Opportunities for Hydrogen to Green Industry

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Detailed demand report available at: https://greet.es.anl.gov/publication-us_future_h2
H2@Scale

DOE initiative focusing on hydrogen as an energy intermediate.

https://www.energy.gov/eere/fuelcells/h2scale
Hydrogen in Today’s Energy System: 10 MMT / yr
**Economic Potential Methodology:** Market Equilibrium

**Demand Curve**: how much are consumers willing and able to pay for a good?

**Supply Curve**: threshold prices showing how much are producers willing and able to produce at each?

**Economic Equilibrium**: Quantity where demand price is equal to the supply price.
- No excess supply or demand.
- Market pushes price and quantity to equilibrium.

# Hydrogen Applications and Threshold Prices

Potential hydrogen demands are based on potential market sizes. Threshold prices are estimates of hydrogen prices necessary to replace incumbent technologies.

<table>
<thead>
<tr>
<th>Application</th>
<th>Hydrogen Threshold Price-1 ($/kg)</th>
<th>Demand at Threshold Price-1 (MMT/yr)</th>
<th>Hydrogen Threshold Price-2 ($/kg)</th>
<th>Additional Demand at Threshold Price-2 (MMT/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refineries and the chemical processing industry (CPI) a</td>
<td>High</td>
<td>7.5</td>
<td>----</td>
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</tr>
<tr>
<td>Metals</td>
<td>$1.70</td>
<td>4.0</td>
<td>$1.40</td>
<td>12</td>
</tr>
<tr>
<td>Ammonia</td>
<td>High</td>
<td>2.5</td>
<td>$2.00</td>
<td>1.1</td>
</tr>
<tr>
<td>Biofuels</td>
<td>High</td>
<td>8.7</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Synthetic hydrocarbons</td>
<td>$1.73</td>
<td>6.0</td>
<td>$0.00</td>
<td>8.0</td>
</tr>
<tr>
<td>Natural gas supplementation</td>
<td>$1.40</td>
<td>16</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Seasonal energy storage for the electricity grid</td>
<td>$1.10</td>
<td>14</td>
<td>$0.26</td>
<td>0.8</td>
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<tr>
<td>Light-duty fuel cell electric vehicles (FCEVs)</td>
<td>$2.20</td>
<td>12</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Medium- &amp; Heavy-Duty FCEVs</td>
<td>$2.20</td>
<td>5.2</td>
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</tbody>
</table>

Hydrogen threshold prices and demands for scenarios using the EIA’s Low Oil and Gas Resource Scenario. Other scenarios have different threshold prices and quantities.
Potential Hydrogen Markets: Metals Refining (Steel)

• Status:
  – 81 MMT_{steel}/yr produced in the U.S. project to grow to 120 MMT_{steel}/yr by 2050
  – Blast furnaces: 430 kg_{coke} / MT_{iron}
  – Direct reduced iron optimally uses hydrogen/CO blends, with 30 kg_{H2} /MT_{hot iron}
    • Can use up to 100% hydrogen (100 kg_{H2} /MT_{hot iron})

• Serviceable Consumption Potential:
  – 12 MMT/yr_{H2} based on 120 MMT_{steel}/yr at 100 kg_{H2}/MT_{hot iron}

• Threshold Price for Economic Potential:
  – 4 MMT_{H2}/yr for market at positive ROI: $1.70/kg_{H2} based on converting all U.S. production to optimal hydrogen/CO ratio of 30 kg_{H2} /MT_{hot iron}
    • Increase threshold price in “R&D Advances Scenario” to $2.50/kg_{H2} based on maintaining domestic production while reducing associated emissions
  – 12 MMT_{H2}/yr: $0.80/kg_{H2} for positive ROI competing with natural gas heat (i.e., using 100% hydrogen – 100 kg_{H2}/MT_{hot iron})

Source: Steel Times International
Potential Hydrogen Markets: Biofuels

• Opportunity:
  – 50% of total jet fuel demand in 2050 (38.6 billion gal/yr AEO Reference)
  – 1.8 billion gal/yr is from fats, oils, & greases (FOGs)
  – 17.5 billion gal/yr based on catalytic fast pyrolysis of biomass

• Serviceable Consumption Potential:
  – FOGs require 76 g H₂/gal → 0.1 MMT/yr
  – Catalytic fast pyrolysis requires 490 g H₂/gal → 8.6 MMT/yr*
  – Total: 8.7 MMT H₂/yr

• Threshold Price: High because of non-hydrogen price drivers → $3.00/kg H₂


* Designs have hydrogen produced from non-condensibles in the process. We assume those can go to higher value products. Further analysis is needed
Potential Hydrogen Markets: Synthetic Hydrocarbons

- Methanol
  - Methanol: Current capacity 9.4 MMT methanol/yr and EIA projects 34.9 MMT methanol/yr by 2030
  - Producing additional 25.5 MMT methanol/yr would require 44 MMT/yr CO₂ (equal to annual ethanol plants production)*
  - Serviceable consumption potential of 6 MMT H₂/yr to convert 44 MMT/yr CO₂ to methanol
  - Threshold price: $1.73/kg H₂ for methanol price equivalent to NG-sourced methanol ($0.5/kg methanol)
- Methanol-to-Gasoline (MTG) **
  - 56 MMT CO₂/yr from SMR and ammonia production could be used to produce MTG
  - Serviceable consumption potential of 8.0 MMT H₂/yr to convert that 56 MMT/yr CO₂ to methanol (no additional H₂ needed for MTG)
  - That 56 MMT CO₂/yr would need concentrating thus not in economic potential (i.e., H₂ price point is too low for any of our scenarios so shows up as $0/kg H₂ in demand curves)
- Total serviceable consumption potential: 14.0 MMT H₂/yr

* 3:1 H₂:CO₂ molar ratio and 79% CO₂ selectivity
** Other chemicals and products are possible and could be considered with further analysis

Source: Supekar and Skerlos, ES&T (2014)
Potential Hydrogen Markets: Natural Gas Supplementation

• Serviceable Consumption Potential:
  – 20% (volume) assumed to not have significant impact on technologies that utilize natural gas
  – 16 MMT\textsubscript{H2}/yr

• Threshold Price:
  – Energy value on a higher heating value (HHV) basis
  – $0.80/kg\textsubscript{H2} for AEO reference case ($5.88/MMBtu)
  – $1.40/kg\textsubscript{H2} for AEO Low Oil & Gas Resource case ($10.23/MMBtu)

Additional Potential Hydrogen Demands – Not Included in this Analysis

• Additional hydrocarbon opportunities
• High-temperature industrial heating applications
• Rail transport
• Marine transport (shipping, ferries)
• Material handling equipment
• Coal-to-Liquids
• Glassmaking
• Rocket fuel
Economic Potential: Limitations and Caveats

- Market equilibrium methodology and market size estimates in 2050
  - Transition issues such as stock turnover are not considered
- New policy drivers, such as emission policies, are not included either for hydrogen or the grid
- Technology and market performance involve many assumptions about adjacent technologies
  - In all but the non-reference scenario, the assumption is that R&D targets are met
- Demand analysis is limited to sectors that could be forecast for the foreseeable future
  - Hydrogen use to convert biomass based market size equal to 50% of aviation demand
  - Hydrogen for industrial heat is not included
  - Single hydrogen threshold price for fuel cell vehicle market estimates
- Estimates of delivery costs were standardized and without location specificity
- Potential long-term production technologies (e.g., photo-electrochemical) not included
- Economic feedback impacts are not considered
- Competing technologies (both for markets that use hydrogen and for resources to generate hydrogen) are addressed in a simplified manner only
### Economic Potential: Five National Scenarios

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Reference</th>
<th>R&amp;D Advances + Infrastructure</th>
<th>Low NG Resource / High NG Price</th>
<th>Aggressive Electrolysis R&amp;D</th>
<th>Lowest-Cost Electrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas prices</td>
<td>Reference</td>
<td></td>
<td></td>
<td>Higher</td>
<td></td>
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<tr>
<td>HTE costs</td>
<td>Current</td>
<td></td>
<td></td>
<td>Improvements</td>
<td></td>
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<tr>
<td>LTE capital costs</td>
<td>Current</td>
<td>Current trajectory</td>
<td>Improvements</td>
<td>Optimistic assumptions</td>
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<tr>
<td>LDE market assumption</td>
<td>Available at retail price</td>
<td>Between retail and wholesale</td>
<td>Wholesale price</td>
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<tr>
<td>Distribution for FCEVs</td>
<td>Current</td>
<td></td>
<td>Cost targets met</td>
<td></td>
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<tr>
<td>Metals demand</td>
<td>Market competition</td>
<td></td>
<td>Premium for hydrogen</td>
<td></td>
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</tbody>
</table>

Key differences in scenarios: 1) natural gas price assumption, 2) distribution costs, 3) electrolyzer cost assumption, 4) electrolyzers’ access to grid service markets, and 5) increased threshold price in metals industry.
New Economic Potential Results

LDE: Low-cost, dispatch-constrained electricity
Summary of Key Conclusions

• The economic potential of hydrogen demand in the U.S. is 2-4X current annual consumption. At those market sizes, hydrogen production is 4-17% of primary energy use.
  – Range across 5 scenarios developed using a variety of economic and R&D success assumptions
  – Total U.S. petroleum use could decline by up to 15% below a scenario with a high renewable penetration on the grid
• An increased hydrogen market size can be realized even if low-cost LTE is not available as long as other hydrogen production options are available
• Grid-integrated electrolysis can increase wind power generation by more than 60% by monetizing additional low-cost, dispatch-constrained electricity
• Up to 60% of current nuclear power plants could improve their profitability by producing hydrogen.
• Scenarios show the potential for up to 20% reduction in U.S. CO₂e emissions over electricity grid improvements alone. Higher reductions may be feasible given policy drivers and development of additional demand sectors.
Musings on Opportunities and Challenges for Hydrogen to Green High-Temperature Manufacturing

**Combustion**
- Higher flame temperature than methane
  - Emissions control
  - Redesign of boilers and direct heating
- Emissions’ humidity
- Energy density – but carriers could improve opportunity

**Molecular Properties**
- Reducing agent (steel and fuels)
- Reactions R&D
- Potential opportunities for hybrid electrochemical processes

**Energy Sector-Wide**
- Potential to increase penetrations of variable renewable generation
- Where is the tipping point for H2@Scale?
Thank You
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