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TECHNOECONOMIC ANALYSIS OF H₂ FUELING INFRASTRUCTURE FOR VARIOUS APPLICATIONS

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Argonne National Laboratory

Presentation at California CEC’s IEPR Commissioner Workshop
June 21, 2022
H₂ fuel cell electric vehicles are attractive zero-emission options when daily energy use is high (vehicle cost perspective)

- Battery
- Slope adj.
- Slope = $/kWh_{battery}

Plus:
- Life of energy storage and fuel cell needs to be factored in
- Fueling/charging cost is additional

- Battery + FC + Hydrogen tank
- Slope adj.
- Slope = $/kWh_{H₂}

- Hydrogen tank (adjusted with FE ratio)

- Low daily fuel use (case of LDVs)
- High daily fuel use (case for HDVs)

- Overall cost [\$]

- Storage amount [kWh]

- FC: Fuel Cell
- FE: Fuel Economy
- LDV: Light-Duty Vehicle
- HDV: Medium- and Heavy-Duty Vehicle
Fuel economy (or powertrain efficiency) is key to enabling a low carbon alternative to diesel ICEV

- Battery Electric: ~90% efficiency
- Hydrogen FC: ~60% efficiency
- Diesel ICE: ~40-45% efficiency

The graph illustrates the efficiency of different powertrain systems at part load and full load, with a comparison of ~2X improvement for Battery Electric at full load and ~1.1:1.2 X for Hydrogen FC.
Low H₂ fueling cost is critical for enabling fuel cell vehicles in the M/HDV applications (fuel cost perspective)

- Mainly due to high daily VMT and low fuel economy of M/HDVs
- Breakeven H₂ cost depends strongly on fuel economy ratio with diesel ICEV

<table>
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<tr>
<th>Class 6 PnD Box Truck</th>
<th>Class 8 Line Haul Truck</th>
</tr>
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<tbody>
<tr>
<td><strong>Diesel ICEV</strong></td>
<td><strong>H₂ FCEV</strong></td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>6.2 mpgd</td>
</tr>
<tr>
<td>Fuel Economy Ratio</td>
<td>~2.5</td>
</tr>
<tr>
<td>Equivalent Fuel Cost</td>
<td>$2/gal</td>
</tr>
<tr>
<td></td>
<td>$3/gal</td>
</tr>
<tr>
<td></td>
<td>$4/gal</td>
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LDVs, [https://greet.es.anl.gov/publication-c2g-2016-report](https://greet.es.anl.gov/publication-c2g-2016-report)

[https://truckingresearch.org/atri-research/operational-costs-of-trucking/](https://truckingresearch.org/atri-research/operational-costs-of-trucking/)

- LCOD: Levelized Cost of Driving
- VMT: Vehicle Miles Travelled
- PnD: Pickup and Delivery
- M/HDV: Medium- and Heavy-Duty Vehicle
- LDV: Light-Duty Vehicle
- FCEV: Fuel Cell Electric Vehicle
Infrastructure of gaseous hydrogen delivery
Infrastructure of **liquid** hydrogen delivery
Argonne’s HDSAM and its derivatives evaluate the economic performance and market acceptance of hydrogen delivery technologies and fueling infrastructure for FCEVs.

- Publicly available with >3000 users, including major gas and energy companies, in more than 25 countries
- Supported by U.S. Department of Energy’s Hydrogen and Fuel Cell Technologies Office (HFTO) since 2004

[Map of the world showing countries and map points]

https://hdsam.es.anl.gov/
Cost of Hydrogen Delivery and Refueling for LD FCEVs is strongly driven by onboard storage requirement.

Today, hydrogen cost at the dispenser in CA is $15-$16/kg.

Bulk of H₂ cost is in delivery and refueling.

- HX: Heat Exchange
- VACD: Variable Area Control Device
- J-T: Joule-Thomson
- CA: California

Diagram: HRS - Hydrogen Refueling Station

- Delivery: $4-6/kg
- Refueling: $6-8/kg
- Production: ~$2/kg
- Compressor: 45%
- Refrigeration: 12%
- Electrical: 3%
- Controls/Other: 11%
- Dispenser: 11%
- Storage: 20%
Versatile refueling configuration options with LH$_2$ delivery

- **350 or 700 bar**
  - Type III or IV cH$_2$
- **350 bar**
  - CcH$_2$
- **Low-P LH$_2$**

Proposed*

*Dormancy may be less of an issue with a predictable duty cycle of M/HDVs

- **LH$_2$**: Liquid Hydrogen
- **cH$_2$**: compressed hydrogen
- **CcH$_2$**: Cryo-compressed hydrogen
- **Low-P**: Low Pressure (<10 bar)
Compression and pumping dominate refueling cost for high-pressure tanks

Fleet Size: 30 buses; Fill Amount: 35 kg @ 350 bar, back-to-back, one dispenser

- Liquid supplied stations can handle faster fills with less cost increase compared to gaseous supply
- Cost of H₂ delivered to the station is additional
**Energy use* and CO₂ emissions are critical for environmental sustainability of H₂ liquefaction**

- Additional H₂ liquefaction plants have been recently announced to serve the growing H₂ market
- Low-carbon electricity is critical for sustainability of LH₂ supply

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<thead>
<tr>
<th>Region</th>
<th>Liquefaction Capacity (MT/day)</th>
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<tbody>
<tr>
<td>California</td>
<td>30</td>
</tr>
<tr>
<td>Louisiana</td>
<td>70 (2x35)</td>
</tr>
<tr>
<td>Indiana</td>
<td>30</td>
</tr>
<tr>
<td>New York</td>
<td>40</td>
</tr>
<tr>
<td>Alabama</td>
<td>30</td>
</tr>
<tr>
<td>Ontario</td>
<td>30</td>
</tr>
<tr>
<td>Quebec</td>
<td>27</td>
</tr>
<tr>
<td>Tennessee</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>263</strong></td>
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*Liquefaction CO₂ emissions* = 0-10 kgCO₂e/kgH₂ (~5 with US mix in 2020)

* At 10 kWh/kgH₂
Fuel economy ratio strongly impacts WTW GHG emissions of SMR-H$_2$ relative to diesel

WTW GHG Emissions (g$_{CO_2e}$/mi)

- **FE Ratio = 2.36** (57%)
- **FE Ratio = 1.67** (39%)
- **FE Ratio = 1.58** (36%)
- **FE Ratio = 1.10** (8%)

* Gaseous H$_2$ supply

- WTW: Well-To-Wheels
- GHG: Greenhouse Gas
- FE: Fuel Economy
- SMR: Steam Methane Reforming

[Source](https://www.sciencedirect.com/science/article/pii/S0378775318304737)
California LCFS generate credits for low-carbon fuels

source: http://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

Last Updated 11/10/2021
Thank You!
aelgowainy@anl.gov

Our models and publications are available at:
https://hdsam.es.anl.gov/
https://greet.es.anl.gov/publications