Low-C Hydrogen in a net-zero economy: Emissions, Arithmetic, Models, and Policy

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Center on Global Energy Policy, Columbia Univ.
Sept 27, 2021
**H₂ is Hot**

**H₂ Economy Today**

Hydrogen, the most abundant element on Earth, is a powerful clean energy carrier when used in a fuel cell — highly efficient and flexible, emitting only electricity, heat and water.

In this study, we explore the potential for a hydrogen-powered future by looking at the

**Key Trends in the Clean Energy Industry**

Hard to separate hype, help and opportunity

Europe is going all in on hydrogen

World's Largest Green Hydrogen Project in Saudi Arabia

DOE: Hydrogen Earthshot
Hydrogen: the Swiss Army knife of deep decarbonization

Heavy Industry
• Replacing/decarbonizing current hydrogen production (70 Mt/y + 477 Mt/y CO₂)
• Industrial heat (cement, iron & steel, chemicals, refining, glass, ceramics, paper)

Transportation Sector
• Direct use as a fuel (heavy duty trucking; port operation)
• Feedstock to synthetic fuels (ammonia, synthetic jet fuel & methanol)

Power Sector
• Alternative power storage (like a long-duration battery) with stationary fuel cells
• Get value from power congestion & curtailment

Multi-sectoral Applications
• Near-term and long-term replacement for natural gas (heat and power)
• Feedstock to a circular carbon economy (fuels, plastics, chemicals)
• CO₂ removal (biomass+CCS to hydrogen; energy for CO₂ removal systems)
Hydrogen is a big part of a net-zero economy
Key applications: Industry, shipping, aviation, trucks, heat
Mix of blue & green

Global supply of low-C fuels

Global H2 production by fuel & use by sector
How hydrogen is made

GRAY

Natural Gas
Water

CO₂ → H₂

BLUE

Natural Gas
Water

CO₂ → H₂

GREEN

Zero-C Electricity
Water

H₂

BIO

Biomass
Water

CO₂ → H₂
Fair question: What’s the true footprint of H₂ production & use?

Source: Global CCS Institute, 2021

Fan et al., 2021
Clean H₂ production and utilisation must increase from ~1Mtpa to hundreds of Mtpa by 2050.
Key challenges

Cost
- **Green**: $3-8/kg (55% electricity, 30% electrolyzer, 15% BOP)
- **Blue**: $1.2-1.8/kg (for D, price of gas & decarb fraction)

Technology limits
- Manufacturing: bespoke production (China, Germany, Korea, Norway, Japan trying to change)
- Pipeline tolerances: 7-20% in most existing natgas pipeline networks
- Safety: Invisible – sensors & controls, home safety, etc.

Infrastructure (EWIIW)
- **Green**: Massive build of transmission & zero-C electricity supply (26,000 TWh = 530 Mtpa)
- **Blue**: CO₂ pipelines, fueling infrastructure, pore volume access; upstream CH₄; acceptance

<table>
<thead>
<tr>
<th>Cost of electricity</th>
<th>Capacity Factor</th>
<th>Cost of H₂ ($/kg)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$30/MWh</td>
<td>90%</td>
<td>$2</td>
</tr>
<tr>
<td>$. 5/MWh</td>
<td>20%</td>
<td>$2</td>
</tr>
</tbody>
</table>

* For $1000/kW electrolyzers

Friedmann et al., 2019
Today, blue beats green most everywhere
Tomorrow (2030*), green looks more promising

* Big grain of salt on this date
2035-2040 more likely for same outcome

Sensitive to learning rates for renewables, electrolyzers

Infrastructure limits & deployment rates both important

Bloomberg NEF, 2021
Eventually (2050), green should beat blue most markets

Bloomberg NEF, 2021

'Blue' hydrogen from natural gas with CCS

'Green' renewable hydrogen

'Gray' hydrogen from natural gas without CCS
Key challenges

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Friedmann et al., 2020

<table>
<thead>
<tr>
<th>Facility</th>
<th>H₂ Production (tonnes/day)</th>
<th>H₂ Production Process</th>
<th>Operational Commencement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue hydrogen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enid Fertiliser</td>
<td>200 (in syngas)</td>
<td>Methane reformation</td>
<td>1982</td>
</tr>
<tr>
<td>Great Plains Synfuel</td>
<td>1,300 (in syngas)</td>
<td>Coal gasification</td>
<td>2000</td>
</tr>
<tr>
<td>Air Products</td>
<td>500</td>
<td>Methane reformation</td>
<td>2013</td>
</tr>
<tr>
<td>Coffeyville</td>
<td>200</td>
<td>Petroleum coke gasification</td>
<td>2013</td>
</tr>
<tr>
<td>Quest</td>
<td>900</td>
<td>Methane reformation</td>
<td>2015</td>
</tr>
<tr>
<td>Alberta Carbon Trunk Line - Sturgeon</td>
<td>240</td>
<td>Asphaltene residue gasification</td>
<td>2020</td>
</tr>
<tr>
<td>Alberta Carbon Trunk Line - Agrium</td>
<td>800</td>
<td>Methane reformation</td>
<td>2020</td>
</tr>
<tr>
<td>Sinopec Qilu</td>
<td>100 (estimated)</td>
<td>Coal/Coke gasification</td>
<td>2021 (planned)</td>
</tr>
</tbody>
</table>

| Green hydrogen               |                           |                                |                          |
| Trondheim                    | 0.3                       | Solar (I)                      | 2017                     |
| Fukushima                    | 2.4 (10 MW)               | Solar                          | 2020                     |
| NEOM                         | 650                       | Wind + Solar                   | 2025 (planned)           |
Infrastructure limits will delay deployment & add to system costs

- Transmission lines
- Power build-out
- Electrolyzer costs

Mix of blue & green H₂ delivers lower cost + greater volumes

Global hydrogen demand (2030 & 2050; IEA scenarios)

Source: Fan et al., 2021
## Key challenges

<table>
<thead>
<tr>
<th>Sector</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioenergy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share of modern biofuels in modern bioenergy (excluding conversion losses)</td>
<td>20%</td>
<td>45%</td>
<td>48%</td>
</tr>
<tr>
<td>Advanced liquid biofuels (mboe/d)</td>
<td>0.1</td>
<td>2.7</td>
<td>6.2</td>
</tr>
<tr>
<td>Share of biomethane in total gas networks</td>
<td>&lt;1%</td>
<td>2%</td>
<td>20%</td>
</tr>
<tr>
<td>CO₂ captured and stored from biofuels production (Mt CO₂)</td>
<td>1</td>
<td>150</td>
<td>625</td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production (Mt H₂)</td>
<td>87</td>
<td>212</td>
<td>528</td>
</tr>
<tr>
<td> of which: low-carbon (Mt H₂)</td>
<td>9</td>
<td>150</td>
<td>520</td>
</tr>
<tr>
<td>Electrolyser capacity (GW)</td>
<td>&lt;1</td>
<td>850</td>
<td>3 585</td>
</tr>
<tr>
<td>Electricity demand for hydrogen-related production (TWh)</td>
<td>1</td>
<td>3 850</td>
<td>14 500</td>
</tr>
<tr>
<td>CO₂ captured from hydrogen production (Mt CO₂)</td>
<td>135</td>
<td>680</td>
<td>1 800</td>
</tr>
<tr>
<td>Number of export terminals at ports for hydrogen and ammonia trade</td>
<td>0</td>
<td>60</td>
<td>150</td>
</tr>
</tbody>
</table>

Note: mboe/d = million barrels of oil equivalent per day; Mt = million tonnes; H₂ = hydrogen.
Upstream emissions receiving greater attention
Howarth & Jacobsen (2021) + NY Times story = controversy

Upstream emissions today
• EPA: 1.1-1.7%
• EDF: 2.0-2.3%
• Flaring regions: closer to 3%

What’s possible
• Monitoring technology getting good
• Able to seal & repair leaks
• Industry voluntary standard:
  • 0.2% (best)
  • BAU (too common)
• Biden admin: proposing new regs.

How green is blue hydrogen?

Robert W. Howarth¹ | Mark Z. Jacobson²


By Hiroko Tabuchi

Do not distribute – OUO – work in progress
A few new and helpful analyses

Pembina Inst. (2021)

includes upstream emissions (~10% LCA if not managed)

Conclusions: Blue H₂ could reduce 85%
Blue H₂ best = solar best
Conclusion: high capture Blue H₂ could contribute to a net-zero world with very low upstream emissions

Bauer et al. (2021)
These numbers matter!

Policy & political dynamic is non-linear & changing quickly
Hydrogen Policy Landscape: US

Hydrogen PTC – ranked against standard SMR
• $3/kg for 95% less; $1/kg for 95-85%; $0.75 for 75-85%
• Not possible to achieve the 95% standard!!

CCS & 45Q
• Could be as high as $85/ton CO₂ – cannot be stacked with H₂ PTC
• “Denial of double benefit” provision could make it difficult

Some Power Sector Bits
• Clean Energy Payment Program (CEPP) – H₂ footprint assumptions & baseline will affect payments
• 9 states have clean electricity standards – not clear how H₂ might qualify for rate recovery

Hydrogen Hubs, Innovation & Infrastructure
• $8B for 4 hydrogen hubs
• Hydrogen earth shot
• Ports, fueling stations, CO₂ and H₂ pipelines, new transmission lines
Hydrogen Policy Landscape: Other nations

UK
• Blue & green H₂ part of national strategy
• Hubs + contract for differences

Canada
• Blue & green H₂ part of national strategy
• Infrastructure, clean fuel standard, $170/t C tax

EU
• Blue & green H₂ part of EU strategy
• Infrastructure, incentives, grants

Middle East
• KSA: Blue & green H₂ part of national strategy
• UAE: Blue & green H₂ part of national strategy
• Qatar: Blue H₂ part of national strategy

Japan
• Low-C green premium (blue & green)
• Focus on fuel cells, electrolyzers, shipping

China
• Green H₂ part of national strategy (also grey)
• Focus on fuel cells & electrolyzers

India
• Announcement of new industrial H₂ program
  (steel and refining/chemicals focus)

Chile
• Green H₂ part of national strategy

Australia
• Blue & green H₂ part of national strategy
A few parting thoughts

Arithmetic matters!!

US policy is being shaped without numeracy
• We may shut out virtuous blue & green options
• Will slow deployment
• Will limit US trade, export, and climate priorities

Other nations are taking an “all of the above” approach

We will see more baseless assessments and aggressive messaging
• Many groups have a business model rewarding shrill & innumerate claims
• More scientists and advocates comfortable with ad hominem attacks

Critical & important role for groups like NETL & GTI
Thank You
Assumptions

Howarth & Jacobsen (2021)

- Assessed steam methane reforming (SMR)
  - New projects use an ATR, not an SMR. This allow both higher capture rates and lower costs.
- Low capture rate - only 65% capture.
  - New projects are >90% and may are >95%
- High methane leakage rates - 3.5% fugitive emissions.
  - US Average: 1.25 (0.85-1.75 range)
  - Best in class: 0.2%
- Large methane consumption in capture tech – liquid solvent adder
  - Factually incorrect
    - Capture from an SMR requires almost no energy
    - Does not use liquid solvent approach for 60% capture
    - This is important, since the incorrectly assumed extra energy would leads to extra methane emissions (& extra fugitive).
- Using a 20-year warming potential for methane
  - This is debatable: IPCC uses 100-year.
  - 20-year impacts higher than 100-year impacts

Conclusion: Blue $H_2$ could not be clean & could never contribute to a net-zero world
Informal revisions of H&J key figure

Romano: 2021

Caldeira: 2021

Assuming 1% leakage, 100-year GWP, emission-free energy, and 100% capture of process CO₂