Hydrogen for Transport

Infrastructure Pathway to Parity and Below

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Infrastructure Pathway to Parity - Overview

- Light-Duty (LDV) and Heavy Duty (HD) Vehicle Cost Reduction Roadmap, what has changed, key differences
- Vehicle Types: Parity Progression with Volume and Size
- Technology Advances, Liquid Hydrogen, and Gaseous Hydrogen use cases
- Heavy Duty as an Early Driver for Cost Reduction
Heavy Duty and Light Duty: Divergent Cost Reduction Triggers

50+ Stations

35 MPa
5 Stations, 2TPD each

$11.72

$1.48
$0.58
$1.16
$0.69

$9.41

$0.37

Green at $0.05/kwh

Parity with gasoline (35 MPG @ 3.50 $/gal)

Pathways to Parity

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<tr>
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<th>LDV</th>
<th>HD</th>
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<tr>
<td><strong>Step 1  (1-5 years)</strong></td>
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<td>50+ stations in a large region (California)</td>
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<td>35 MPa Fleets</td>
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<td>Low-cost renewables</td>
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<td>County-scale density</td>
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<td>Large stations (75+ buses or 100+ delivery vehicles each)</td>
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<td><strong>5-15 years</strong></td>
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<td>Equipment Improvements – compressors, tube trailers, construction, liquefiers</td>
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<td>Greater density of HRS, 70MPa, etc.</td>
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<td><strong>Future</strong></td>
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<td>Pipelines from low-cost renewables, better H₂ production tech, 60-65+% efficient fuel cells</td>
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Why FCEV for HD? Infrastructure, Scaling, and Power Demand of EVs

- The peak load at the substation level is challenged by a B-EV fleet
- Larger scale means FC is better able to handle fueling with a lower TCO
- Volt charge rate 3.3 kw, truck 15 kw, bus 60kw (4-6 hours to full charge for bus)
Demand Will Drive Infrastructure Changes

- Increasing volumes of sales will drive cost-reducing infrastructure changes
- Progressively lower cost levels will open the market for larger volume and scale opportunities, further reducing costs
- Many Standards and fueling for heavy duty systems still need to be define
- The heaviest duty and longest haul vehicles will very likely need LH₂
**LH₂ for Heaviest Use Cases, GH₂ for LDV and Distribution**

**GH₂ vs LH₂ Distribution: 15 Year NPV Break-Even**

**LH₂ vs. GH₂ – Key Differences in 15 Year NPV Costs**

**Economic Limits:** There are limits to economic overland shipment of H₂ with either GH₂ or LH₂.

**LH₂ - More Capital Intensive:** Liquefaction is capital intensive, and the process does not get great returns to scale.

**GH₂ for Regional Production and Distribution:** Low-cost H₂ will require <$1/kg distribution costs. With current technology, the $1/kg isoline for delivery distance is always underneath the break-even cost for considering LH₂ vs GH₂.

**LH₂ is necessary for several large use cases**

**Next Steps for Technologies:** LH₂: Lower cost liquefaction facilities (50%+ reduction); more efficient liquefaction (kWh/kg). GH₂: Lower cost carbon fiber for tube trailers; compressors that are less expensive, more reliable, and more efficient (kWh/kg).
## Major Liquid Use Cases

### Marine
**Ferries & Cruise Ships**
Electrically driven, space limited, massive power requirements (50 tons per day)

### Mining
**Very Large Mining Equipment**
Tons of use per day per rig, often remote and off-grid

### Intercontinental Market Arbitrage
**All Use Cases**
Low-cost energy availability in other countries, LH2 to export energy

June 2019
Current Opportunities: Scale and Demand Drive Cost Reduction

70 MPa Pilot

Same, but 35 MPa

10 TPD Hub-and-Spoke

Renewable Electrolysis
SMR Grey
With Contingency
SMR w/ RNG

35 MPa Use Case

- Pressure to Reduce Cost: 35 MPa in use cases with <250 miles per day range allows for down-sizing of expensive and less reliable Hydrogen Refueling Station equipment
- Centralize Production: Returns to scale with construction and locating near low-cost inputs reduce cost
- Increase Station Size: Returns to scale on construction and distribution reduce cost
Cost Reduction and Technology with Scaling

DEMAND AND SCALE UNLOCK COST REDUCTIONS

Demand drives costs lower through each fueling paradigm – 70 MPa car, 35 MPa truck, 50-70 MPa truck, LH₂ vessels

Larger vehicles drive exponentially increasing demand, driving costs down further

MEDIUM TERM COST REDUCTIONS WITH FIT-TO-CASE SOLUTIONS

Tailoring heavy-duty refueling systems to specific use cases can provide low-cost H₂ now for specific segments

Cost reductions in HRS and distribution allow for lower-cost refueling paradigms for these segments

Industry consortiums contribute to system cost reductions

LONG TERM EFFICIENCY GAINS

Increasing numbers of stations will reduce costs for components, driving down overall costs

Regional H₂ use rates will dictate emplacement of pipelines to drastically lower future transport costs
Summary

- Refueling station scale and density of refuelling are both necessary to achieve lower costs.
- Centralized production and next-gen gaseous distribution are both pathways to reduce cost in the next decade.
- High volumes of H$_2$ production from heavy duty applications, particularly return-to-base applications like buses, drayage trucks, and fleet vehicles, will drive down hydrogen production costs, reducing the entire cost stack.
- Liquid H$_2$ will be necessary for specific use cases and for some the largest H$_2$ use cases.
Questions and Answers