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

D. Papadias and R. K. Ahluwalia
Argonne National Laboratory

E. Connelly and P. Devlin
Fuel Cell Technologies Office
U.S. Department of Energy

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

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
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>10</td>
<td>1.7</td>
<td>0.59</td>
<td>[8,13-19]</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 LH₂

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-$H_2$
  \[ 1 \text{ MGE} = 7.0 \text{ L-LNG} = 17.2 \text{ L-LH}_2 \]
- On price basis, LSMGO = $0.016$/MJ; LNG = $0.013$/MJ; LH₂ = $0.075$/MJ

<table>
<thead>
<tr>
<th></th>
<th>Density kg/m³</th>
<th>LHV MJ/kg</th>
<th>Bunkered Price, $/ton</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<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/m³</td>
</tr>
<tr>
<td>LH₂</td>
<td>70.8</td>
<td>120</td>
<td>9,000</td>
<td>LH₂ cost: Eudy and Post [23]</td>
</tr>
</tbody>
</table>

In this report, ton (t) refers to metric ton and equals 1000 kg
TCO Analysis for Selected Maritime Applications

**Wärtsilä LNG Tugboat¹**
- 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 Ferry²**
- Main Dimensions: 100(L)X24(W)X5.1(D)m
- Performance: 1200 passengers, 124 Vehicles
- Fuel Tank: Diesel (2X43 m³ LNG – conceptual)
- Propulsion: 4.5 MW main, 1.2 MW auxiliary

**Isla Bella LNG Container Ship³**
- Main Dimensions: 233(L)X32(W)X10(D)m
- Performance: 2100-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 Ship⁴**
- 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.
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-m³ LNG (475,000 gallon)

<table>
<thead>
<tr>
<th>Container Ship</th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH₂-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Slot Capacity, TEU</td>
<td>2100</td>
<td>342</td>
<td>163</td>
</tr>
<tr>
<td>Roundtrip Distance, nm</td>
<td>2200</td>
<td>1,800</td>
<td>3,300</td>
</tr>
<tr>
<td>Roundtrip Duration, h</td>
<td>168</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Sail time, h</td>
<td>116</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Speed, h</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service Life, y</td>
<td>25</td>
<td></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
Container Ship – TCO

- 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

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

**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 LH₂ (or LNG) once every 5 d. LSMGO tank has excess capacity.
  - 2 x 43 m³ LNG tanks vs. 2 x 95 m³ LH₂ tanks
  - Above-deck location, tank size may not be a critical issue
- On LHV basis, LH₂-FCS has higher efficiency on ferry duty cycle: 52% vs. 43% for LSMGO and LNG systems

<table>
<thead>
<tr>
<th>Washington State Ferries (WSF) - Issaquah Class RoPax</th>
<th>LSMGO</th>
<th>LNG</th>
<th>LH₂-FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Passengers</td>
<td>1200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Cars</td>
<td>124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route</td>
<td>Seattle-Bremerton, 13.5 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time, min</td>
<td>Engine Power, kW</td>
<td># of Engines</td>
<td>Total Power, kW</td>
</tr>
<tr>
<td>Transit</td>
<td>50</td>
<td>1,721</td>
<td>2</td>
</tr>
<tr>
<td>Maneuvering</td>
<td>10</td>
<td>391</td>
<td>2</td>
</tr>
<tr>
<td>Docked</td>
<td>20</td>
<td>379</td>
<td>1</td>
</tr>
<tr>
<td>Auxiliary</td>
<td>80</td>
<td>202</td>
<td>2</td>
</tr>
<tr>
<td><strong>Fuel Storage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<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></td>
<td></td>
</tr>
<tr>
<td>Main Fuel, m³</td>
<td>200</td>
<td>86</td>
<td>190</td>
</tr>
<tr>
<td>Secondary Diesel, m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Consumption</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>

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

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 LSMGO and LNG options at slightly below ultimate H₂ cost target

<table>
<thead>
<tr>
<th>CAPEX</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></td>
<td></td>
</tr>
<tr>
<td>Gearbox/Electric Motor, $/kW</td>
<td>70</td>
<td>70</td>
<td>120</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></td>
<td></td>
<td>1,375</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OPEX</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fuel, $/ton</td>
<td>700</td>
<td>620</td>
<td>4000</td>
</tr>
<tr>
<td>Secondary Diesel, $/ton</td>
<td></td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Maintenance, k$/yr</td>
<td>83</td>
<td>105</td>
<td>78</td>
</tr>
<tr>
<td>Comsumables, k$/yr</td>
<td>53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime Overhaul, k$</td>
<td></td>
<td></td>
<td>33</td>
</tr>
</tbody>
</table>
**Harbor Tug – Engine and Fuel Systems**

### LNG: 25 m³ tank, below deck

![Image of Harbor Tug](image)

*Image courtesy of Wärtsilä*

<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>3.6</td>
<td>3.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Auxiliary Genset, kW</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

**Fuel Storage**

- **Main Fuel, t**
  - LSMGO: 48
  - LNG: 10
  - LH₂: 3
- **Secondary Diesel, t**
  - LSMGO: 10
  - LNG: 10

**Main Fuel, m³**

- LSMGO: 50
- LNG: 25
- LH₂: 41

**Secondary Diesel, m³**

- LSMGO: 10
- LNG: 10

**Fuel Consumption**

- **Main Fuel, g/kWh**
  - LSMGO: 221
  - LNG: 195
  - LH₂: 53
- **Genset Fuel, g/kWh**
  - LSMGO: 235
  - LNG: 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 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
Harbor Tug – TCO

- 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 > LH₂ 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 LH₂ 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 $245/t (low), $700/t (current), and $1185/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
References

21. [https://shipandbunker.com/prices](https://shipandbunker.com/prices)
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 LH₂ storage could compete with low sulfur diesel and LNG ferries and tugs (if cost targets are met)