Hydrogen’s role in achieving net-zero carbon emissions for the global economy

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Retired Shell Chief Scientist – Chemical Engineering

Stanford Energy Seminar
1 March 2021
Agenda

While electricity will assume a dominant role in conveyance of clean energy to end users, sectors such as heavy-duty trucking and transport, marine, aviation, and heavy industry are more difficult to decarbonize, and will benefit from the higher energy density and storage afforded by hydrogen as a vector. Hydrogen can also be used to synthesize other molecular energy carriers and chemicals for recycle of carbon to achieve circularity. This seminar will examine the challenges and multiple synergistic opportunities for hydrogen in future energy and chemical systems. Is now the time for a hydrogen economy?

- Electrification is key to future low carbon, clean energy economy
- Where can hydrogen complement?
- What are the alternatives?
Disclaimer

Any cost information is approximate and derived from open literature and data. Do not take any observations as investment advice.
Hydrogen

- Most abundant element: 75% of mass and 90% of atoms in the universe.
- 73% of sun is Hydrogen: plasma via H-fusion to helium, giving off light
  - Hydrogen on sun is primary energy source for solar light on earth!
- H does not exist in free form on earth: incorporated into elements
- \( \text{H}_2 \) forms flammable mixtures with air: 4% - 74%;
  - nearly invisible to blue flame depending on \( \text{O}_2 \) content
- \( \text{H}_2 \) molecular weight 2.016 vs. 29.97 air (buoyant)
- \( \text{H}_2 \) energy density 120 MJ/kg:
  - 3X more than gasoline or diesel
- Boiling point: -253 C (20 K)
Global Energy Demand

1 Petawatt = 1000 Terra watts
1 Terra watt = 1000 Gigawatts
1 Gigawatt = 1000 Megawatt
1 Megawatt = 1000 Kilowatt (kW)

Global direct primary energy consumption does not take account of inefficiencies in fossil fuel production.

150,000 Twh = 540 EJ = 511 Quad BTU = 12.9 Btoe = 88 Bboe = 242 Mboe/day

Hydrogen is not a primary energy source on earth!

32 Gigatonnes CO₂
Energy storage: duck curve CA

The duck curve shows steep ramping needs and overgeneration risk

- David Mooney | Large Scale Energy Storage | GCEP Symposium 2015. Stanford Energy
Hydrogen History

- 1520’s Discovery
- 1660’s Boyle’s law PV / acid-metals
- 1780’s Lavoisier “Hydro” “Gene”
- 1780’s Hydrogen Balloon flight “La Charliere”
- 1780’s Iron – steam process
- 1789: Water electrolysis
- 1801: Fuel cell (Humphry Davy)
- 1806: Internal combustion engine
- 1874: Jules Verne “Mysterious Island”
- 1884: Airship La France
- 1901: Hydrogenation of unsaturated fats
- 1910: Haber process (ammonia)
- 1923: Synthetic methanol (Leuna)
- 1937: Hindenburg fire
- 1943: Rocket fuel
- 1951: Salt dome storage
- 1957: Jet engine
- 1960: Forklift
- 1965: NASA Project Gemini
- 1966: General Motors “Electrovan”
- 1970’s: DOE Fuel Cell R&D
- 2000: Ballard commercial fuel cell
- 2003: George Bush “Hydrogen Economy”
- 2010: Shell forecourt Aqueous Phase reforming

**References:**
- https://en.wikipedia.org/wiki/The_Mysterious_Island (1875);
Energy Transition: Shell Sky Scenario

Population Increase: 7.9 → 10 Billion
Global Energy demand: Increase by > 30%
Carbon emissions: Net zero via negative emissions
Stakeholder Market Forces

**Rebecca Elliott and Bradley Olson, Sept. 22, 2019 WSJ**

**SCOPE-3 Emissions:**

“greenhouse-gas emissions from the oil byproducts they sell, such as gasoline. These releases constitute roughly 88% of major oil-and-gas companies’ greenhouse-gas footprint, according to estimates from Redburn, a London-based research firm”

Pandemic panorama: Skies were clear above San Francisco, on March 25, about a week after California’s stay-at-home order took effect. PHOTO: DAVID PAUL MORRIS/BLOOMBERG NEWS

Coronavirus Offers a Clear View of What Causes Air Pollution: Jim Carlton, WSJ May 3, 2020

With factories and vehicles idle, nitrogen dioxide levels hit lows not seen since the early 20th century; ‘We didn’t know...how significantly it could drop’
Energy vectors to end-use customers

Important role for CCS to decarbonize existing assets + future negative emissions
Shell Scenarios 2021

Waves

Islands

• [www.shell.com/scenarios](http://www.shell.com/scenarios)
Shell Scenarios 2021

Sky 1.5

Hydrogen demand

• www.shell.com/scenarios

Copyright: Shell SIEP
Final energy to users

Energy use in industry – Sky 1.5 scenario

Energy use in transport – Sky 1.5 scenario

Copyright: Shell SIEP

www.Shell.com/scenarios
Policy impact on H$_2$ demand (US)

Global Perspective

Solar energy as a logistic and utility challenge

• Population distribution (USDA)

Dense (molecular) energy carriers
- Long distance transport of energy
- Long term & large-scale energy storage (energy security, seasonality)
- Convenient use in (high-performance) transportation

Lowest cost storage of electrons
- Energy penalty for energy carrier conversion is very high – society will want to use electrons where possible facilitated by electro-chemical storage

Direct solar insolation

Source: DEC LRR, World Bank, SolarGIS, PVSyst

Copyright: Shell SIEP
Hydrogen as Energy Vector

- Improves local air quality
- Only water vapour emissions while driving
- Low-carbon transport if made via green or clean pathways
- High range – up to 700 km per refuel
- Minutes to refuel

R. Heinberg and D. Fridley, *Our Renewable Future: Laying the path to One Hundred Percent Clean energy.*

Copyright of Shell International B.V.
AIM:
- Meet 10% of yearly NYC power demand using renewable energy
- Base load, not tracking demand fluctuations

SCENARIO 1: Ship DECs from Southwest to Northeast
- Texas Panhandle is a good source of both wind and solar
- Produce DECs in Amarillo, TX using solar PV and wind turbines
- Transport DECs to NYC using railroads
- Convert DECs back to electricity in NYC

SCENARIO 2: Local production at Northeast
- Store local energy using solar PV and/or wind turbines and NaS battery in NYC
- Suffolk County, NY (Long Island)
  - Most available land for solar and wind near NYC

SCENARIO 3: DECs + Local production
- Combined Scenario 1 and 2

ANALYZE:
- Minimize total cost of meeting the electricity demand (LCOE)
- Optimal technologies for energy storage

LH₂ & Ammonia First Choice
Hydrogen Energy Carriers

Renewable Electrons (Cheap & Excess)

Water electrolysis

H₂

LOHC

NH₃

MeOH

Synthesis

Cost of synthesis

Economic & Society optimum unknown

Ease of use (transport, storage)

“Cost” of “Feed”

Water

Atmospheric N₂

Atmospheric CO₂

Fischer Tropsch

Haber Bosch (potentially single step electrolysis)

(Needs conventional HC carrier)

Cost of synthesis

HC Fuel
Molecular energy carriers have poorer cycle efficiency than electrochemical energy storage (Battery). The value of transport as Dense Energy Carrier plus Storage must be considered in evaluating options!
Hydrogen vs Power to Liquids / Synthetic Natural Gas

Copyright: Shell SIEP
Consumption required Power to Liquids

California
- 14.57 billion gallons gasoline / yr
- 0.1 m²/(L/yr)-solar gasoline
- 1.36 million acres CA
- 1.30% of California land mass
- 418.3% of undeveloped land for sale

Average amounts of energy and feedstock needed to produce 1 litre of an average PtL fuel (decane), which could be either diesel (F1 route) or gasoline (methanol route). Efficiencies are those of a PtL plant in 2030. Chemical synthesis processes comprise Reverse Water Gas Shift and Fischer-Tropsch steps or Reverse Water Gas Shift, methanol synthesis, and methanol-to-gasoline steps. Upgrading is included.
Shell Hydrogen

- Liquid H₂ Tanker: AU → JP

From Shell website 2020

Copyright: Shell SIEP
H2@ Scale

Rustagi and Satyapal (2018), in


US Hydrogen Roadmap (FCHEA, 2020):
http://www.fchea.org/us-hydrogen-study
Hydrogen Roadmaps

1) IPHE = International Partnership for Hydrogen and Fuel Cells in the Economy

2) Hydrogen Roadmap - Europe

https://www.iphe.net/communications-archive
IPHE Presentation: H2IQ Hour Webinar 27 April 2020 | Virtual

Hydrogen: US Opportunities

- Green / clean H₂ from West TX renewable + SE TX (Houston GC) waste heat
  - SMR/ Methane pyrolysis / water electrolysis
- H₂ heavy duty trucking, industry
- Commercial ride-share (Uber fleet)?
- City lift trucks / buses?
- H₂ Rail transit to US States with clean energy incentives; H₂ + NH₃ pipelines
  - LH₂ or NH₃
- Leveraged demo hub

**Clean Hydrogen** | **(2030)**
--- | ---
Manufacturing Cost* | < 2 USD / kg
Dispensed Cost | < 4 USD / kg
Scale (per Site) | > 1500 kg / d

* Distributed small/medium scale

**H₂ at Scale Energy System**

- Electric Grid
- Solar PV
- Natural Gas
- Renewable
- Electric Vehicle
- Hydrogen Storage/Distribution
- Hydrogen Transportation
- Power Generation
- Value Added Applications

**ARCHETYPE DOMESTIC SUPPLY CHAIN**

- Renewable energy rich region
- Urban Consumers
H2@Port

• Clean air, low CO₂, rapid refuel: leverage warehouse forklift roll out.

Potential Hydrogen Demand at U.S. Ports

<table>
<thead>
<tr>
<th>Port</th>
<th>Drayage</th>
<th>CHE</th>
<th>Total / Day (kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>438,742</td>
<td>26,718</td>
<td>465,460</td>
</tr>
<tr>
<td>Long Beach</td>
<td>335,580</td>
<td>13,429</td>
<td>349,009</td>
</tr>
<tr>
<td>New York</td>
<td>98,883</td>
<td>29,896</td>
<td>128,779</td>
</tr>
<tr>
<td>Houston</td>
<td>61,430</td>
<td>9,132</td>
<td>70,562</td>
</tr>
<tr>
<td>SEATAC</td>
<td>37,839</td>
<td>15,880</td>
<td>53,719</td>
</tr>
</tbody>
</table>

Port Terminal Equipment kg/day H₂

- RTG Crane 45 kg/day
- Forklift 5 kg/day
- Straddle Carrier 46 kg/day
- Container Handler 56(L) 25(E) kg/day
- Reach Stacker 33 kg/day
- Yard Tractor 21 kg/day

Infrastructure Utilization: Ports and stacked sector uses

- **Rotterdam Harbor:**
  - [https://www.porthosco2.nl/en/](https://www.porthosco2.nl/en/)
H2 demand growth Global & UK

• H2@Scale USA (HTAC meeting March 2019)

2. Source: Hydrogen Council
Hydrogen break-even cost

Breakeven hydrogen costs at which hydrogen application becomes competitive against low-carbon alternative in a given segment
USD/kg

Hydrogen is the only alternative for industry feedstock for existing applications

Commercial mobility applications become viable around $3/kg
On average, passenger vehicles become viable around $2/kg
Hydrogen-based steel production in China breaks even at low-carbon hydrogen costs of $1.9/kg

H2 value in CO₂ Mitigation

$/ton CO₂ abatement cost

Figure 7: Marginal abatement cost curve from using $1/kg hydrogen for emission reductions, by sector in 2050

Source: BloombergNEF. Note: Sectoral emissions based on 2018 figures. Abatement costs for renewable hydrogen delivered at $1/kg to large users, $4/kg to road vehicles. Aluminum emissions for alumina production and aluminum recycling only. Cement emissions for process heat only. Refinery emissions from hydrogen production only. Road transport and heating demand emissions are for the segment that is unlikely to be met by electrification only, assumed to be 50% of space and water heating, 25% of light-duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.

GHG emissions

2018 U.S. GHG Emissions by Sector

U.S.

[Images of pie charts showing 2018 U.S. GHG emissions by sector, with transportation accounting for the largest share followed by electricity and industrial sectors.]

[Links to EPA and IPCC reports for U.S. data.]

https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

Global

IPCC-3 (2014)

Faster refueling = reduced labor and fewer units needed.

More than 35,000 forklifts
Over 20 million refuelings

Hydrogen Production Across the U.S.

- 10 million metric tons produced annually
- More than 1,600 miles of H₂ pipeline
- World’s largest H₂ storage cavern

Hydrogen costs & services

• Today (local hydrogen refueling, 10,000 vehicles scale)
  • $10 - $18/kg dispensed cost in California
  • € 9.5 ($10.5) dispensed cost Germany
  • $7 / kg dispensed cost Texas?
* Compression, storage, and dispensing

Cost reduction via H2@Scale!


Figure 16. Hydrogen production costs for different technology options, 2030

Notes: WACC is weighted average cost of capital. Assumptions refer to Europe in 2020. Renewable electricity price is USD 40/MWh at 4,000 full load hours at best locations; sensitivity analysis based on ±10% variation in CAPEX, OPEX and fuel costs; ±10% change in default WACC of 8% and a variation in default CO₂ price of USD 40/ton CO₂ to USD 10/ton CO₂ and USD 100/ton CO₂. More information on the underlying assumptions is available at www.iea.org/hydrogen2050.

Source: IEA 2019. All rights reserved.
Viability of Hydrogen Economy?

Price paid for energy services


Battery vs. Fuel Cell Electric Vehicles

Scania: “hydrogen's wastefully inefficient use of renewable energy, as well as additional system complexity, cost, safety and ongoing maintenance factors.”

GM / Navistar FCV: 500+ mile range

Hydrogen Council / McKinsey % Co. (Feb 2021) Hydrogen Insights A perspective on hydrogen investment, market development and cost competitiveness

https://www.theverge.com/2021/1/27/22251582/gm-hydrogen-truck-navistar-oneh2-range-date

TCO value proposition: Electric Vehicles

Includes purchase incentives

C. Harto, Electric Vehicles Offer Big Savings for Consumers, Consumer Reports, October 2020

MIT Trancik; https://www.carboncounter.com/#/explore
Viability of Hydrogen Economy?

Price paid for energy services

Total cost of ownership SUV


Figure 54. Total cost of car ownership by powertrain, range and fuel

Figure 55. Break-even fuel cell cost to be competitive with BEV in the long term

Source: IEA 2019. All rights reserved.

Fuel cell electric cars are most competitive on a total cost of ownership basis with BEV cars over longer driving ranges. To break even with battery costs below USD 100/kWh could require achieving fuel cell costs below USD 60/kW.

•IEA Future of Hydrogen 2019
Figure 55. Parameters contrast of different drayage trucks

Kenworth T680:
- Prototype launch: 2018.02
- Purpose: proof of concept
- Drivetrain capacity: 420 kW and 1,880 pound-feet (2,507 Nm) torque
- Fuel cell system: 85 kw
- Hydrogen tank storage capacity: 30 kg
- Battery capacity: 100 kWh
- Gross combined weight capacity: ≥36.3 metric tons
- Driving distance: ≥239km

Toyota Beta:
- Prototype launch: 2018.07 (for deployment in Q4 2018)
- Purpose: proof of commercial viability
- Drivetrain capacity: 670-plus horsepower (500 kW) and 1,325 pound-feet (1,796 Nm) of torque
- Fuel cell system: 2x Mirai fuel system, each rated at 114 kw
- Fuel cell tank storage capacity: 60kg
- Battery capacity: 124kWh
- Gross combined weight capacity: ≥36.6 metric tons
- Driving distance: ≥480km

BEV:
- Drivetrain capacity: 340-740 horsepower (250-550 kW) and 2,000-4,000Nm of torque
- Battery capacity: 200-600kWh
- Gross combined weight capacity: 20-47 metric tons
- Driving distance: 160-800km

ICEV:
- Drivetrain capacity: 400 horsepower (around 300 kW) and 1,200-1,800 pound-feet (1,600-2,400Nm) of torque
- Gross combined weight capacity: 40 metric tons
- Driving distance: >1,000km

Figure 59. TCO break down (USD/100km)

Figure 60. Total cost of ownership/ USD per 100km

<table>
<thead>
<tr>
<th>CO$_2$ free Fuels</th>
<th>H$_2$/Fuel Cell</th>
<th>Battery Electric</th>
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<tbody>
<tr>
<td>Average Propulsion Power [KW]</td>
<td>Operation Time [h/pa]</td>
<td></td>
</tr>
<tr>
<td>60,000</td>
<td>50,000</td>
<td>40,000</td>
</tr>
<tr>
<td>12,000</td>
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<td>5,000</td>
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<td>0</td>
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<td>0</td>
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</table>

Copyright: Shell PDT/Warnecke 2019_01
H₂ Aviation

Airbus:

- H₂ combustion-based aviation testing since 1988
- Battery-power not plausible for larger planes; fuel-cell could be option?
- Hybrid systems: fuel cell for on-board power, plus propulsion

Note: volumetric energy density for H₂ is lower than for aviation fuels. Range impacts.

Liquid hydrogen has about four times the volume for the same amount of energy of kerosene-based jet-fuel. In addition, its highly volatile nature precludes storing the fuel in the wings, as with conventional transport aircraft. Therefore, most liquid hydrogen aircraft designs store the fuel in the fuselage, leading to a larger fuselage length and diameter than a conventional kerosene fueled aircraft. This lowers the performance due to the extra wetted area of the fuselage. The larger fuselage size causes more skin friction drag and wave drag. On the other hand, hydrogen is about one-third of the weight of kerosene jet-fuel for the same amount of energy. This means that for the same range and performance (ignoring the effect of volume), the hydrogen aircraft would have about one-third of the fuel weight. For a Boeing 747-400 type aircraft, this would reduce the takeoff gross weight from 360,000 to 270,000 kg (800,000 to 600,000 lb). Thus, the performance of a hydrogen-fueled aircraft is a trade-off of the larger wetted area and lower fuel weight. This trade-off depends essentially on the size of the aircraft.

Power density and storage

**Power Densities for Energy Sources and End Uses**

*Source: Smil (1991)*

- **Coal Fields**
- **Thermal Power Plants**
- **Oil Fields**
- **Steel Mills, Refineries**
- **Central Solar Towers**
- **Highrisers**
- **Supermarkets**
- **Industry**
- **Tidal**
- **Wind**
- **Photovoltaics**
- **Houses**
- **Cities**
- **Hydro**
- **Photosynthesis**
- **Ocean Heat**

**AREA (m²)**

- **10^0**
- **10^1**
- **10^2**
- **10^3**
- **10^4**
- **10^5**
- **10^6**
- **10^7**
- **10^8**
- **10^9**
- **10^10**

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**Nuclear**

**Grid storage**


- **Solar PPA (US):** $0.03/kWh (2020)
  - $1/kg-H₂ or $1/gallon equivalent energy as electrons.
- Cannot produce H₂ this cheaply.
- Hydrogen must provide “service” in energy transport or storage to be valuable.
Residential Storage

- **First Hydrogen Battery:** Lavo, New South Wales, Australia
  - Electrolyzer $\text{H}_2$
  - Metal Hydride Storage: 40 kWh
  - $29,500 for 3X days full house storage

**Tesla Powerwall:**
- 3x 13.5 kWh = 40.5 kWh = $24,000

**Natural gas whole-house generator:**
- $8,000 for unlimited duration

**Gasoline generator:**
- $900 + 2.5 gal/day gasoline x 3 days = $925

$10,000/ton CO₂ mitigation!
Decarbonize Trucking

\[
\text{EROI} = \frac{\text{Energy Delivered}}{\text{Energy Required to Deliver that Energy}}
\]

Oil = 11:1 \text{ EROI},

corn ethanol = \text{ EROI} of 1.5:1

1) 5000 visitors per day / 5-day storage
2) PV-BEV / H\textsubscript{2} / Biofuel options.
   - 120 MW or smaller power requirement (BEV = \frac{1}{2}H\textsubscript{2})
   - Land use costs for biofuels high: plausible for advanced; questionable for corn ethanol.
   - BEV with no storage lowest cost due to higher efficiency; Battery storage cost high!
   - H\textsubscript{2} better option if 5-day storage included!

Iowa 80 is the world's largest truck stop, located along Interstate 80 off exit 284 in Walcott, Iowa. 220-acre (89 ha) plot of land (four times larger than an average truckstop)—75 acres (30 ha) of which are currently developed. 5,000 visitors daily, 67,000 sq ft (6,200 m\textsuperscript{2}) main building, parking for 900 trucks, and 15 diesel fuel pumps. www.Wikipedia.org

300-mile range Tesla Semi = 568.44 kWh battery; 500-mile Semi = 947.40 kWh capacity. Weight = 4.7 and 7.9 tons and cost $108K and $180k respectively. https://www.tanktwo.com/why-tesla-semi-isnt-revolutionizing-the-trucking-industry/
Where is hydrogen economy emerging?

- Far east (Japan, China, Korea with sourcing from Australia); Europe
- Policy incentives important

Hydrogen Council / McKinsey % Co. (Feb 2021)
Hydrogen Insights on hydrogen investment, market development and cost competitiveness

WSJ 2/26/2021: BEV sales driven by subsidy
Renewable PPA vs. Natural Gas


BP statistical review of global energy
Safety codes and standards

- Hydrogen Refueling Station permitting
- State / municipal road transit (tunnel) permitting

https://www.aiche.org/chs
https://h2tools.org/
Conclusions / Q&A / Follow-up

Hydrogen is an energy vector, not a primary energy source
- Electrification will occur as the world decarbonizes.
- Electricity is efficient for direct generation from wind / solar
Is Hydrogen Necessary?
- Benefits:
  • Higher energy density
  • Storage and transport (% uptime; lower cost sources)
  • Faster refuel
- Challenges
  • Infrastructure cost, lower cycle efficiency (1/2 e⁻)
  • Roll out lagging vs. electrification

Utilization:
- Long-distance energy carrier
- Medium to long-term energy storage
- Zero-emission / air quality vs. hydrocarbon fuels
- Commercial fleets requiring high % uptime & fast refuel
- High energy density services:
  • Industry
  • Residential heating and power
  • Heavy duty transport

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Backup slides
# Hydrogen costs & services

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
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<tbody>
<tr>
<td>8.8</td>
<td>kg H₂ / MMBtu (Lower heating value)</td>
</tr>
<tr>
<td>1</td>
<td>Gallon of gasoline equivalent / kg-H₂</td>
</tr>
<tr>
<td>$3 / MMBtu</td>
<td>Today’s natural gas (no CCS)</td>
</tr>
<tr>
<td>$8 - $13 / MMBtu</td>
<td>Todays use of natural gas with CCS retrofit</td>
</tr>
<tr>
<td>$16 / MMBtu = $1.8/kg-H₂</td>
<td>H₂ today via SMR + CCS or 2030 renewable</td>
</tr>
<tr>
<td>$6 - $9/MM Btu = $0.67 - $1.0 kge-H₂=gge</td>
<td>Wind / solar today PPA, if used as electrons</td>
</tr>
<tr>
<td>+ $ 1 to $ 3 / kg-H₂</td>
<td>H₂ transport + CSD compress store dispense</td>
</tr>
<tr>
<td>+ $0.50/kge-H₂</td>
<td>BEV power connection &amp; charging (no LT storage)</td>
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<table>
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<th>PARAMETERS:</th>
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<tr>
<td>1 kg H₂ = 1 gallon of gasoline equivalent</td>
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<tr>
<td>8.8 kg H₂ / MMBtu (LHV)</td>
</tr>
<tr>
<td>$1.80 / kg H₂ today’s SMR + CCS (blue) or 2030 renewable H₂ = $16 /MMBtu</td>
</tr>
<tr>
<td>$1.25 / kg H₂ today SMR (grey) or future renewable = $11/MM Btu</td>
</tr>
<tr>
<td>$1 - $2 / kg H₂ transport + compression/storage/dispensing costs for vehicles. Add this to H₂ production cost Vs. $2/gallon gasoline.</td>
</tr>
<tr>
<td>Today: $3 / MMBtu for Natural Gas (grey): 80% efficient furnace</td>
</tr>
<tr>
<td>Add + ($5 to $10)/MMBtu if add CCS = $8 to $13 / MMBtu retrofit CCS</td>
</tr>
<tr>
<td>33.8 kWh / kg H₂ electrical (max)</td>
</tr>
<tr>
<td>$0.02 - $0.03/kWh PPA wind/solar = $0.67 to $1/kge = equivalent energy of 1 kg H₂ or 1 gallon of gasoline, but in form of electrons or battery storage</td>
</tr>
<tr>
<td>$6 to $ 9 / MMBtu clean energy, used at nearly 100% efficiency in vehicle (low dispensing and distribution cost)</td>
</tr>
<tr>
<td>Cheapest clean energy, but very high cost storage!</td>
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