120</td>
</tr>
<tr>
<td>Gearbox/Electric Motor, $/kW</td>
<td>70</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Power Conditioning, $/kW</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Fuel Storage System, $/m³</td>
<td>50</td>
<td>12,606</td>
<td>8,540</td>
</tr>
<tr>
<td>Ship Upgrade, k$</td>
<td>1,375</td>
<td>1,375</td>
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</table>

### OPEX

<table>
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<tr>
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<th>LSMGO</th>
<th>LNG</th>
<th>LH₂-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, $/ton</td>
<td>700</td>
<td>620</td>
<td>4000</td>
</tr>
<tr>
<td>Secondary Diesel, $/ton</td>
<td>700</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Maintenance, k$/yr</td>
<td>83</td>
<td>105</td>
<td>78</td>
</tr>
<tr>
<td>Consumables, k$/yr</td>
<td>53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime Overhaul, k$</td>
<td></td>
<td>33</td>
<td></td>
</tr>
</tbody>
</table>

### 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
- LH₂ storage system cost > propulsion system cost > FCS cost
- TCO sensitive to fuel cost: LNG option comparable to diesel and much cheaper than LH₂
- LH₂ break-even cost at 60% efficiency: 2360 $/ton
  - FCS may compete with LSMGGO and LNG options at slightly below ultimate H₂ cost target
**LNG: 25 m³ tank, below deck**

![Image courtesy of Wärtsilä](image.png)

<table>
<thead>
<tr>
<th>Fuel Storage</th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH₂-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, t</td>
<td>48</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Secondary Diesel, t</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Fuel, m³</td>
<td>50</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td>Secondary Diesel, m³</td>
<td></td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel Consumption</th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH₂-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, g/kWh</td>
<td>221</td>
<td>195</td>
<td>53</td>
</tr>
<tr>
<td>Secondary Diesel, g/kWh</td>
<td>235</td>
<td>205</td>
<td></td>
</tr>
</tbody>
</table>

**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 LH₂ (or LNG) once every 4 d. LSMGO tank has excess capacity.
  - 25 m³ LNG tank vs. 41 m³ LH₂ tank
  - Below deck location, tank size may not be a critical issue
- On LHV basis, LH₂-FCS has higher efficiency on tug duty cycle: 57% vs. 38% for LSMGO and LNG systems

---

1Boyd, E. and Macperson, D. Using Detailed Vessel Operating Data to Identify Energy-Saving Strategies, ITS 2014, Germany
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
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 LH₂

- Break-even cost of bunkered LH₂ ($/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 H₂ 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 $4/kg-H₂ for light-duty vehicles and medium-duty and heavy-duty trucks
Backup Slides
H$_2$ 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.

### Rail Refueling Infrastructure

<table>
<thead>
<tr>
<th>District</th>
<th>Operator</th>
<th>Fueling Location</th>
<th>Fuel Usage (gal/year)</th>
<th>Lines Serviced</th>
<th>No. of Locomotives</th>
<th>H(_2) Equivalent Usage (kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milwaukee</td>
<td>Metra</td>
<td>Western Avenue</td>
<td>6,235,935</td>
<td>MDN, MDW, NCS</td>
<td>38</td>
<td>14,522</td>
</tr>
<tr>
<td>Rock Island</td>
<td>Metra</td>
<td>49th street</td>
<td>2,692,684</td>
<td>RI</td>
<td>20</td>
<td>6,271</td>
</tr>
<tr>
<td>BNSF</td>
<td>BNSF</td>
<td>14th street</td>
<td>5,741,447</td>
<td>BNSF, SWS</td>
<td>30</td>
<td>13,370</td>
</tr>
<tr>
<td>UP</td>
<td>UP</td>
<td>M19 Ogilvie</td>
<td>3,620,785</td>
<td>UPW, UPN, UPNW</td>
<td>51</td>
<td>8,432</td>
</tr>
</tbody>
</table>

**Total**: 25,461,783  
139  
59,295

\(^1\)Locomotive Alternative Energy Fuel Study, LTK Engineering Services, 2019

---

**Chicago Metropolitan Area\(^1\)**
Projected LH₂ System Costs

Current Technology

- LN₂ pre-cooled Claude cycle
- Max liquefier unit: 100,000 kg/day
- Electricity consumption: 10 kWh/kg-H₂
- H₂ losses due to compressor seal: 0.5%
- Storage: Spherical layout, vacuum insulated with glass-bubbles
- LH₂ storage: 10 days for plant outages

Projected LH₂ Delivery Costs

Current Technology

- Cryogenic tank-truck, 4,000 kg usable H₂
- Cost of tank and cab: $900,000
- Pump rate: 25 kg/min
- Fuel consumption: 5 miles/gal
- H₂ losses during unloading: 0.35%
- Cost of diesel fuel: $3/gal
LH₂ can meet hydrogen fuel cost targets today for a large capacity refueling depot

- H₂ production by **NG SMR**: Cost of NG ($5.5/mmBTU), cost of electricity ($0.067/kWh)¹
  - Large refueling depot assumed H₂ production, liquefaction and dispensing can be co-located in the railyard of refueling depot. No need for LH₂ distribution.
    - Incurs the lowest H₂ production cost due to economy of scale (~$4/kg)
    - Boil-off losses during dispensing and storage recaptured. Total H₂ losses: $1/kg-H₂
    - Modest LH₂ 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-H₂
  - Distribution cost amount to $0.25/kg-H₂. (Total of 13 trucks needed for daily refueling
  - Boil-off losses during dispensing are not recoverable: Total H₂ losses: $3/kg-H₂
  - LH₂ production cost >$4/kg-H₂ due to lower plant capacity

¹NG and electricity prices based on EIA 2018 average for entire year in Illinois
Diesel Fuel Costs and H₂ Fuel Break-Even

LH₂ 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)

- Hauler: Difficult to compete with H₂ at current low diesel fuel prices ($2.25/gal).
- Diesel fuel at $3.2/gal. LH₂ competitive at $3.95/kg and 57% FC efficiency

1Historical diesel fuel costs collected for BNSF through waybill data stb.gov
Backup Slides
Hydrogen Fuel Cells in Maritime Applications
Bio-Diesel and Ammonia Options
Option A: Conventional SR plant with PSA for $\text{H}_2$ 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)$^1$

- $\text{H}_2$ needed during sail-time: 34,000 kg-$\text{H}_2$/day

- $\text{H}_2$ needed at port (Aux Power) 1,000 kg/day

- Need to either store $\text{H}_2$ for aux. power at port or have a dedicated reformer

- Size of plant:
  - 10% of SOA central SMR
  - Efficiency (Fuel to $\text{H}_2$): 74.8%

---

$^1$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 Nm³/h

Topsoe HTCR 6,000 Nm³/h

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Capacity (Nm³/h)</th>
<th>Capacity (kg/d)</th>
<th>L (m)</th>
<th>W (m)</th>
<th>H (m)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HyGear</td>
<td>50</td>
<td>108</td>
<td>4</td>
<td>2.5</td>
<td>2.6</td>
<td>7,500</td>
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<tr>
<td>HyGear</td>
<td>100</td>
<td>216</td>
<td>6</td>
<td>2.5</td>
<td>2.6</td>
<td>12,500</td>
</tr>
<tr>
<td>Osaka Gas</td>
<td>100</td>
<td>216</td>
<td>5.8</td>
<td>2.6</td>
<td>2.8</td>
<td>11,000</td>
</tr>
<tr>
<td>H2Gen</td>
<td>268</td>
<td>578</td>
<td>7.7</td>
<td>2.4</td>
<td>2.7</td>
<td>11,800</td>
</tr>
<tr>
<td>HyGear (Linde)</td>
<td>330</td>
<td>712</td>
<td>14</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Topsoe</td>
<td>6,000</td>
<td>12,946</td>
<td>25</td>
<td>18</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>H₂ needed at Sail</td>
<td>34,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Main Engine</td>
<td></td>
<td></td>
<td>15</td>
<td>9.5</td>
<td>12.2</td>
<td>539,000</td>
</tr>
</tbody>
</table>

~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%

ISO Container (ft) | L (m) | W (m) | H (m) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6.1</td>
<td>2.43</td>
<td>2.6</td>
</tr>
<tr>
<td>40</td>
<td>12.2</td>
<td>2.43</td>
<td>2.6</td>
</tr>
<tr>
<td>53</td>
<td>16.1</td>
<td>2.43</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Reformer Option

- Hydroprime® 330 (712 kg-H₂/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
- 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.
Container Vessel Engine Requirements: 3,100 to 3,700 TEU Equivalent

- Specific Fuel consumption (SFC) affected by hull size and sail speed:
  \[ SFC(v) = SFC(v_0) \left( \frac{v}{v_0} \right)^3 \]

- 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 H₂Gen 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

1C.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 m³ 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**: \(\text{LH}_2 > \text{LNG} > \text{Ammonia} > \text{LSMGO}\)

\(^1\)Ship upgrade costs include hull enlargement (as needed), double wall pipes, and ventilation/fire-proofing spaces of gas-production
### Container Ship Summary – TCO

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Engine (LSMGO)</th>
<th>Engine (LNG)</th>
<th>PEM (Reforming)</th>
<th>PEM (LH₂)</th>
<th>PEM (Cracker)</th>
<th>SOFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>LSMGO</td>
<td>LNG</td>
<td>Bio-Diesel (FAME)</td>
<td>H₂</td>
<td>NH₃</td>
<td>NH₃</td>
</tr>
<tr>
<td>Cargo Capacity (TEU)</td>
<td>3,100</td>
<td>3,040</td>
<td>3,100</td>
<td>2,980</td>
<td>2,980</td>
<td>3,005</td>
</tr>
<tr>
<td>Cargo Utilization (%)</td>
<td>100</td>
<td>98</td>
<td>100</td>
<td>96</td>
<td>96</td>
<td>97</td>
</tr>
<tr>
<td>Peak Power Requirement (MW)</td>
<td>25.2</td>
<td>25.2</td>
<td>28.8</td>
<td>25.2</td>
<td>27.1</td>
<td>26.2</td>
</tr>
<tr>
<td>Fuel Efficiency (%)</td>
<td>49</td>
<td>49.6</td>
<td>37.7</td>
<td>50</td>
<td>40.7</td>
<td>52</td>
</tr>
<tr>
<td>Fuel Consumption at Sail (TPD)</td>
<td>96</td>
<td>78</td>
<td>155</td>
<td>34</td>
<td>278</td>
<td>201</td>
</tr>
<tr>
<td>Fuel LHV (MJ/kg)</td>
<td>42.8</td>
<td>48.6</td>
<td>38.8</td>
<td>120</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Fuel Density (kg/m³)</td>
<td>960</td>
<td>428</td>
<td>878</td>
<td>70.8</td>
<td>690</td>
<td>690</td>
</tr>
<tr>
<td>Fuel Cost ($/Tonne)</td>
<td>700</td>
<td>616</td>
<td>1,050</td>
<td>4,000</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>Fuel Cost ($/kJ)</td>
<td>16.36</td>
<td>12.67</td>
<td>27.06</td>
<td>33.33</td>
<td>22.11</td>
<td>22.11</td>
</tr>
</tbody>
</table>

*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

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

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