US Perspective on the Hydrogen Economy

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Asia Pacific Energy Research Centre
Annual Conference 19-21 April 2021

Topics to cover:

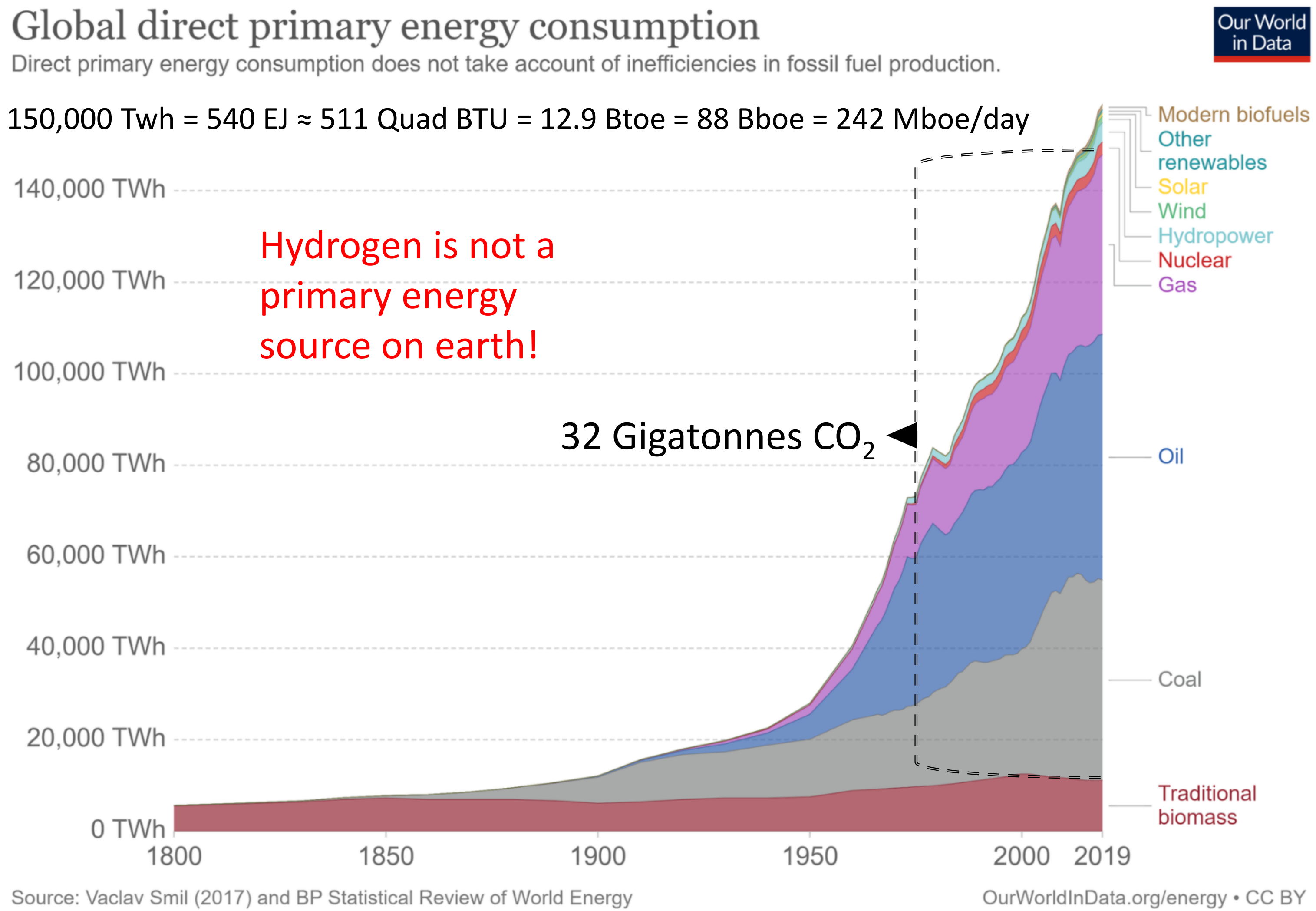
- Could hydrogen play a significant role in a decarbonized US in the future?
- Would the US be a potential importer or exporter?
- What are the key barriers (policy, technology, economic, social, etc)?

Disclaimer:

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

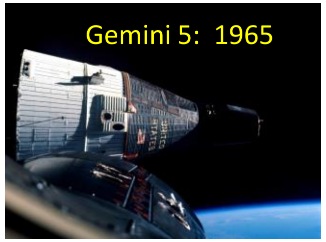
Global Energy Demand

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



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



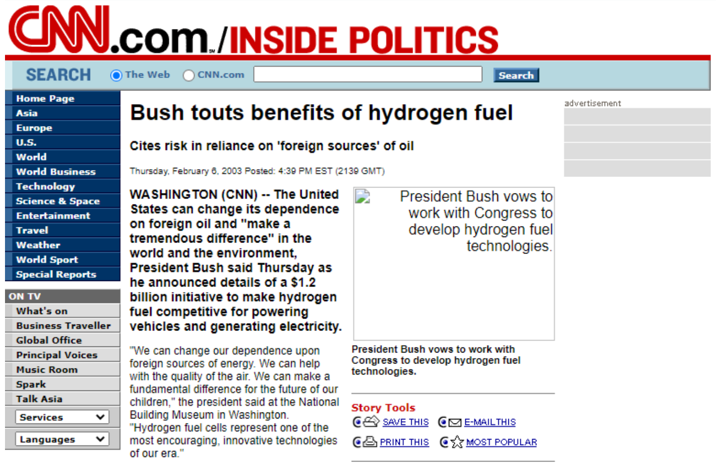
www.fchea.org/fuelcells

www.NASA.gov

Gemini 5 fuel cell.

1970s A group of scientists and DOE managers met at Los Alamos to set the foundation for DOE fuel cell programs

Lab researchers taught scientists around the world how to fabricate fuel cell electrodes. GM relocated to Los Alamos.



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Bush touts benefits of hydrogen fuel

Cites risk in reliance on 'foreign sources' of oil

Thursday, February 6, 2003 Posted: 4:39 PM EST (2139 GMT)

WASHINGTON (CNN) -- The United States can change its dependence on foreign oil and "make a tremendous difference" in the world and the environment, President Bush said Thursday as he announced details of a $1.2 billion initiative to make hydrogen fuel competitive for powering vehicles and generating electricity.

"We can change our dependence upon foreign sources of energy. We can help with the quality of the air. We can make a fundamental difference for the future of our children," the president said at the National Building Museum in Washington. "Hydrogen fuel cells represent one of the most encouraging, innovative technologies of our era."

President Bush vows to work with Congress to develop hydrogen fuel technologies.

President Bush vows to work with Congress to develop hydrogen fuel technologies.

Story Tools
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https://en.wikipedia.org/wiki/The_Mysterious_Island (1875);
Satyapal 2017: https://www.energy.gov/sites/prod/files/2017/03/f34/fcto-energy-talks-2017-satyapal.pdf
https://en.wikipedia.org/wiki/Timeline_of_hydrogen_technologies

Hydrogen & Fuel Cells U.S.

December 2020 U.S.

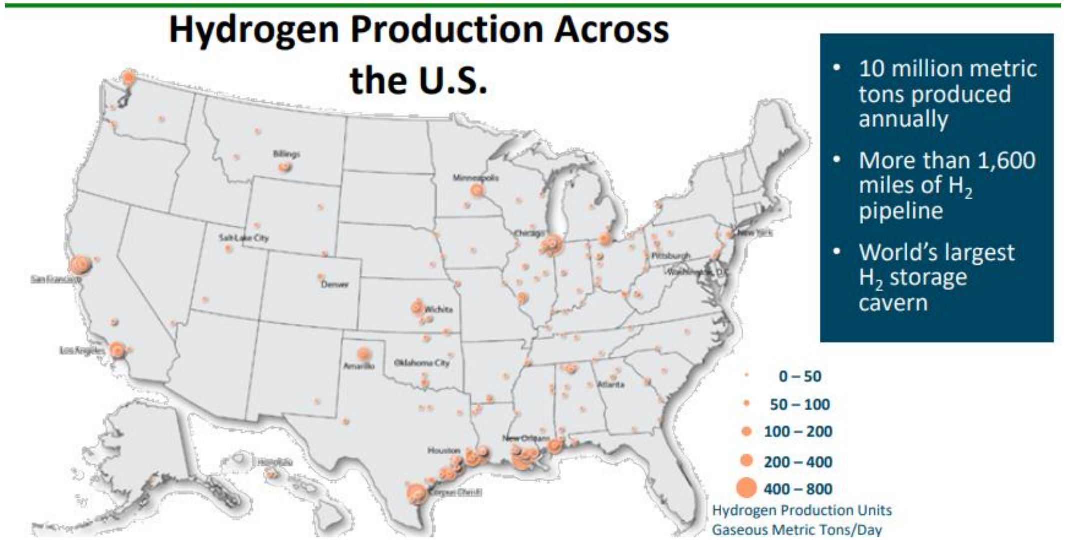
>500MW
Stationary Power

>35,000
Forklifts

>60
Fuel Cell Buses

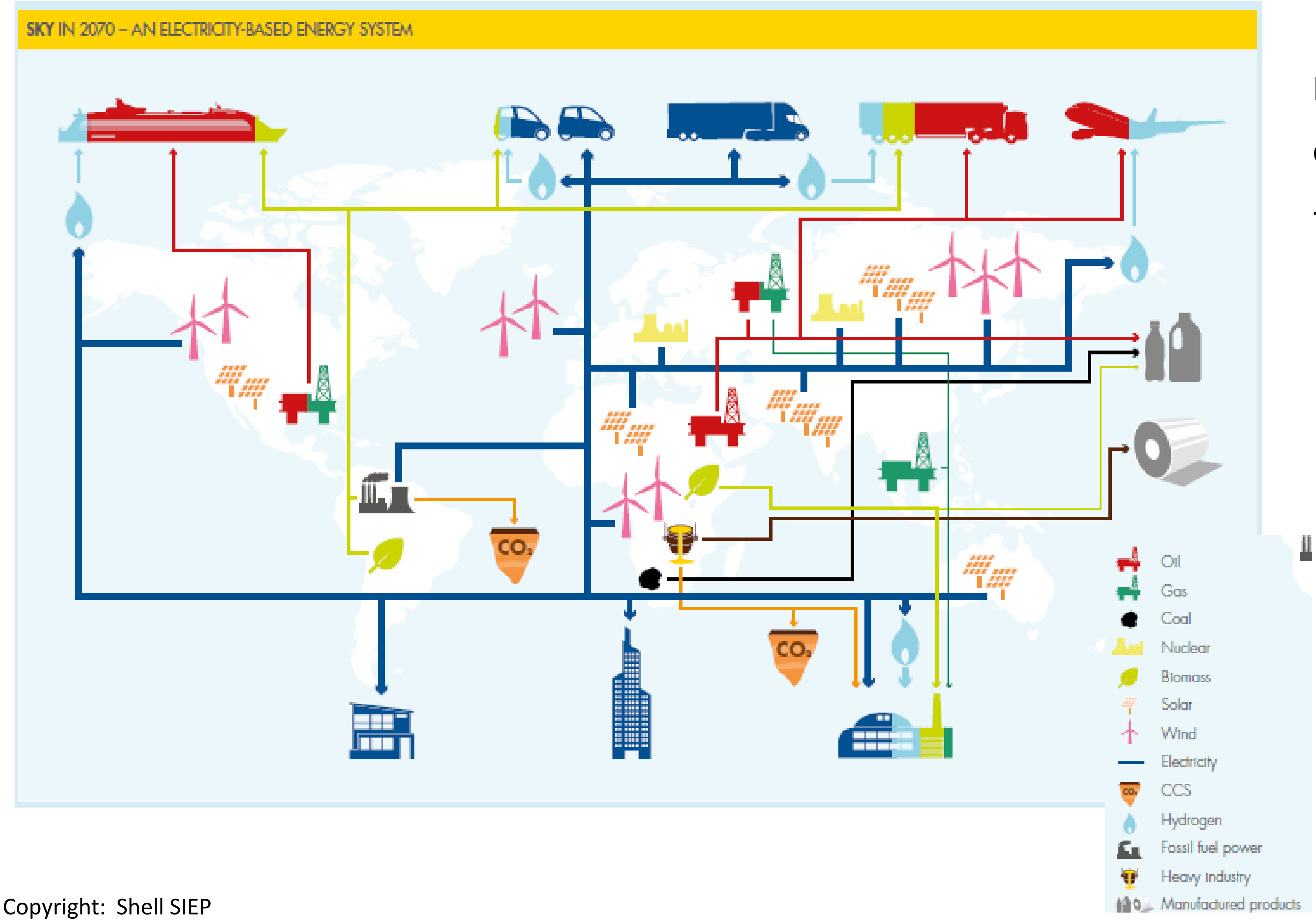
>45
H_2 Retail Stations

>8,800
Fuel Cell Cars

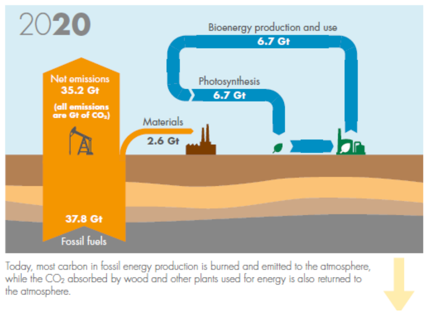


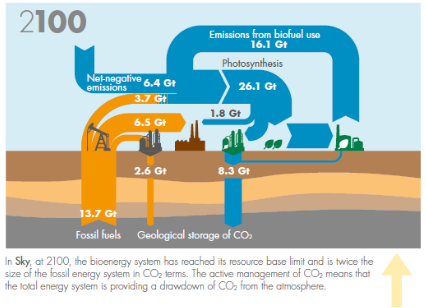
Satyapal: www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office

Energy vectors to end-use customers



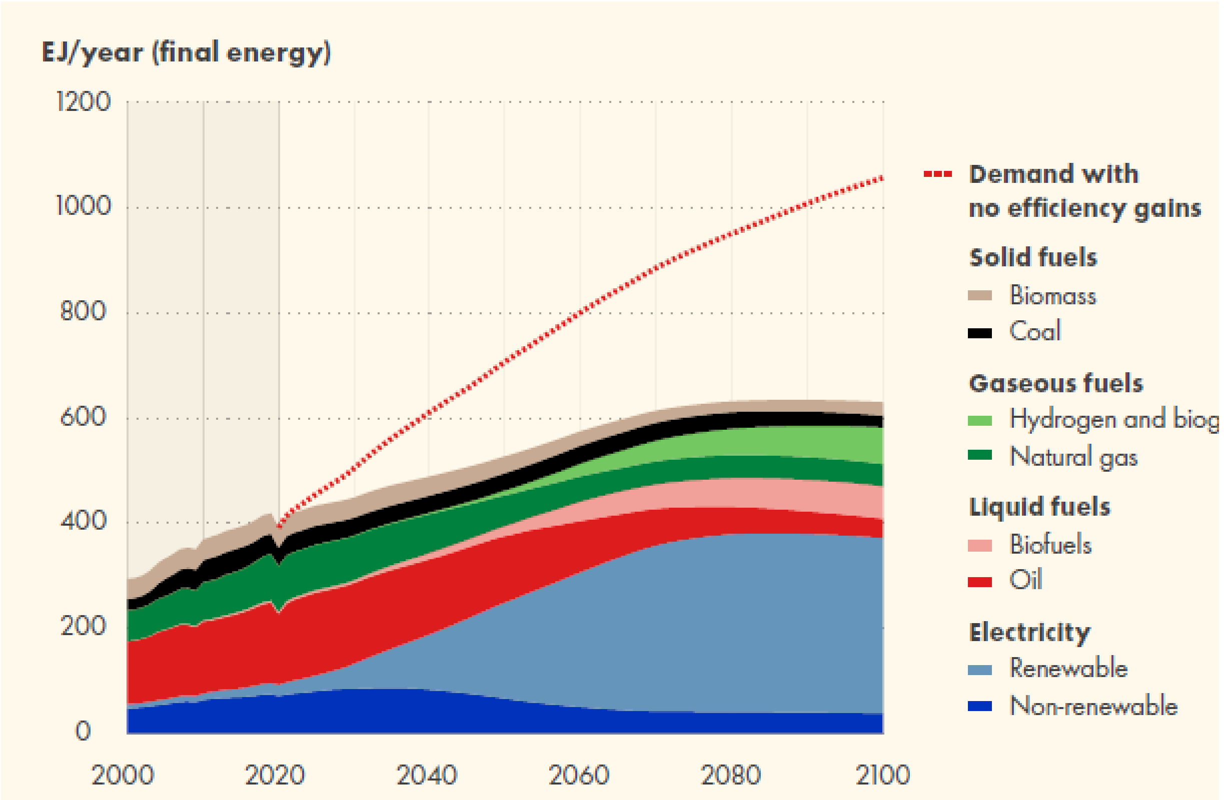
Important role for CCS to decarbonize existing assets + future negative emissions



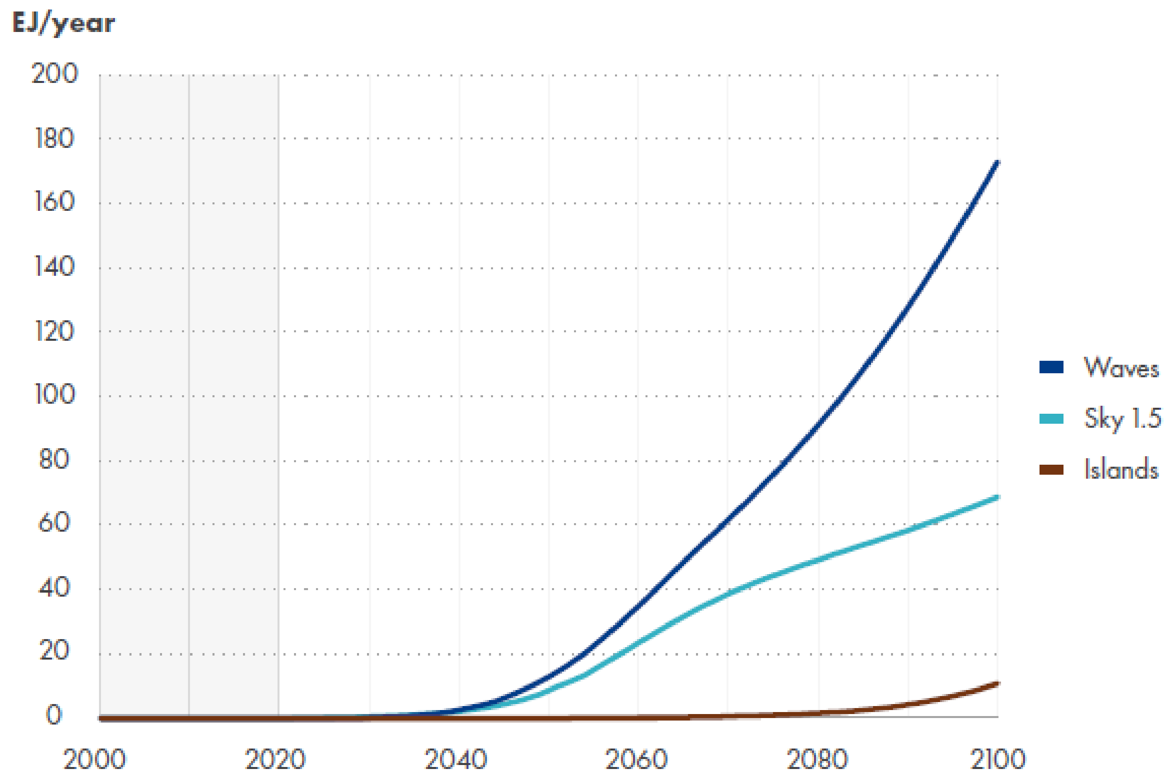


Shell Scenarios 2021

Sky 1.5



Hydrogen demand



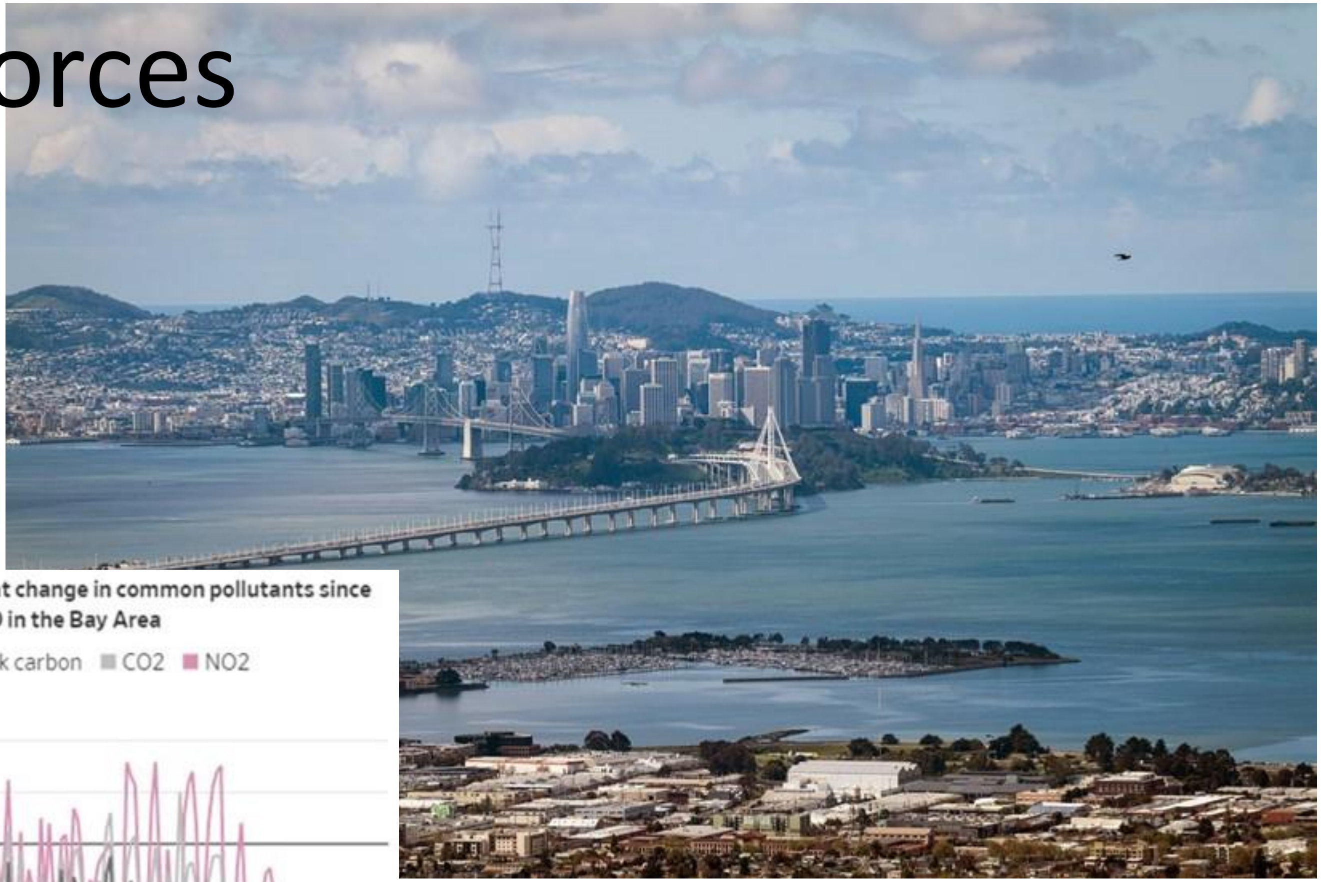
- www.shell.com/scenarios

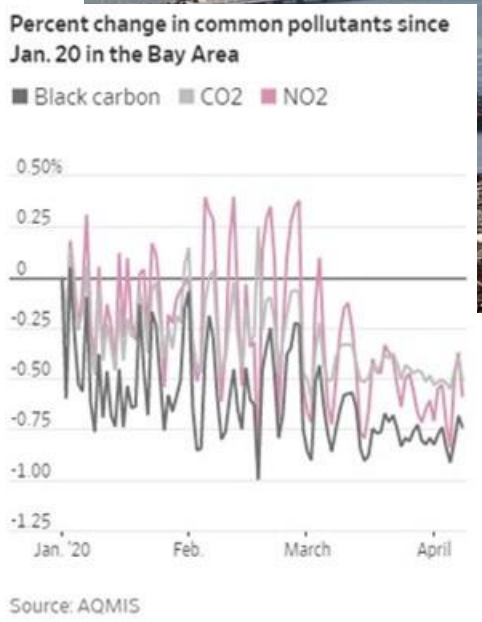
Stakeholder Market Forces

•*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”*

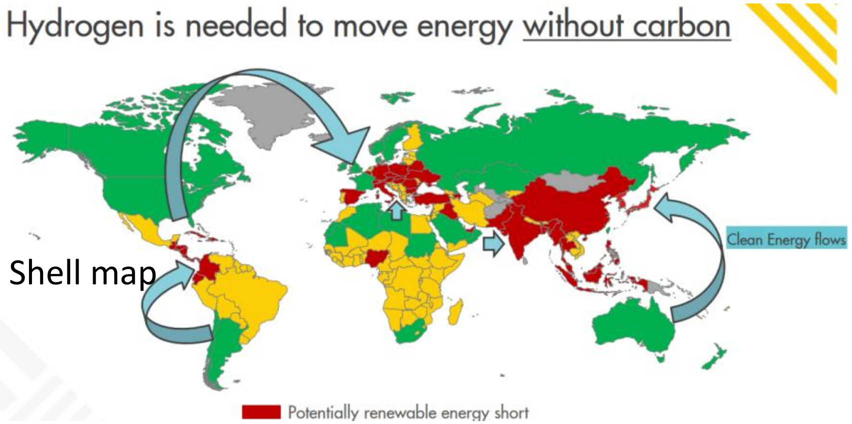




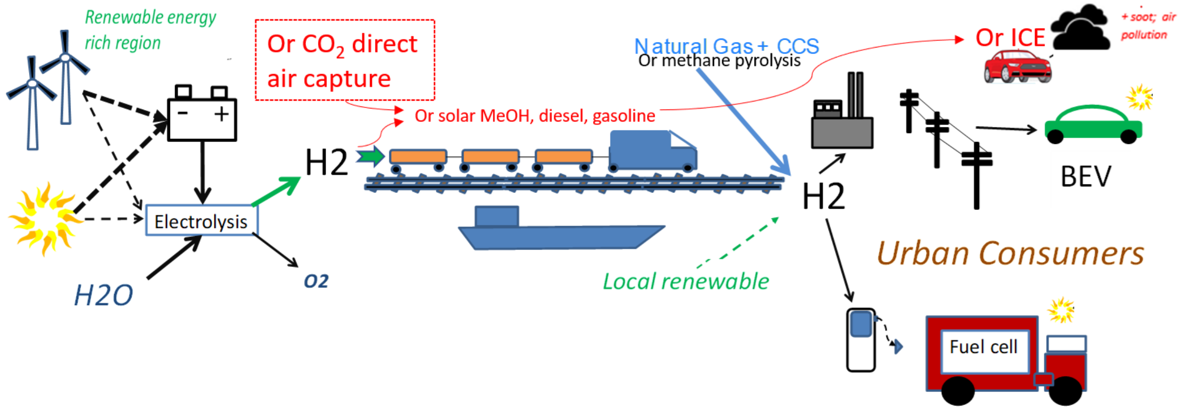
Pandemic panorama: Skies were clear above San Francisco, on March 25, about a week after California’s stay-at-home order took effect. PHOTO: DAVID PAUL MORRIS/BLOOMBERG NEWS

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’

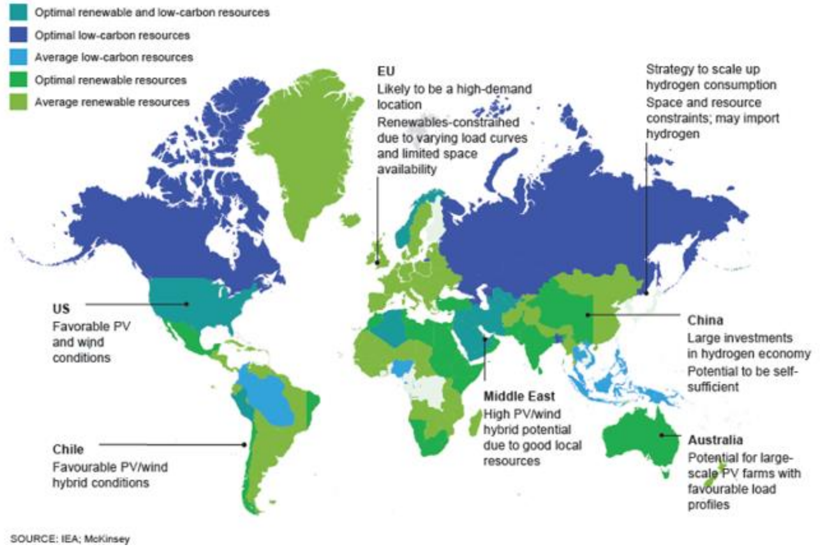
Hydrogen as Energy Vector



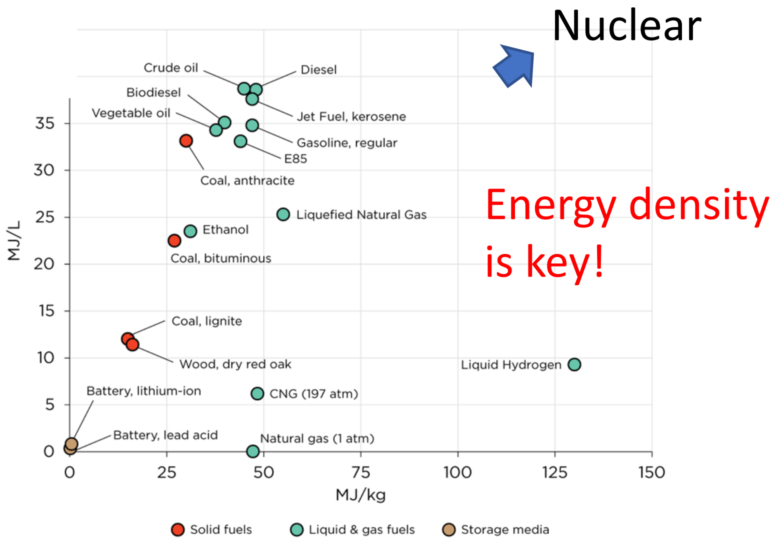
Shell map



Best source of low carbon hydrogen:



Hydrogen Council: Path to Hydrogen Competitiveness (2019)

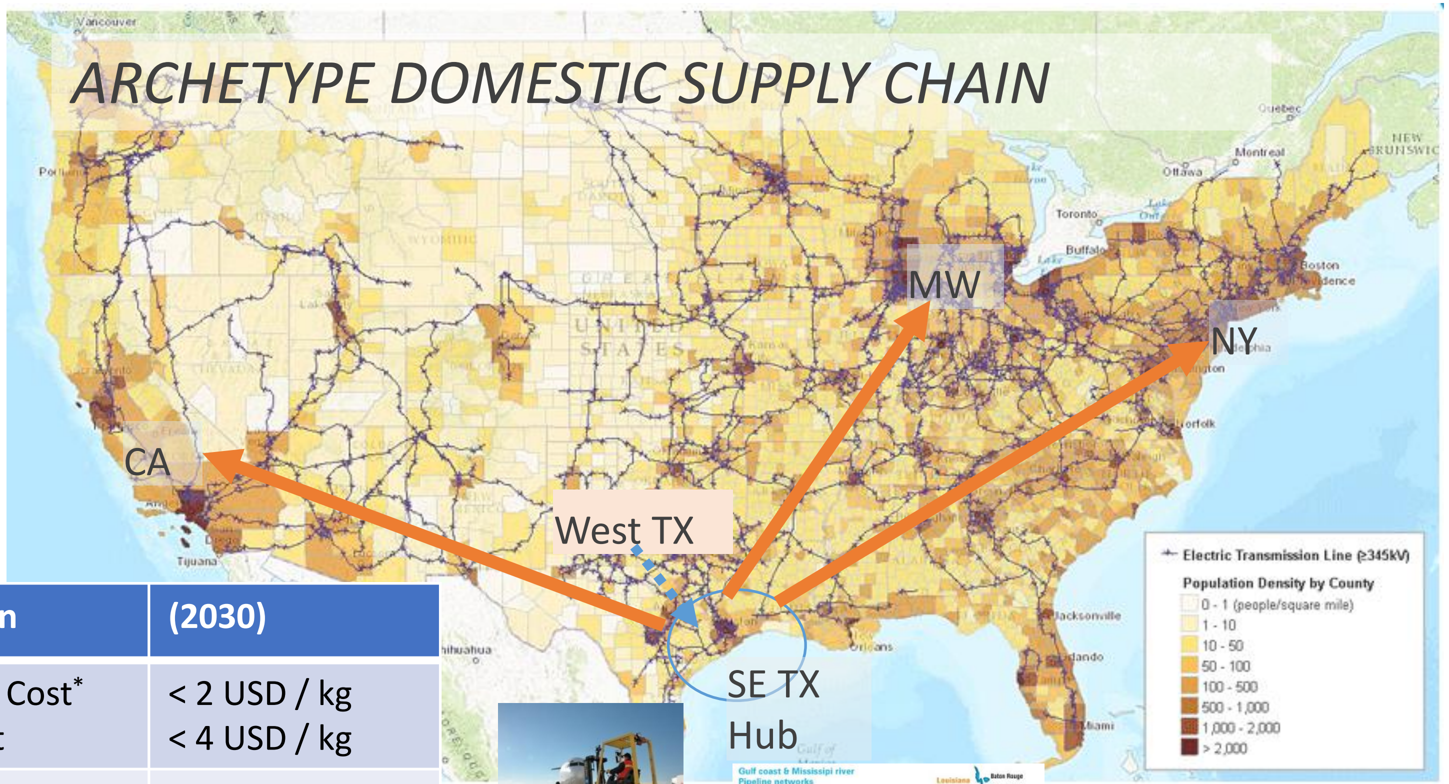


R. Heinberg and D. Fridley, *Our Renewable Future: Laying the path to One Hundred Precent Clean energy.*

- 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

Hydrogen:
US Opportunities

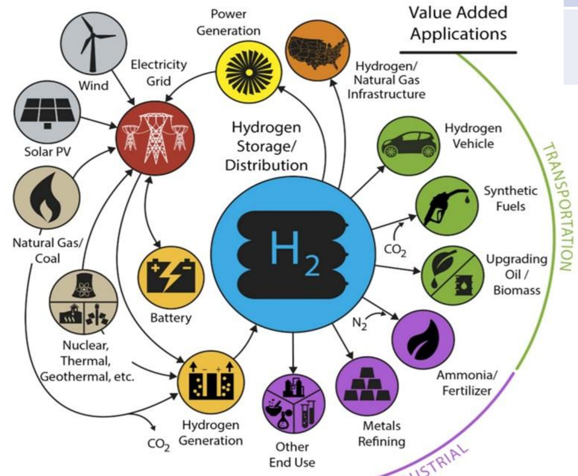
- Green / clean H_2 from West TX renewable + SE TX (Houston GC) waste heat
  - SMR/ Methane pyrolysis / water electrolysis
- H_2 heavy duty trucking, industry
- Commercial ride-share (Uber fleet)?
- City lift trucks / buses?
- H_2 Rail transit to US States with clean energy incentives; H_2 + NH_3 pipelines
  - LH_2 or NH_3
- Leveraged demo hub



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

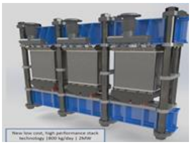
* Distributed small/medium scale

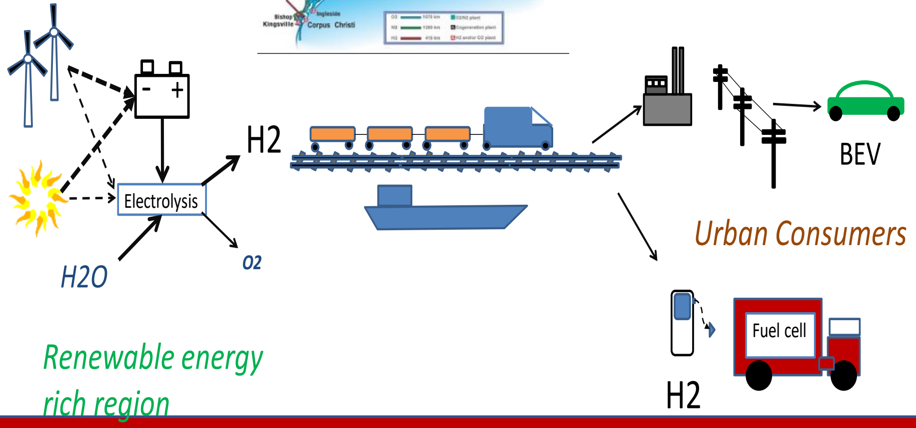
H_2 at Scale Energy System



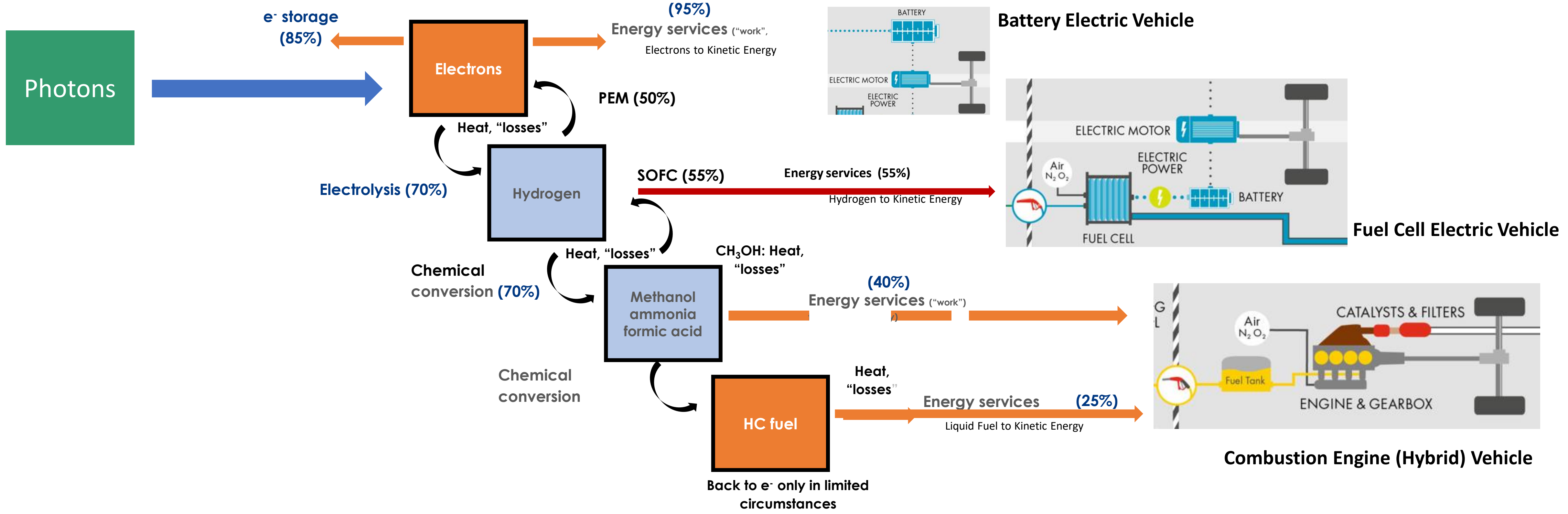
*Illustrative example, not comprehensive
Source: NREL

Fuel Cell Electric Vehicle Prototype 2



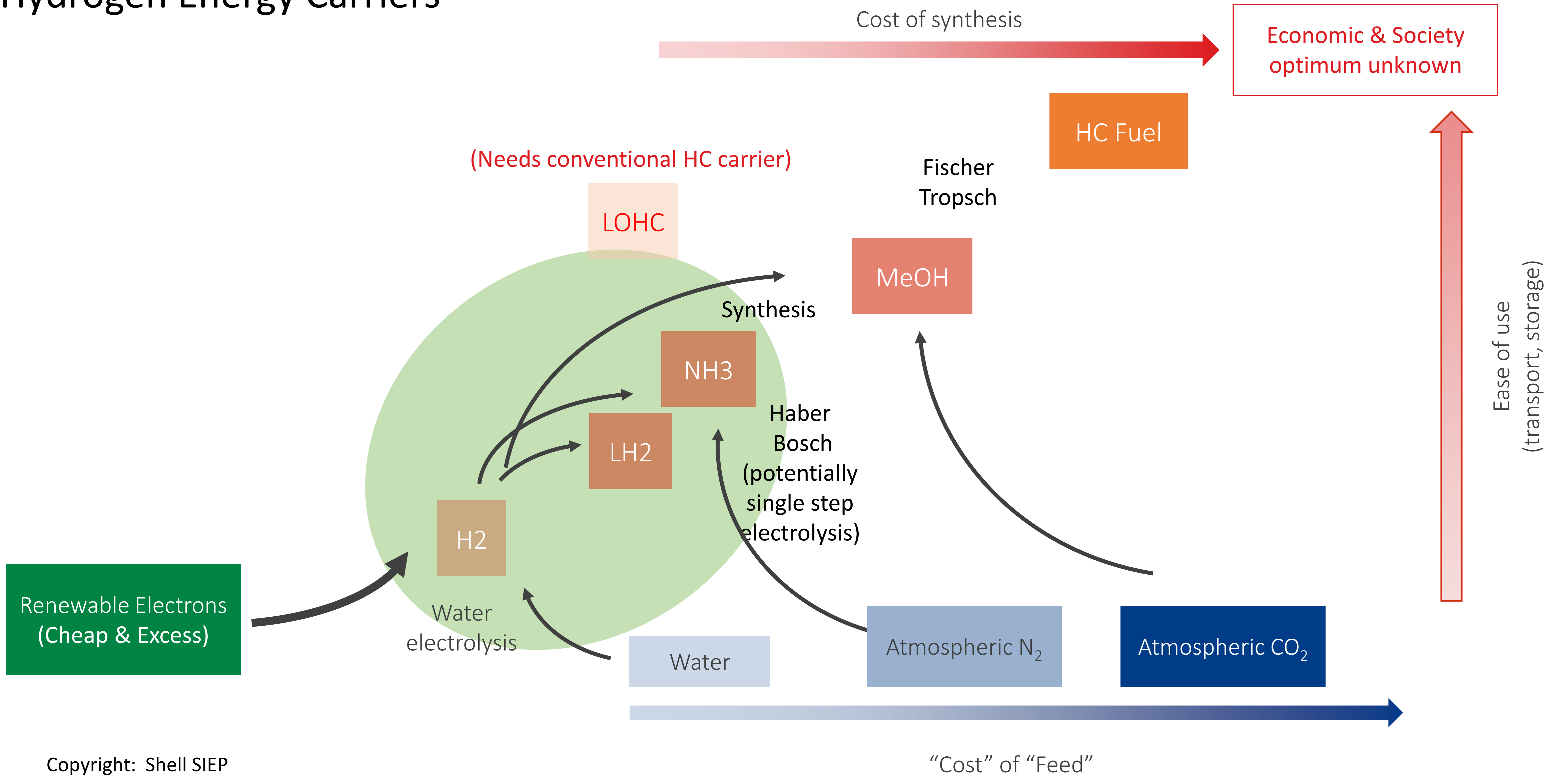


Competitive Outlets for Electrons: Use or Store

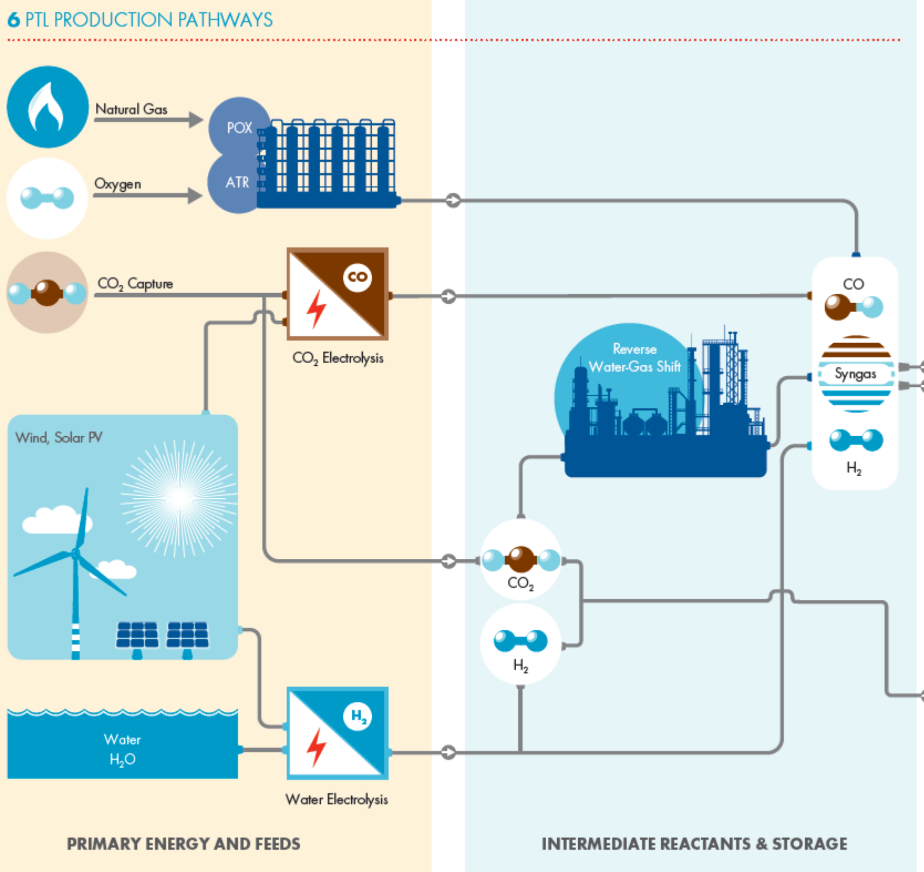


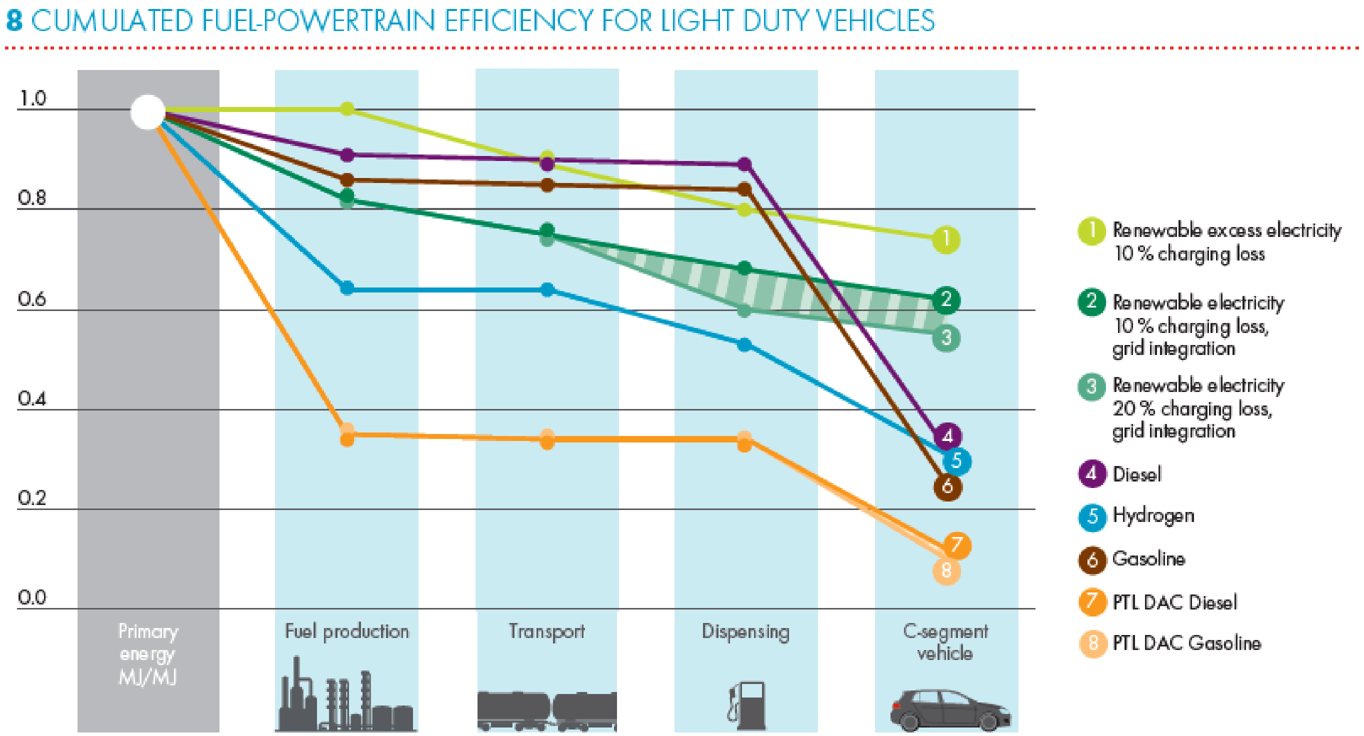
Molecular energy carriers have poorer cycle efficiency than electrochemical energy storage (Battery). The value of transport as Dense Energy Carrier plus Storage must be considered in evaluating options!

LH_2 & Ammonia First Choice Hydrogen Energy Carriers



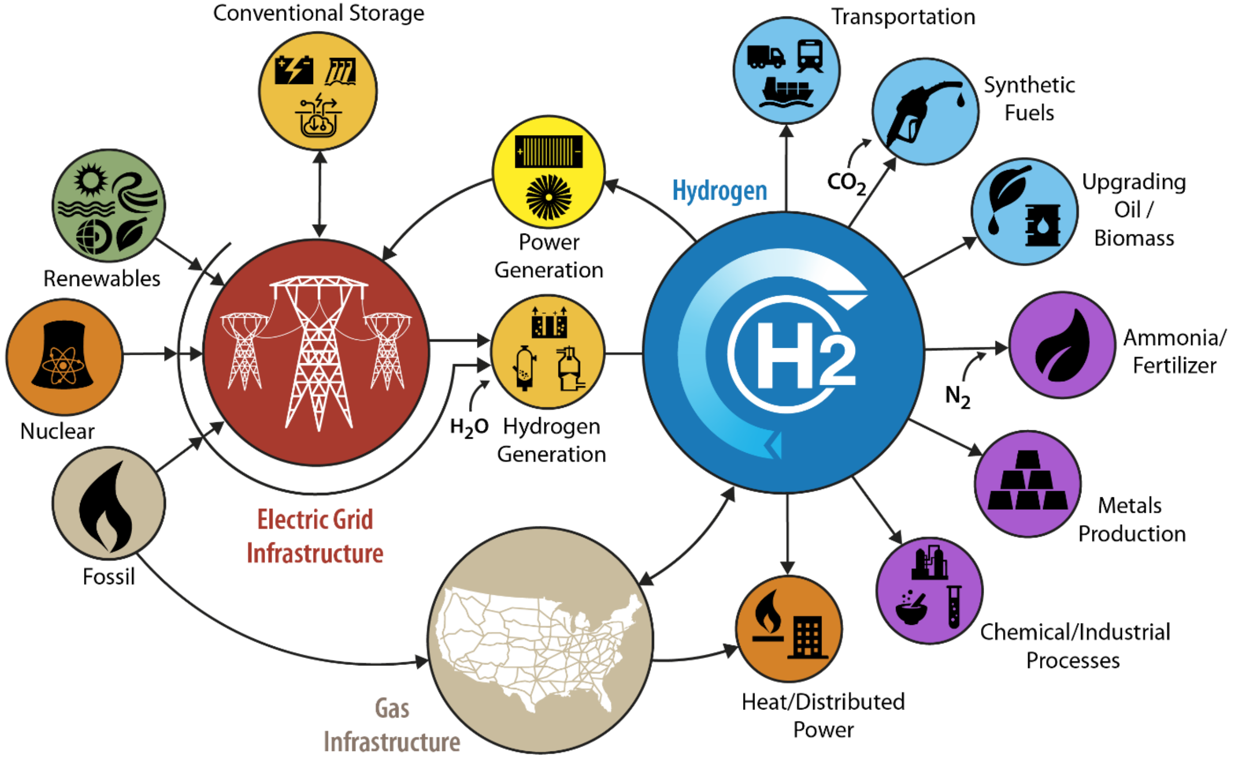
Hydrogen vs Power to Liquids / Synthetic Natural Gas





• W. Warnecke,et al., *The Route to Sustainable Fuels for Zero Emissions Mobility,* 39th International Vienna Motor Symposium, 2018.

H2@ Scale



Rustagi and Satyapal (2018), in

Ruth, Mark, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy. 2020. *The Technical and Economic Potential of the H2@Scale Concept within the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77610. https://www.nrel.gov/docs/fy21osti/77610.pdf.

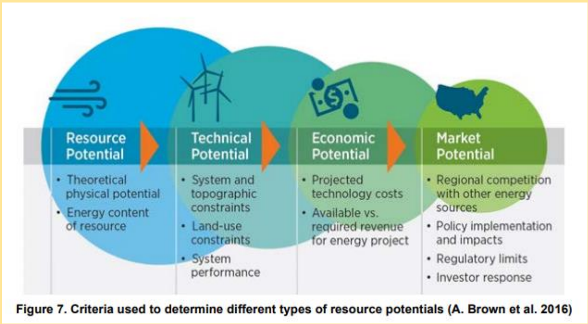
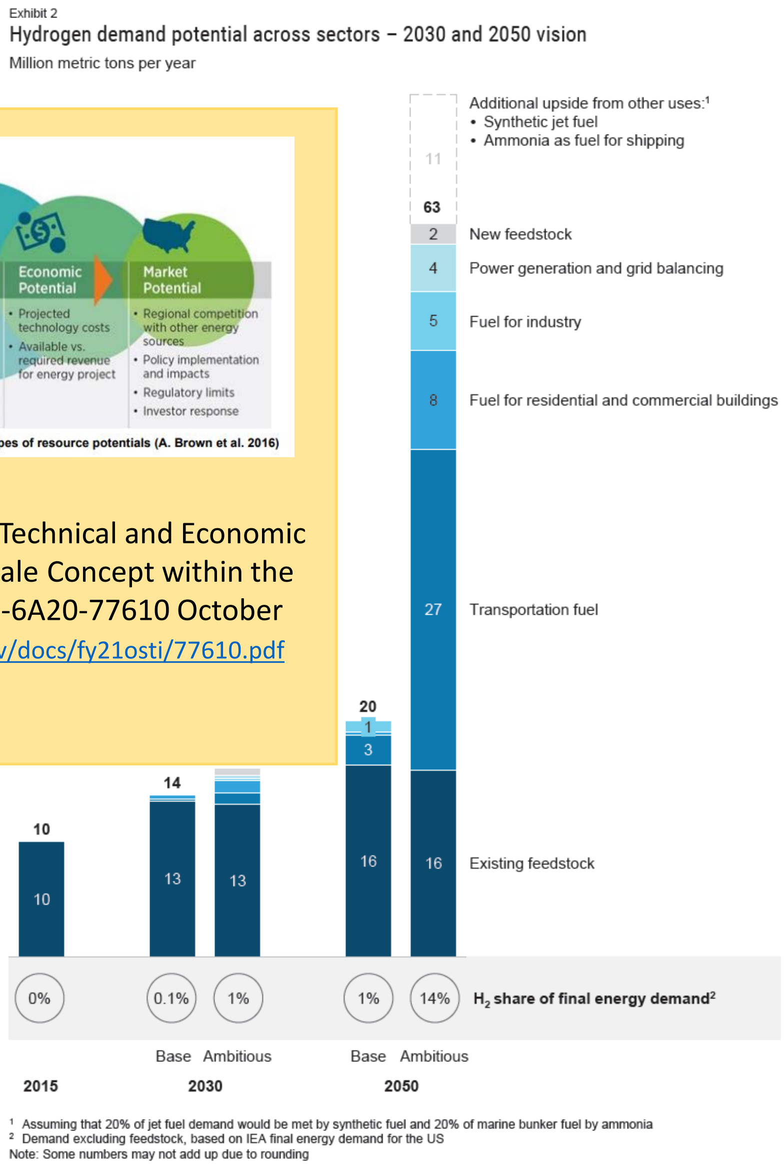


Figure 7. Criteria used to determine different types of resource potentials (A. Brown et al. 2016)

Mark F. Ruth et al, The Technical and Economic Potential of the H2@Scale Concept within the United States, NREL/TP-6A20-77610 October 2020 https://www.nrel.gov/docs/fy21osti/77610.pdf

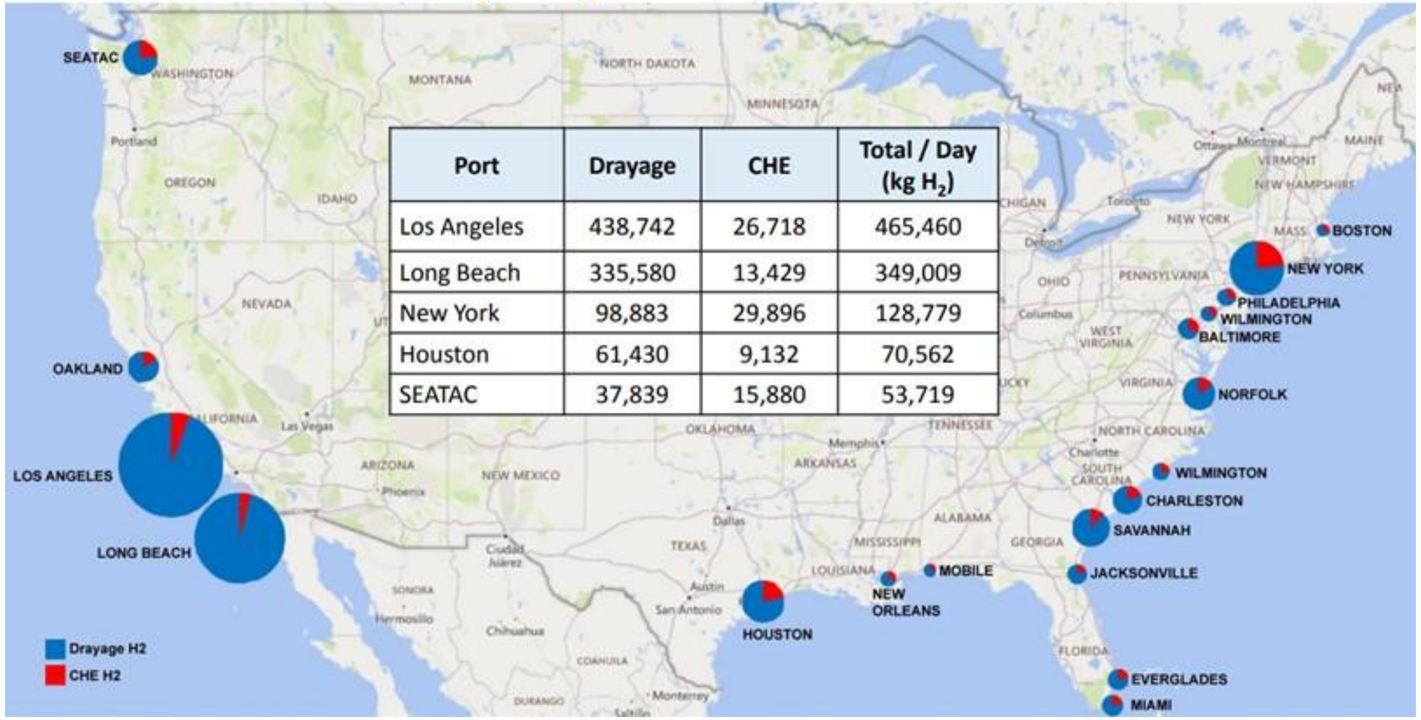


US Hydrogen Roadmap (FCHEA, 2020): http://www.fchea.org/us-hydrogen-study

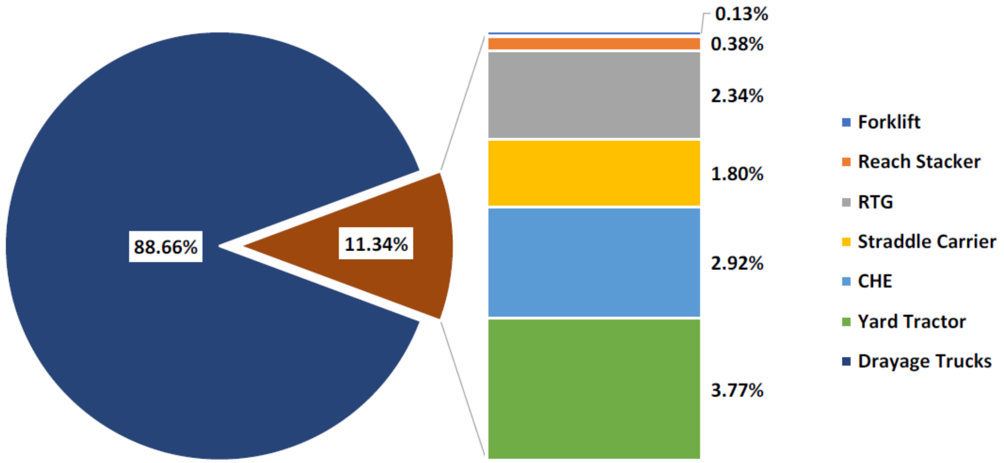
H2@Port

- Clean air, low CO_2, rapid refuel: leverage warehouse forklift roll out.

Potential Hydrogen Demand at U.S. Ports



Port	Drayage	CHE	Total / Day (kg H_2)
Los Angeles	438,742	26,718	465,460
Long Beach	335,580	13,429	349,009
New York	98,883	29,896	128,779
Houston	61,430	9,132	70,562
SEATAC	37,839	15,880	53,719



Total Potential H_2 Demand = 1,385 tonnes per day (19 U.S. Ports)

Port Terminal Equipment kg/day H_2

RTG Crane
45 kg/day

Forklift
5 kg/day

Straddle Carrier
46 kg/day

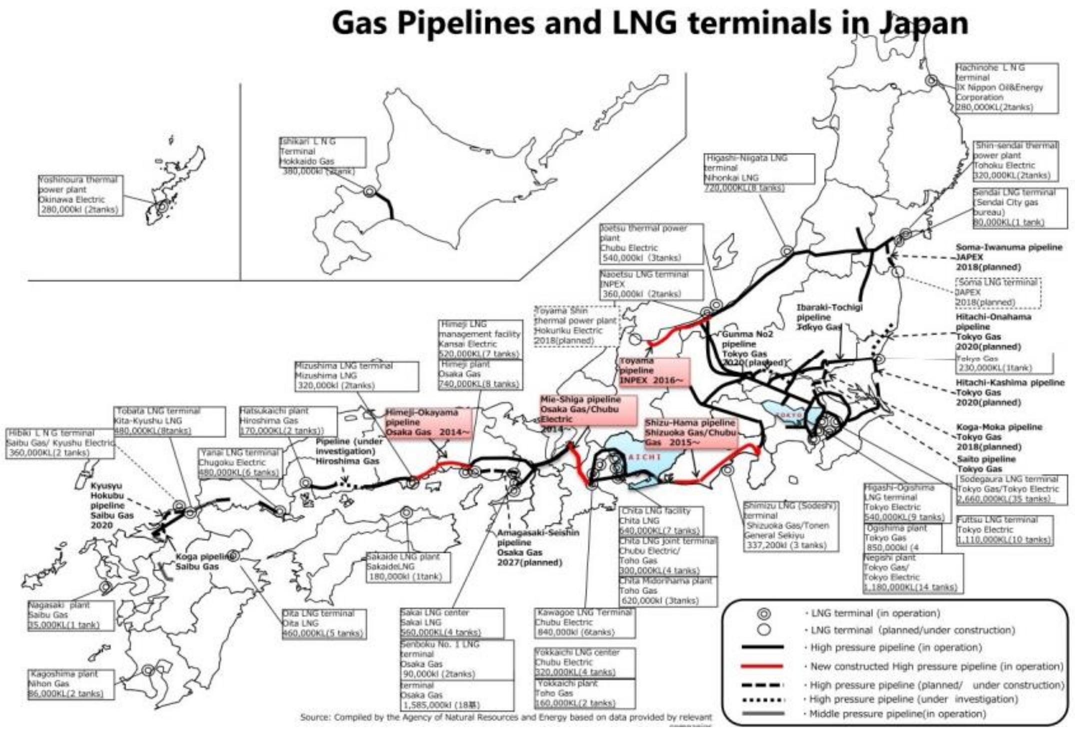
Container Handler
56[L] 25[E] kg/day

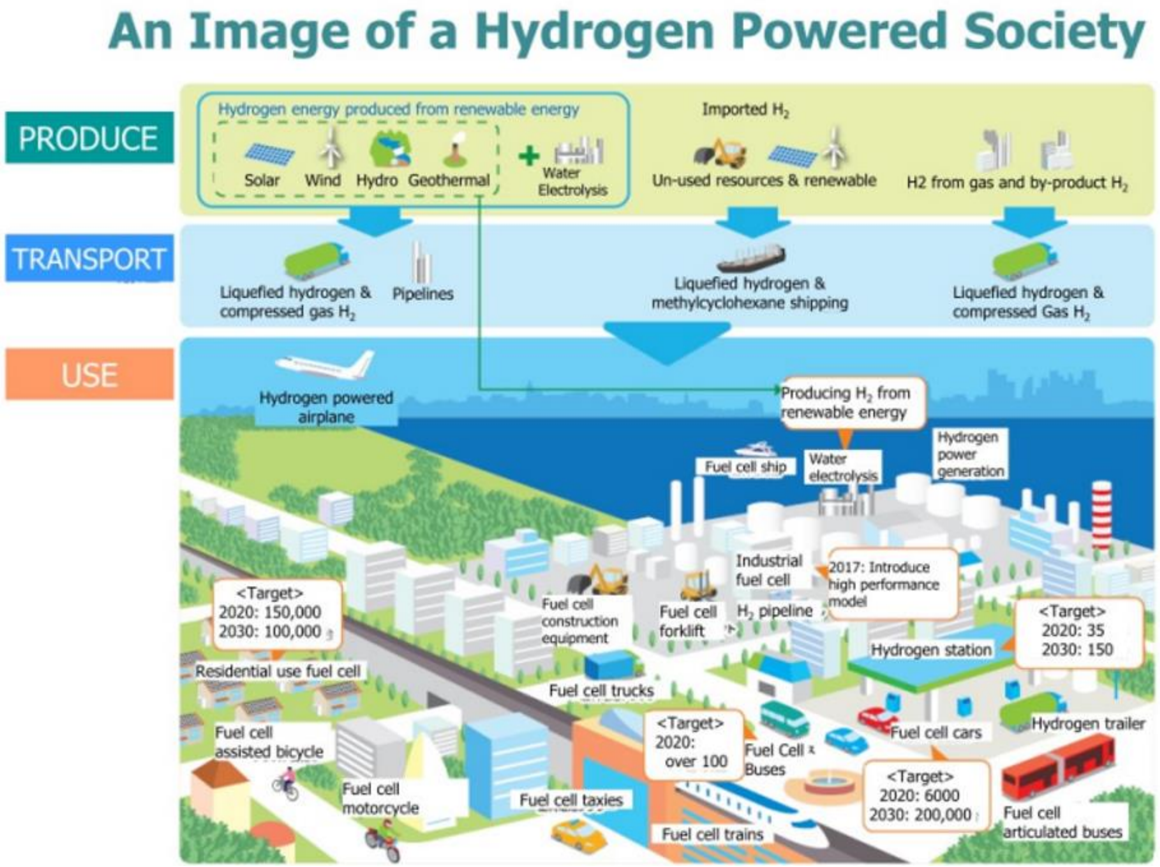
Reach Stacker
33 kg/day

Yard Tractor
21 kg/day

Lindsay M. Steele (PNNL), Charlie Myers (ORNL), PNNL-SA-147032 H2@Ports International Workshop San Francisco, September 2019. https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-viii3-steele.pdf

Japan: Ports

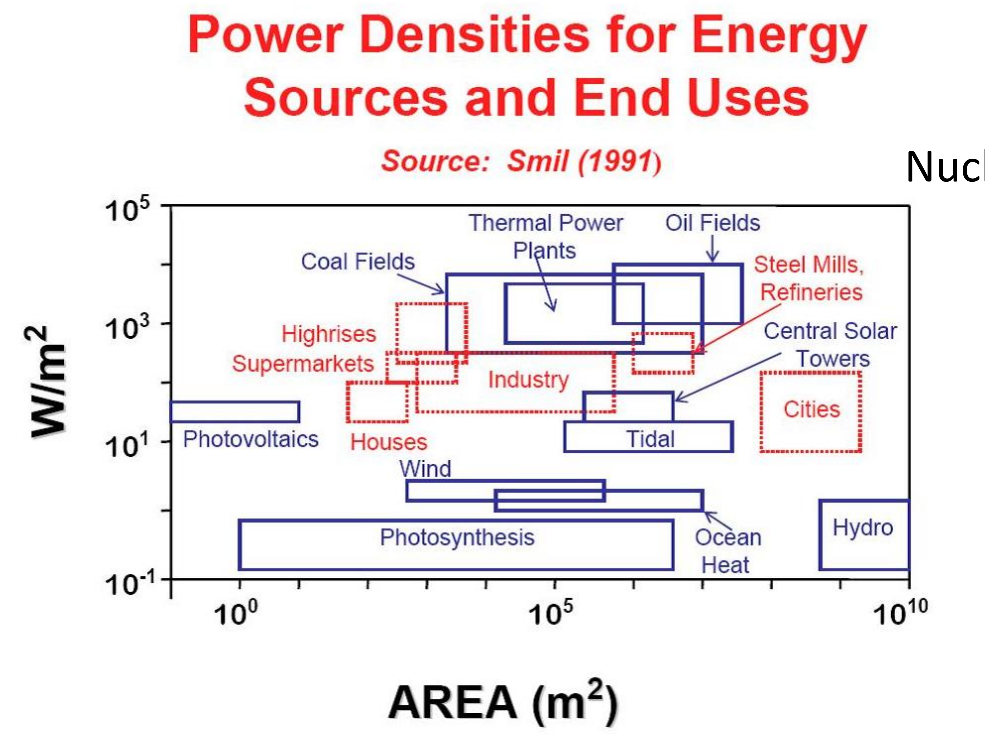




Source: METI

- Sources: Meti, Tokyo Metropolitan Gov

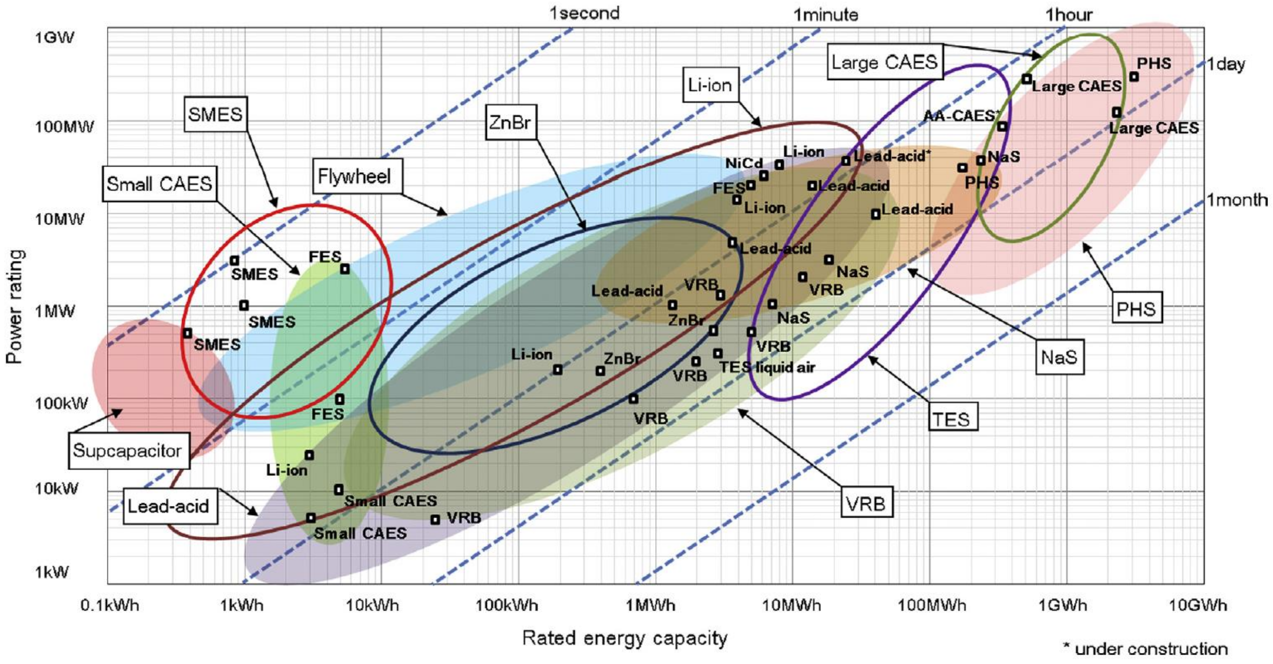
Power density and storage



Nuclear

Vaclav Smil, **Power Density: A Key to Understanding Energy Sources and Uses, MIT Press 2015;** General Energetics Energy in the Biosphere and Civilization. John Wiley, New York,(1991)

Grid storage



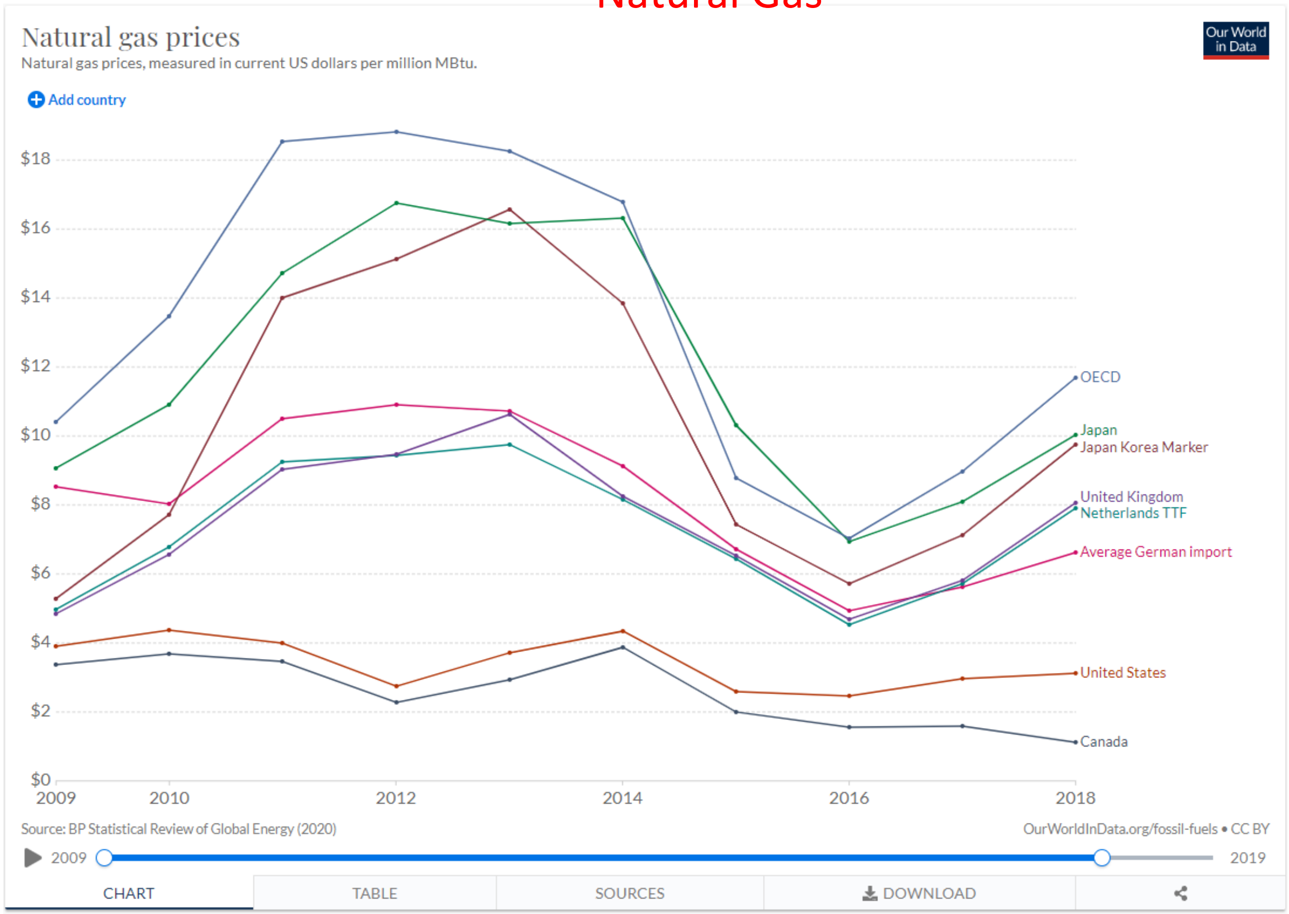
X. Luo et al. / Applied Energy 137 (2015) 511–536

Solar PPA (US): \$0.03/kwHr (2020)
\$1/kg-H_2 or \$1/gallon equivalent energy as electrons.

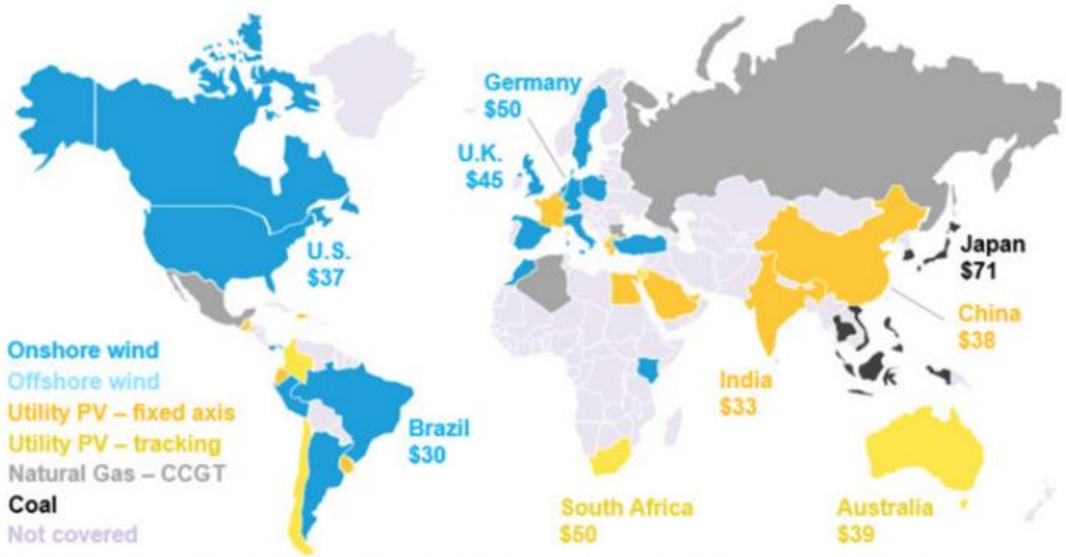
- Cannot produce H_2 this cheaply.
- Hydrogen must provide “service” in energy transport or storage to be valuable.

Renewable PPA vs. Natural Gas

Natural Gas



LCOE



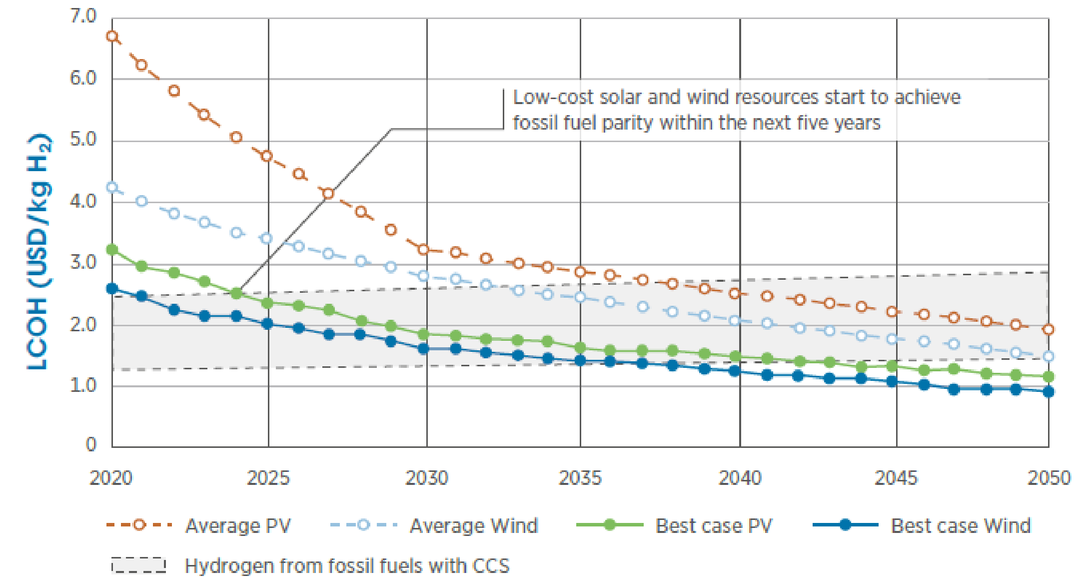
Source: BloombergNEF. Note: LCOE calculations exclude subsidies or tax-credits. Graph shows benchmark LCOE for each country in $ per megawatt-hour. CCGT: Combined-cycle gas turbine.

BNEF 2020b. "Scale-up of Solar and Wind Puts Existing Coal, Gas at Risk." BloombergNEF (blog). April 28, 2020. https:// about.bnef.com/blog/scale-up-of-solar-and-wind-puts existing-coal-gas-at-risk/.

https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/

BP statistical review of global energy

Hydrogen costs: Blue vs Green & Infrastructure vs. BEV



Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

IRENA (2019), *Hydrogen: A renewable energy perspective*, International Renewable Energy Agency, Abu Dhabi

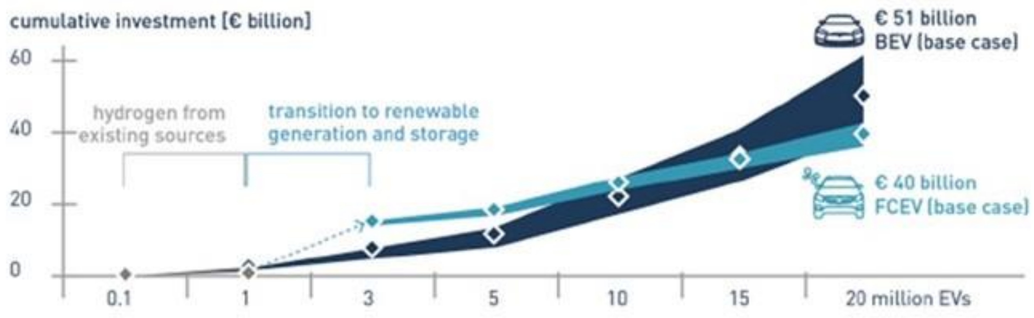
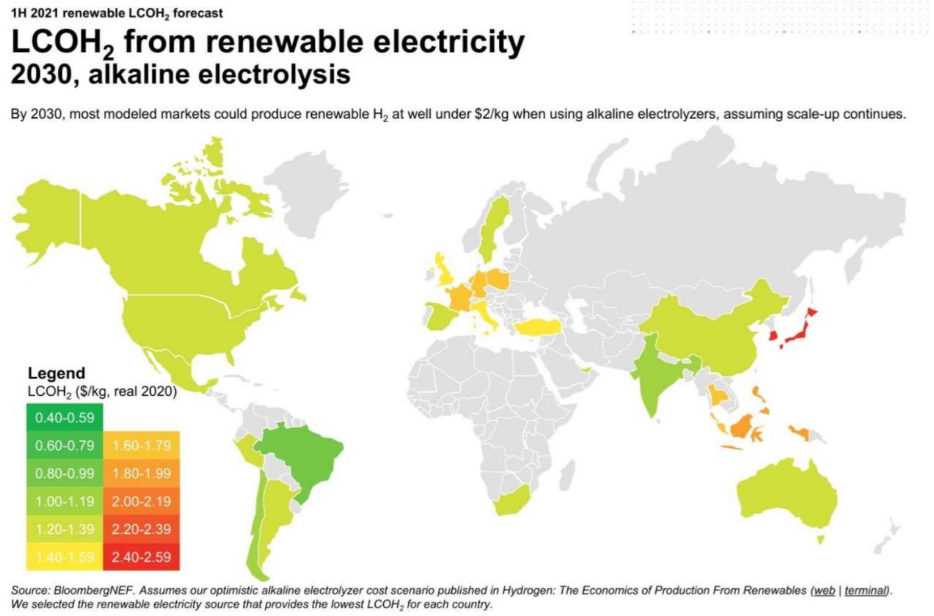


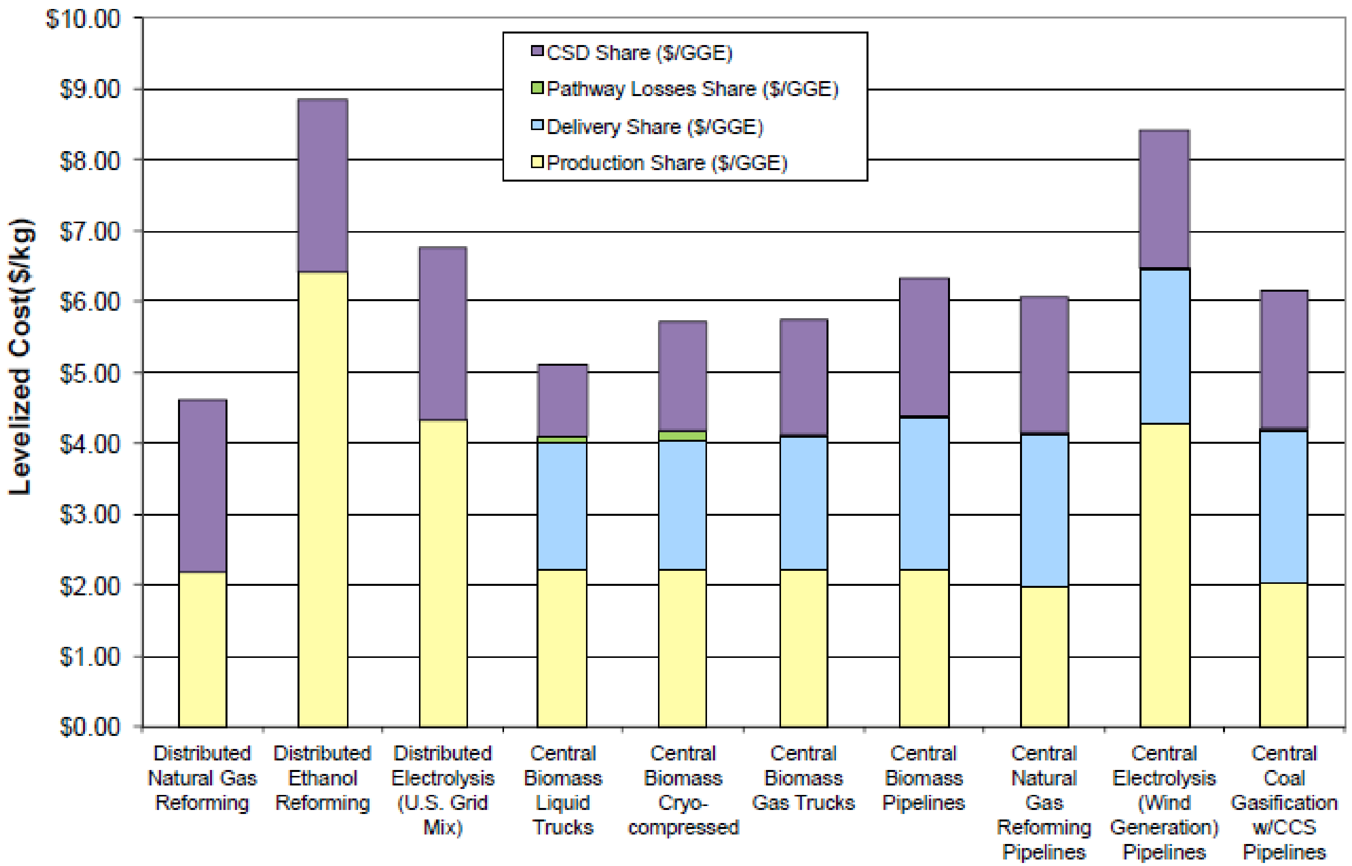
Figure 0-2: **Comparison of the cumulative investment of supply infrastructures.**

H2 Mobility Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles, Martin Robinius, Jochen Linßen, Thomas Grube, Markus Reuß, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz and Detlef Stolten, Energie & Umwelt / Energy & Environment Band / Volume 408 ISBN 978-3-95806-295-5: **Forschungszentrum Jülich Research Centre and the H2 Mobility**



https://insideevs.com/photo/5735195/green-hydrogen-will-be-cheaper-than-blue-hydrogen-by-2050-says-bnef/

Hydrogen Dispensed Cost



- **Hydrogen Pathways Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios** T. Ramsden, M. Ruth, V. Diakov *National Renewable Energy Laboratory* M. Laffen, T.A. Timbario *Alliance Technical Services, Inc.* **Technical Report** NREL/TP-6A10-60528, March 2013

Viability of Hydrogen Economy?

Price paid for energy services

http://www.fchea.org/us-hydrogen-study (2020)

Total cost of ownership SUV

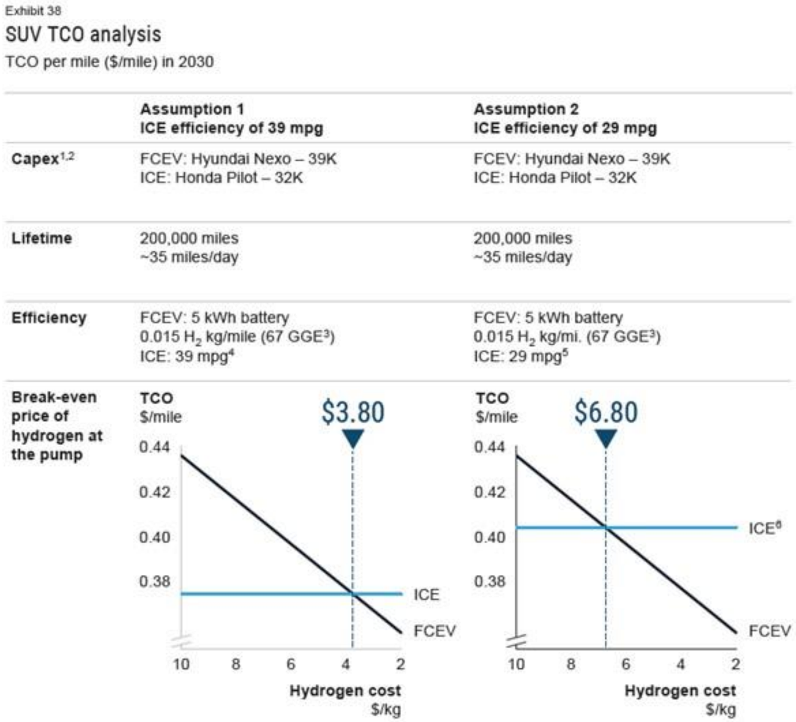


Exhibit 38
SUV TCO analysis
TCO per mile ($/mile) in 2030

	Assumption 1 ICE efficiency of 39 mpg	Assumption 2 ICE efficiency of 29 mpg
Capex[1,2]	FCEV: Hyundai Nexo – 39K ICE: Honda Pilot – 32K	FCEV: Hyundai Nexo – 39K ICE: Honda Pilot – 32K
Lifetime	200,000 miles ~35 miles/day	200,000 miles ~35 miles/day
Efficiency	FCEV: 5 kWh battery 0.015 H_2 kg/mile (67 GGE[3]) ICE: 39 mpg[4]	FCEV: 5 kWh battery 0.015 H_2 kg/mi. (67 GGE[3]) ICE: 29 mpg[5]
Break-even price of hydrogen at the pump	TCO $/mile; $3.80	TCO $/mile; $6.80

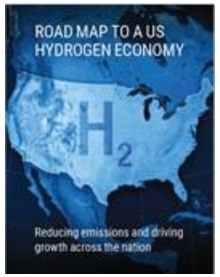
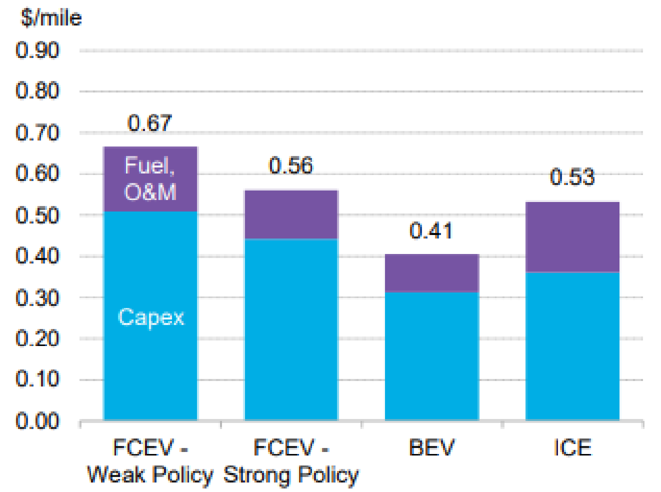


Figure 9: Total cost of ownership of SUVs in the U.S., 2030



Source: BloombergNEF. Note: FCEV – fuel cell electric vehicle, BEV – battery electric vehicle, ICE – internal combustion engine.

https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

IEA (2019). https://www.iea.org/reports/the-future-of-hydrogen

Figure 55. Parameters contrast of different drayage trucks

Kenworth T680 [206]

- Prototype launch: 2018.02
- Purpose: proof of concept [207]
- Drivetrain capacity: 420 kW and 1,850 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 [201]
- Driving distance: ~209km

Toyota Beta

- Prototype launch: 2018.07 (for deployment in Q4 2019)
- 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 [201] each rated at 114 kW [202]
- Fuel cell tank storage capacity: 60kg [200]
- Battery capacity: 12kWh
- Gross combined weight capacity: ~36.3 metric tons [201]
- Driving distance: ~480km [201]

BEV

- Drivetrain capacity: 340-740 horsepower (250-550 kW) and 2,000-4,000Nm of torque
- Battery capacity: 200-600kWh [203]
- Gross combined weight capacity: 20-47 metric tons
- Driving distance: 150-300km [203]

ICEV

- Drivetrain capacity: 400 horsepower (around 300 kW) and 1,200-1,800 pound-fee (1,600-2,500Nm) of torque [204]
- Gross combined weight capacity: ~40 metric tons [204]
- Driving distance: >1,000km [205]

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

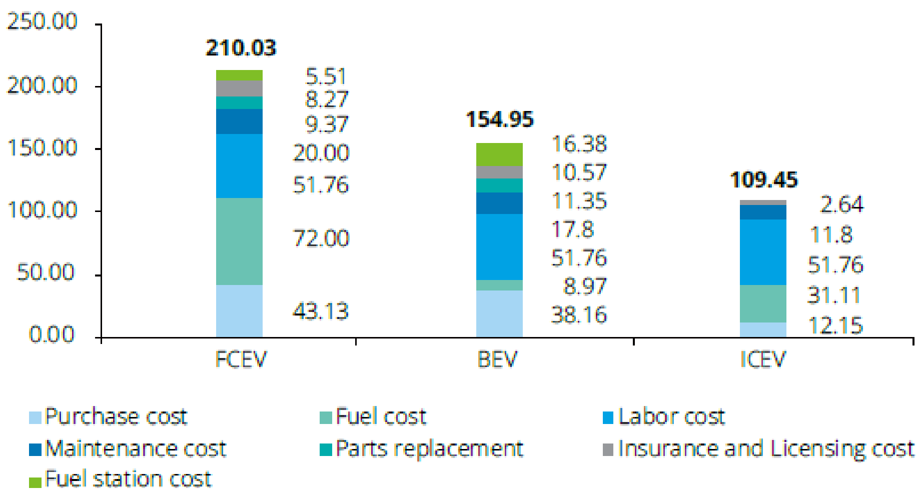
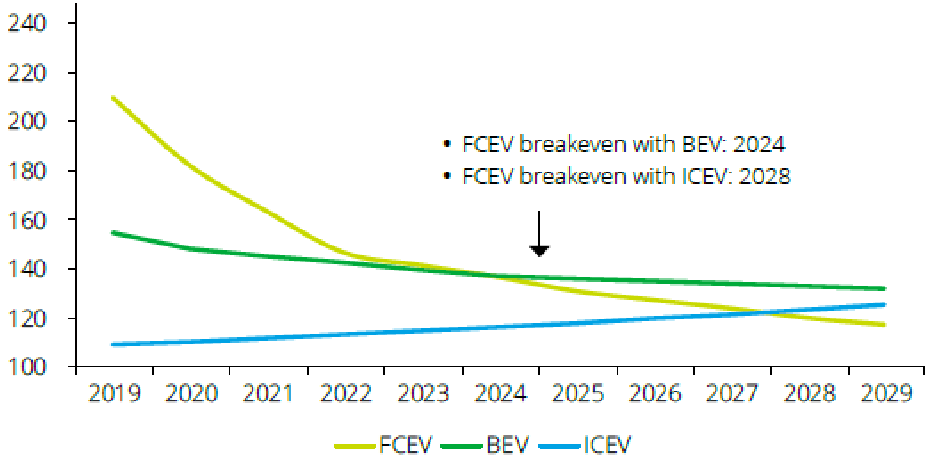
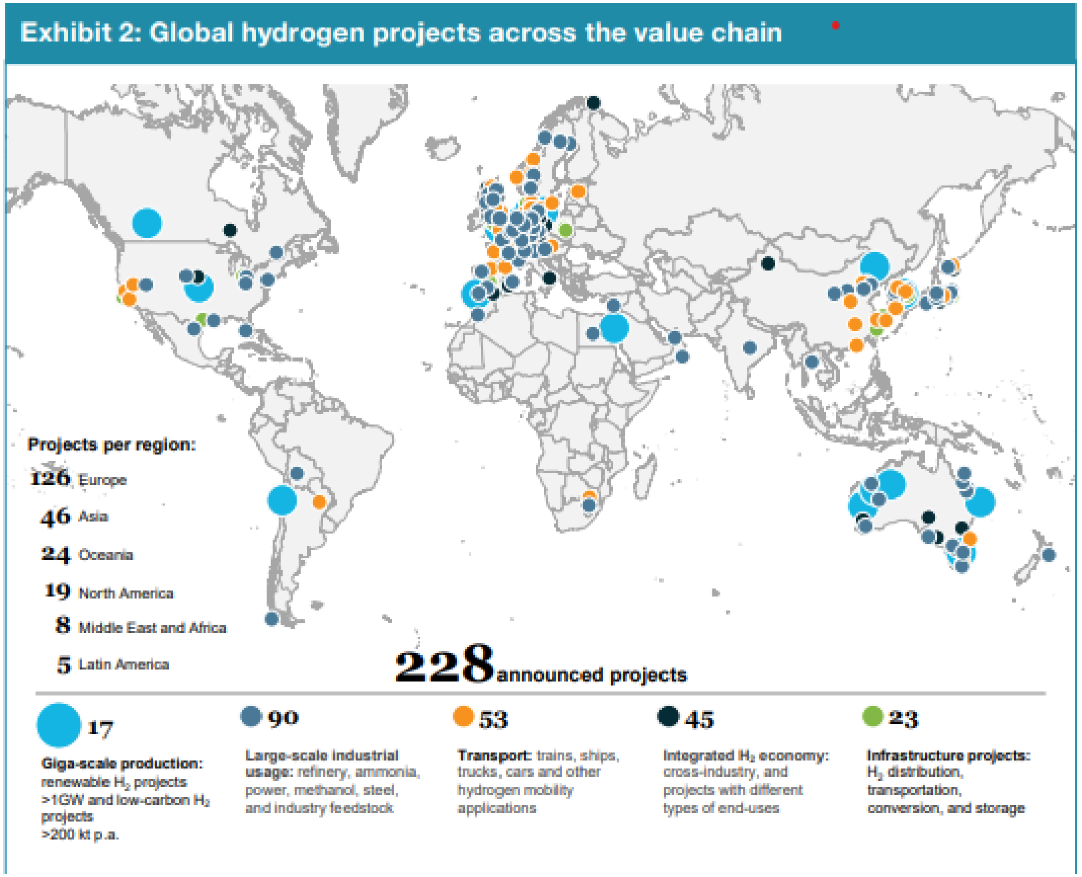


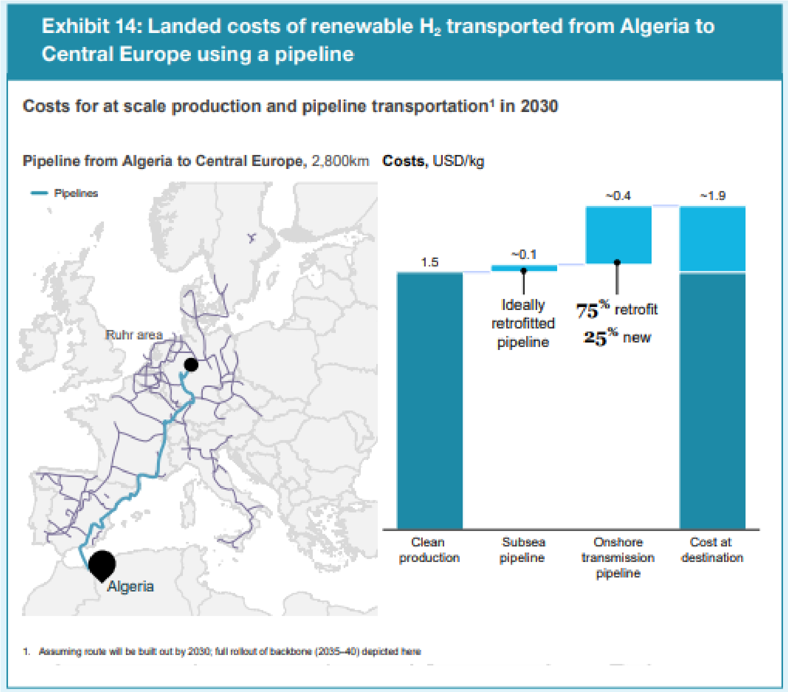
Figure 60. Total cost of ownership/ USD per 100km

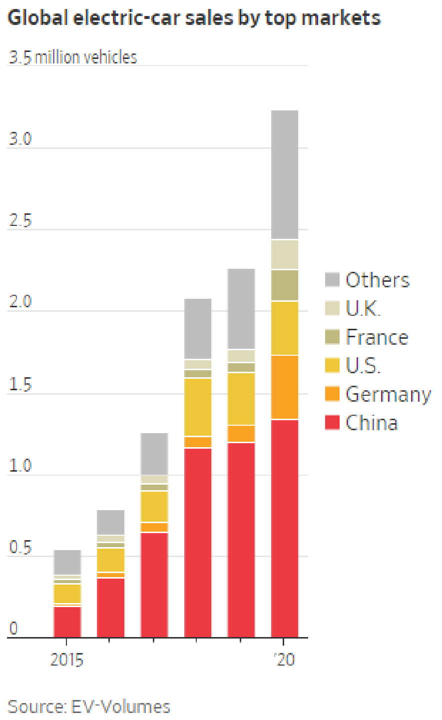


www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf

Where is hydrogen economy emerging?





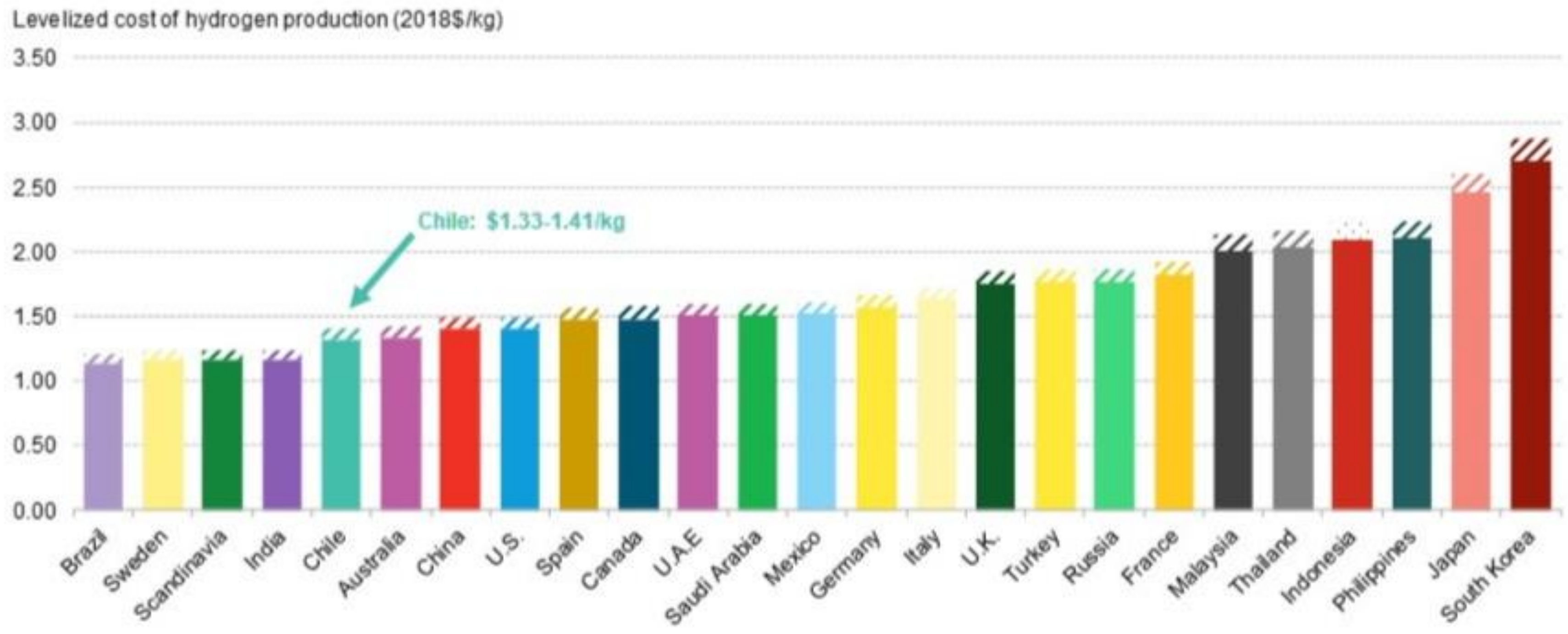


Hydrogen Council / McKinsey % Co. (Feb 2021) Hydrogen Insights on hydrogen investment, market development and cost competitiveness https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

WSJ 2/26/2021: BEV sales driven by subsidy https://www.wsj.com/articles/how-europe-became-the-worlds-biggest-electric-car-marketand-why-it-might-not-last-11614508200?mod=hp_lead_pos8

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

Cost of hydrogen, global



https://www.bloomberg.com/news/articles/2021-03-10/investors-lining-up-for-hydrogen-subsidies-in-top-copper-miner?sref=w5YUJnwX

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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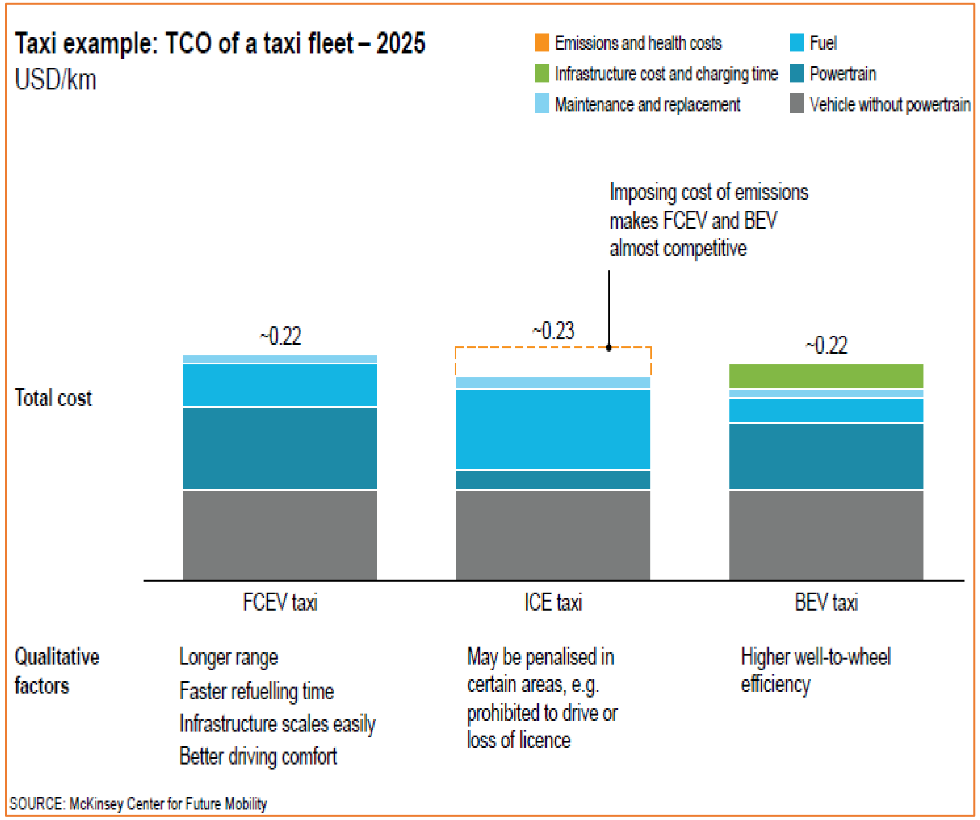
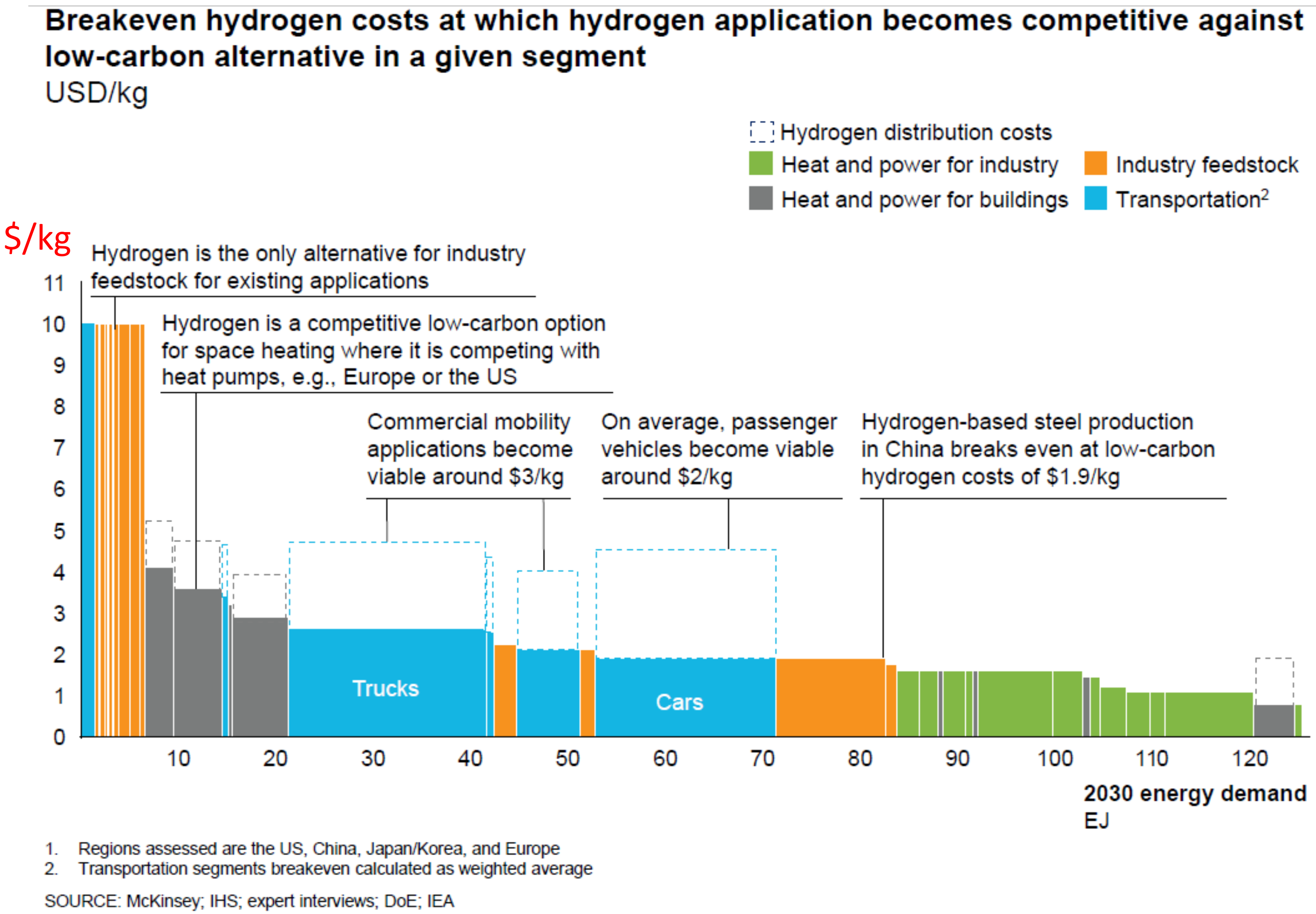
Hydrogen break-even cost





•IEA, *The Future of Hydrogen* (2019)