The Gulf Coast Hydrogen Ecosystem: Opportunities and Solutions: Technology Sessions: Hydrogen Production, Use, Distribution

Dr. Joe Powell

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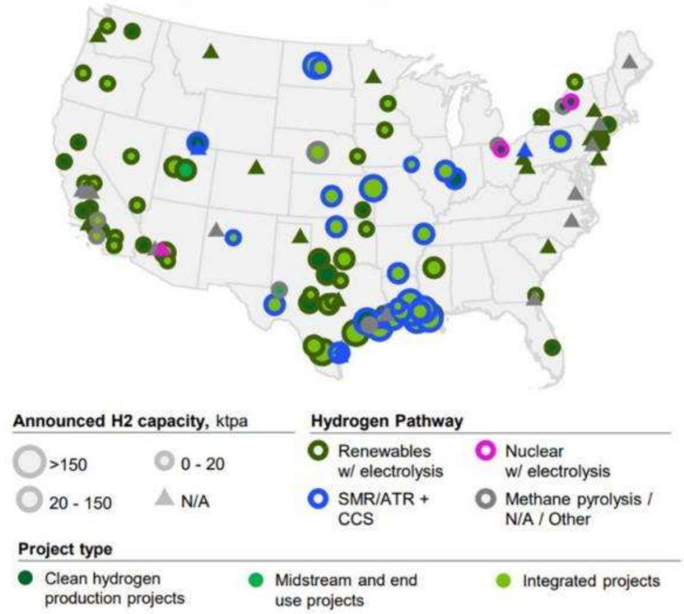
- Aspire Endowed Chair, William A. Brookshire Department of Chemical and Biomolecular Engineering
- Retired Shell Chief Scientist – Chemical Engineering
- National Academy of Engineering; Fellow AIChE
- https://www.uh.edu/uh-energy/

17 April 2024

Current publicly announced clean hydrogen production projects*



*as of EOY 2022, DOE Commercial Liftoff Report

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

THE HYDROGEN ECONOMY

UNIVERSITY OF HOUSTON MICRO-CREDENTIALING PROGRAM

Future Hydrogen Production

Technologies, Opportunity Framing
Fossil production methods; Life Cycle Assessment

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University of Houston Hydrogen Class Lecture
Spring 2024

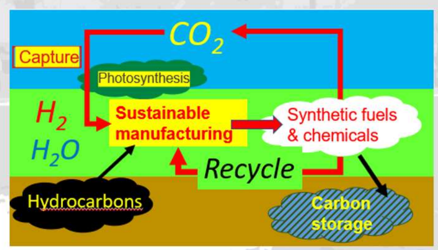
UNIVERSITY of HOUSTON
UH ENERGY

Energy Transition Institute
UH ENERGY
Shell FOUNDING PARTNER

Hydrogen, Circularity, Carbon Management

- Student education and engagement
- Top Tier Fundamental Research
- Thought leadership

Leverage Houston's Global Presence in Energy & Chemicals via Best Practices, Knowledge Management, shared commitment, industry & community engagement



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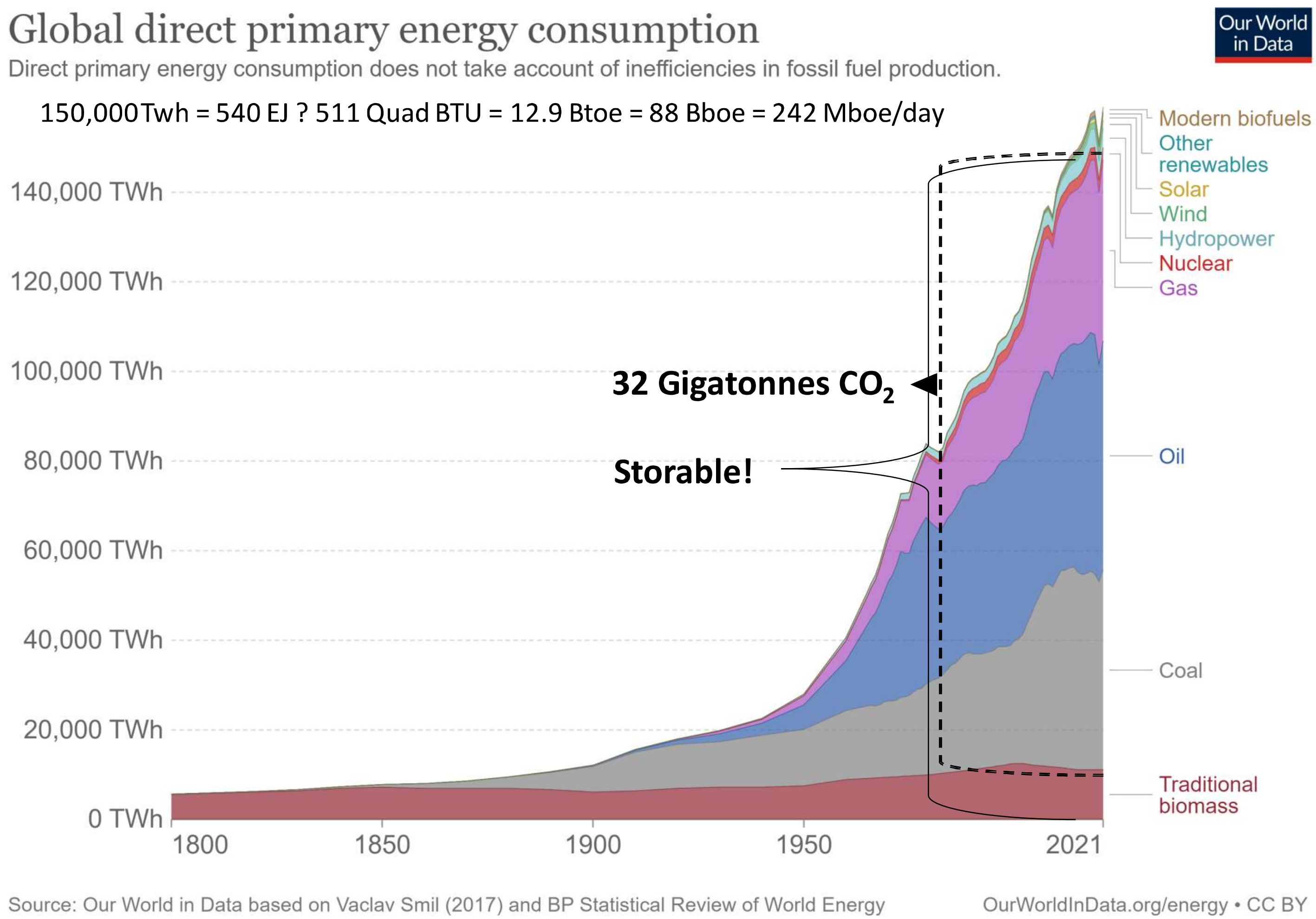
Global Energy Demand

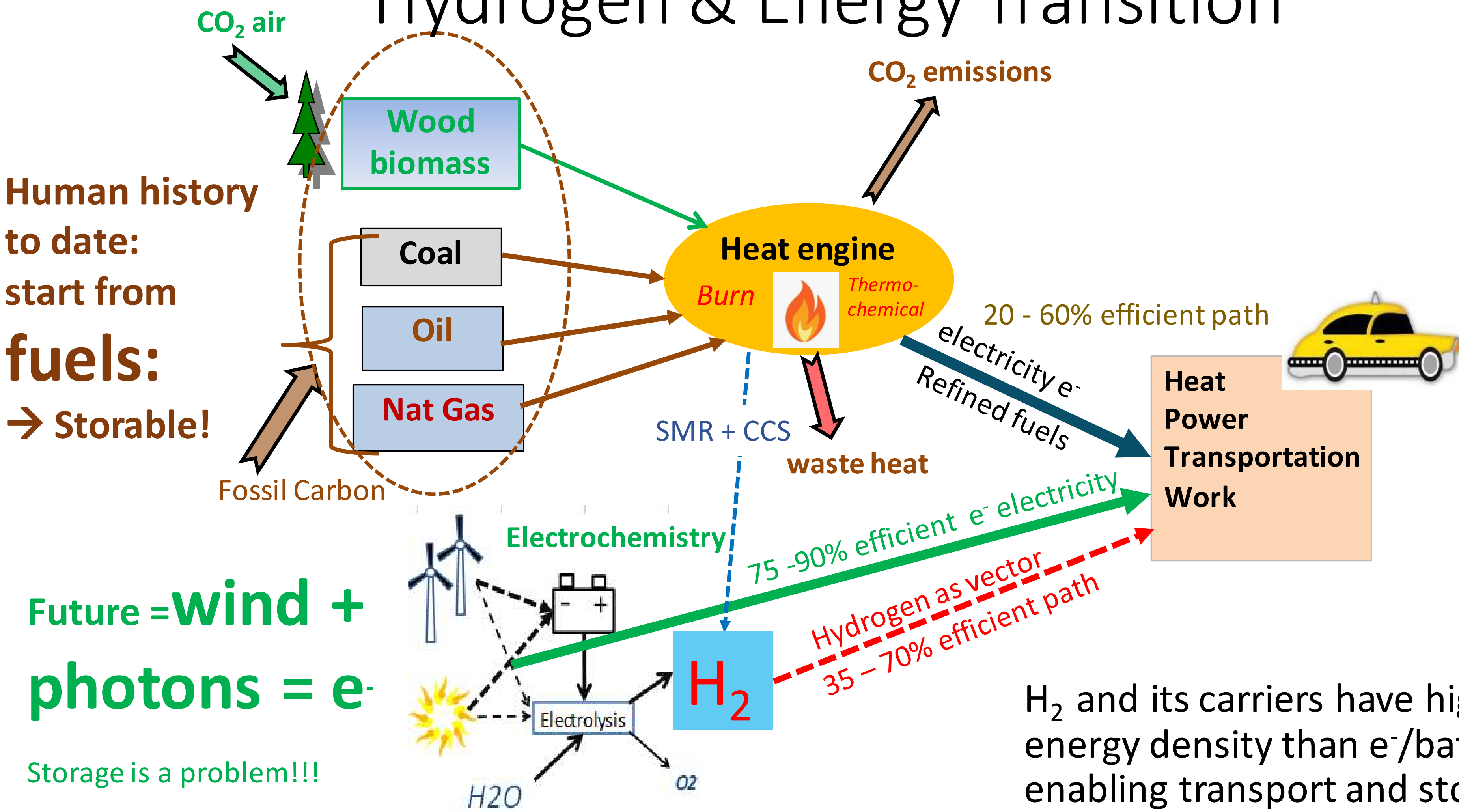
Energy transitions over time

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



Move from storable fuels to cheap instantaneous renewable energy

Hydrogen & Energy Transition



H_2 and its carriers have higher energy density than e^-/batteries, enabling transport and storage

The colors of hydrogen?

Grey	Produced from natural gas using steam methane reforming. Most common form of hydrogen production currently in use. Results in CO_2 emissions.
Brown	Produced from gasification of fossil fuel feedstock, usually coal. Often discussed as a potential future use of coal. Results in CO_2 emissions.
White	Produced as a by-product of an industrial process. CO_2 emissions are dependent on the industrial process.
Yellow	Produced by electrolysis using electricity from solar power. No CO_2 emissions depending on the source of power generation. Can also leverage existing power grid. Can be CO_2 neutral if carbon capture is deployed at sources of fossil-generated power.
Blue	Grey or brown hydrogen with carbon capture. CO_2 emissions are substantially reduced. Modifies existing production methods, thus leveraging legacy, or existing, infrastructures.
Turquoise	Produced by methane pyrolysis with a solid carbon by-product. CO_2 emissions are substantially reduced. Leverages existing natural gas infrastructures. Opens 'carbon-to-value' propositions as solid carbon can be a replacement for carbon black and used as a feedstock in advanced carbon material applications.
Green	Produced by electrolysis using electricity from renewables. No CO_2 emissions.
Pink	Produced by electrolysis using nuclear power. No CO_2 emissions.

National Grid:

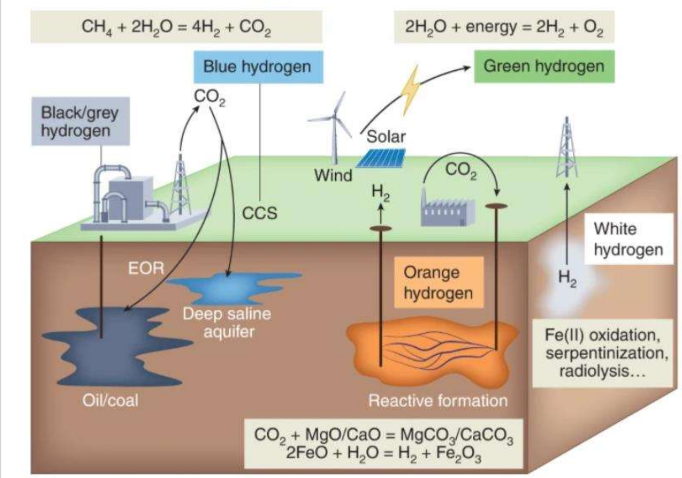
Black = coal

White = naturally occurring

Gold: microbial H2 from depleted oil wells

Orange: induced subsurface H2

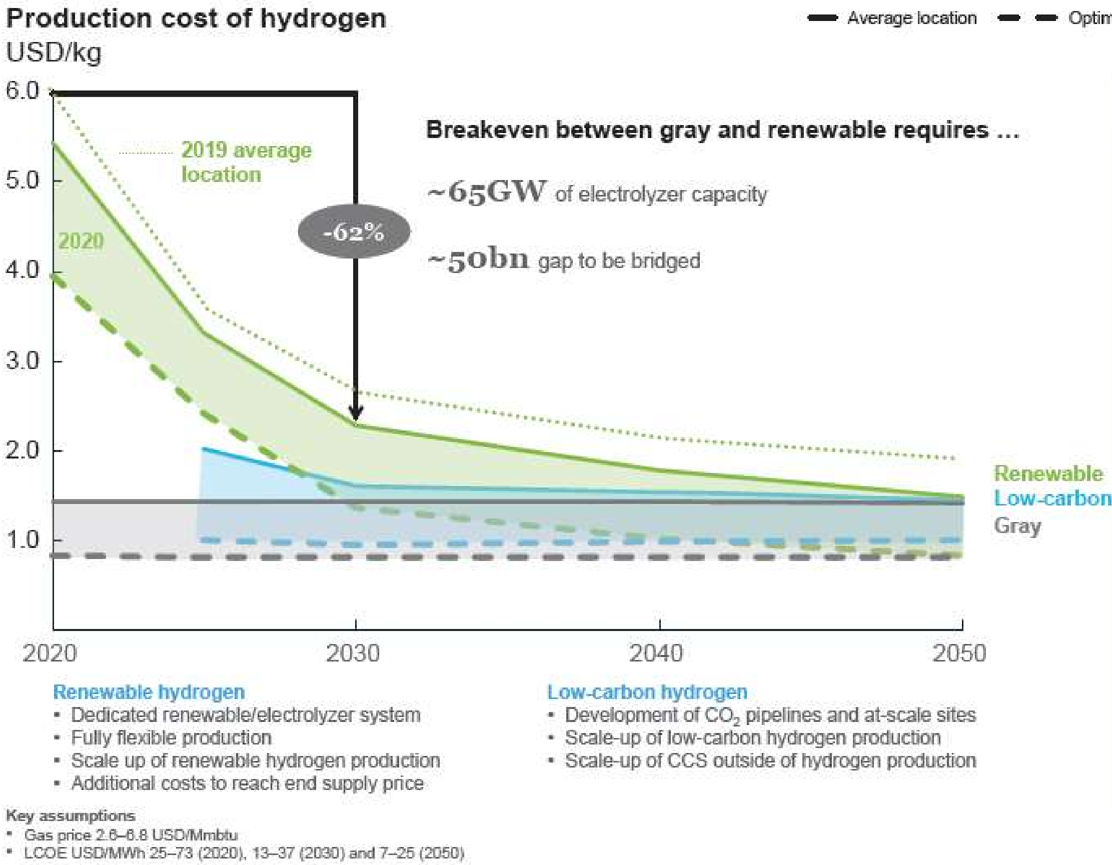
Fig. 1: The different colours of hydrogen.

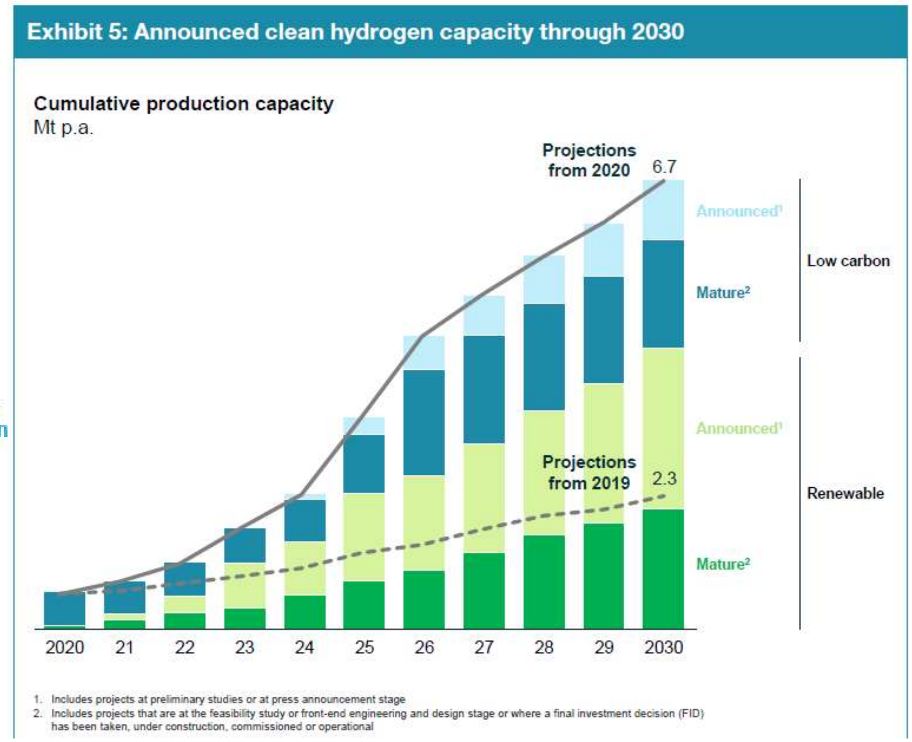


F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet and M. Pichavant, Orange hydrogen is the new green, Nat. Geosci., 2022, 15, 765–769.

The Oxford Institute for Energy studies, May 2021: ISSUE 127' https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum#:~:text=What%20are%20black%20and%20brown; North American Council for Freight Efficiency (2020), 'Hydrogen color spectrum', *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors*, *https://nacfe.org/emerging-technology/electric-trucks-2/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/*.,and%20the%20most%20environmentally%20damaging. Gold H2: www.goldhydrogen.com;

McKinsey / Hydrogen Council





Hydrogen Council / McKinsey: **Hydrogen Insights A perspective on hydrogen investment, market development and cost competitiveness February 2021** https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf

Inflation Reduction Act (IRA)

Clean Hydrogen Production Tax Credit (45V) up to $3/kg

Carbon Intensity (kg CO_2 per kg H_2)*	Max Tax Credit ($/kg H_2)
4–2.5	$0.60
2.5–1.5	$0.75
1.5–0.45	$1.00
0.45–0	$3.00

Qualified Commercial Clean Vehicles Credit (45W)

Creates a **new 30% credit** for commercial fuel cell electric vehicles through 2032, capped at **$40,000**:

- Class 1–3 vehicles: **$7,500 tax credit** for purchase of qualified clean vehicles
- Class 4 and above: **$40,000 tax credit**

Alternative Fuel Refueling Property Credit (30C)

Tax credit up to 30% of the cost of alternative fuel refueling property up to **$100,000**

* Well-to-gate, using GREET

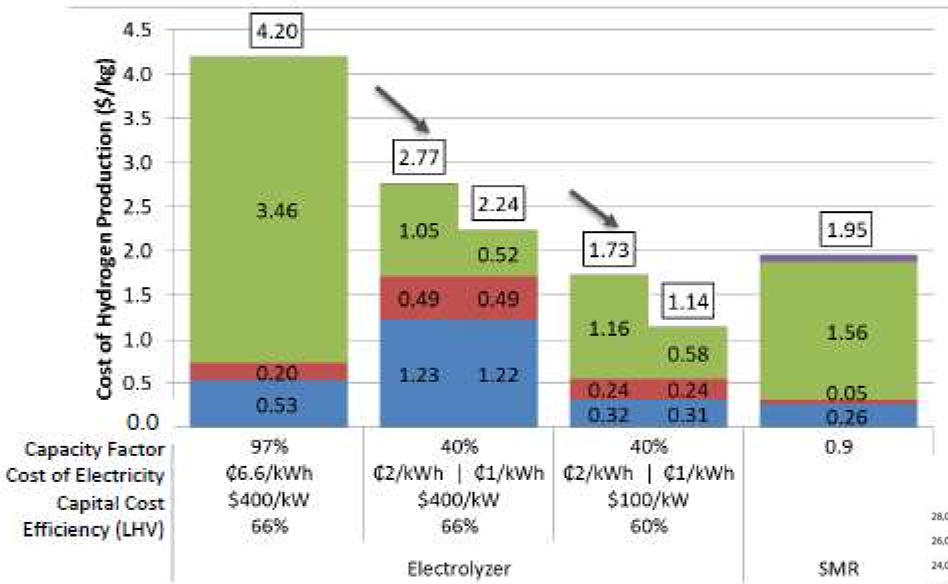
View more at: www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects

Sunita Satyapal, US DOE Hydrogen Annual Merit Review, June 2023

Future Hydrogen Costs: electrolyzers + cheap electricity

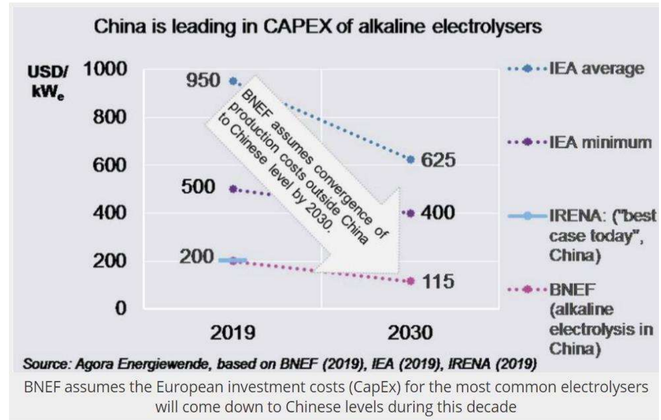
US Hydrogen Earthshot: \$1/kg H_2 by 2030 "1 for 1 by 1"

Potential Levelized Costs of H_2 Production

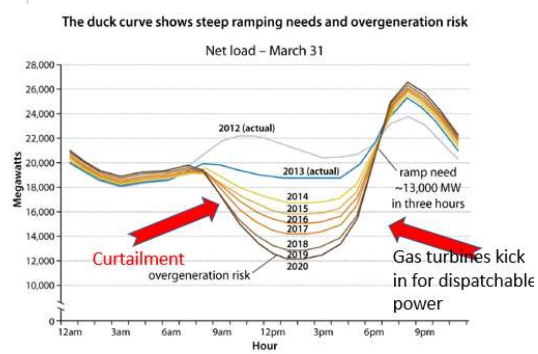


Source: Bryan Pivovar & Josh Eichman

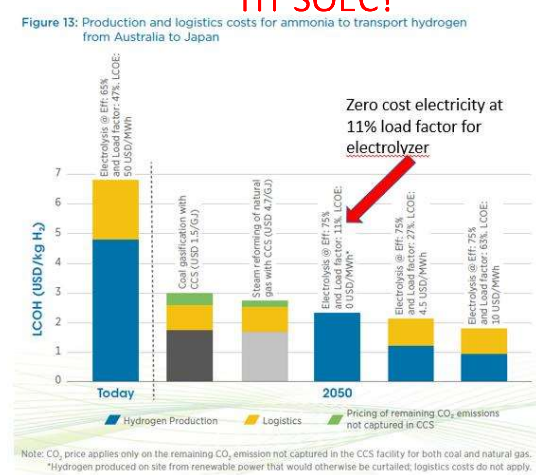
- Mark Ruth (NREL) , MITei presentation 2021, PEM electrolyzers



https://energypost.eu/who-will-be-the-hydrogen-superpower-the-eu-or-china/

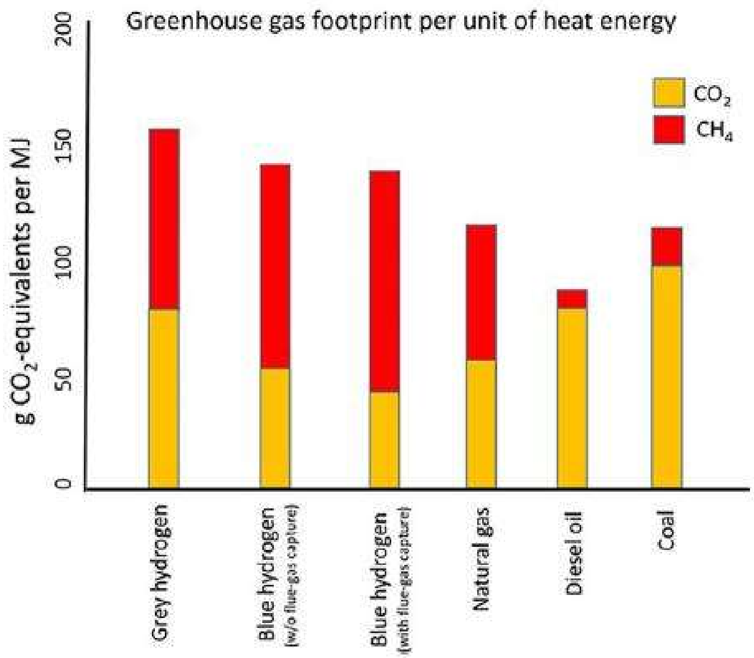


HT SOEC?



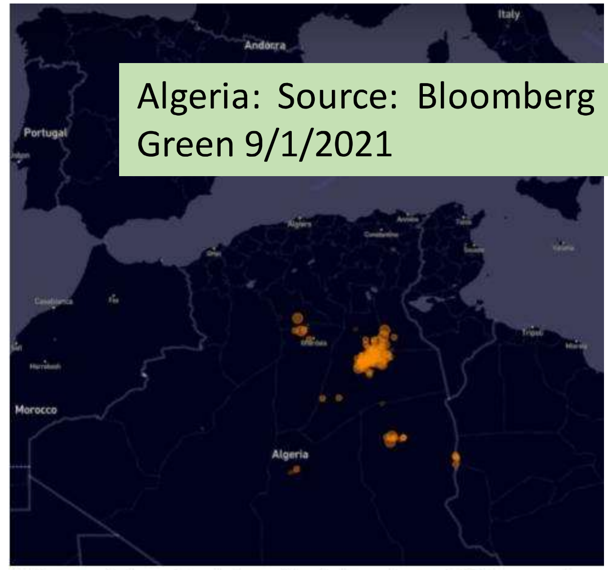
Methane Leakage

R. W. Howarth and M. Z. Jacobson, How green is blue hydrogen?, *Energy Sci Eng*, 2021, ese3.956



Methane Global Warming Potential GWP: 25 – 110X CO_2 (depending on timeframe)

Algeria: Source: Bloomberg Green 9/1/2021

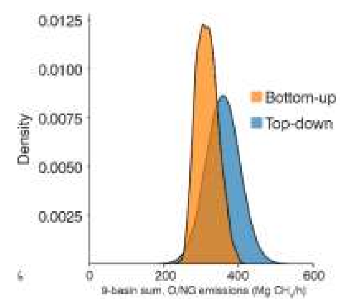


Methane emissions detected over Algeria from January 2019 to present including five observed this month. *Source: Kayrros SAS*

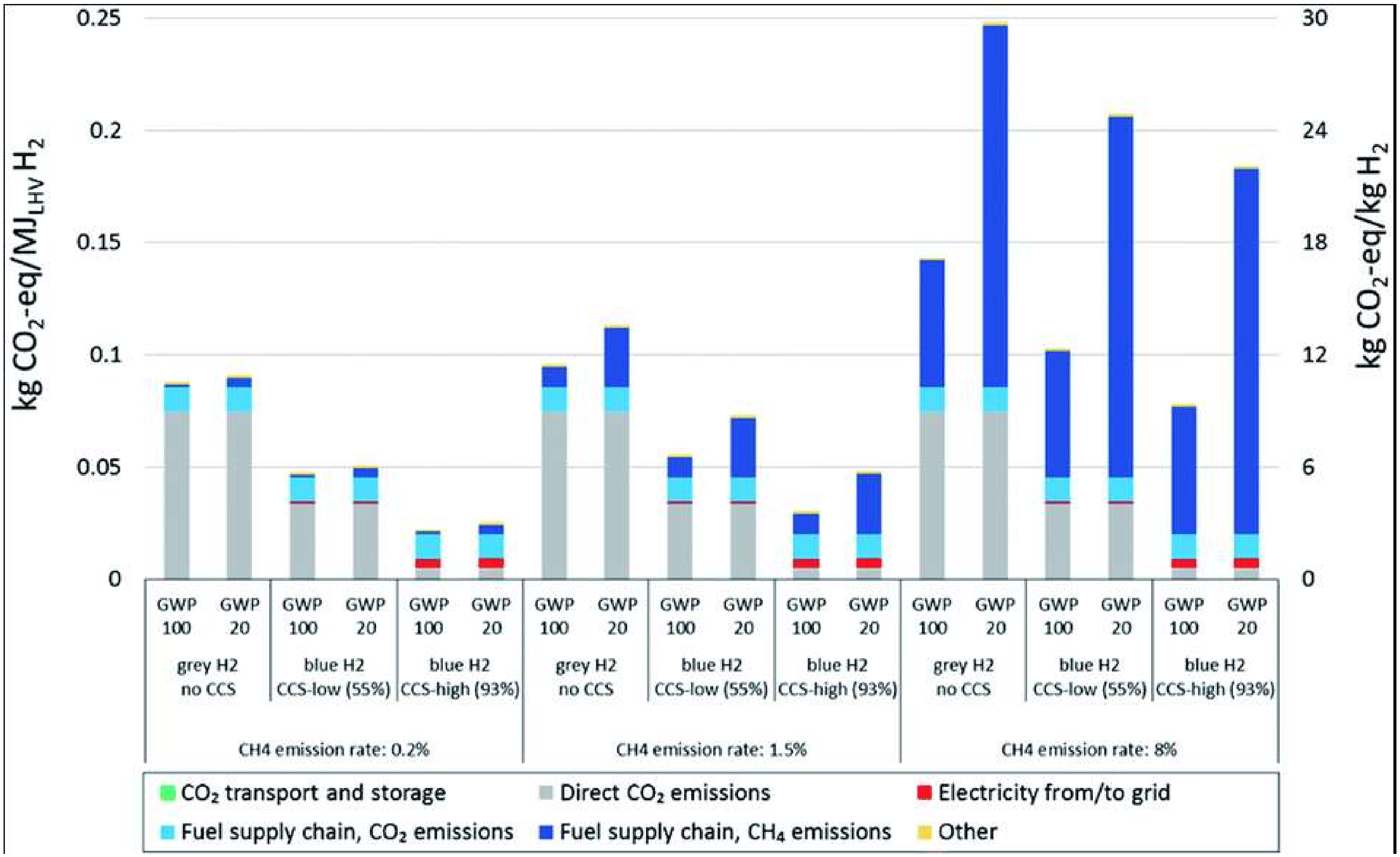
We're tackling methane on every front — with methane hunters Dr. David Lyon (EDF) and Dr. Anna Robertson (U. of Wyoming) in the Permian Basin, MethaneSAT and with Google Earth Outreach. bottom right.

https://www.edf.org/climate/methane-crucial-opportunity-climate-fight

R. A. Alvarez, D. T. Allen et al., Assessment of methane emissions from the U.S. oil and gas supply chain, *Science*, 2018, eaar7204. https://www.science.org/lookup/doi/10.1126/science.aar7204

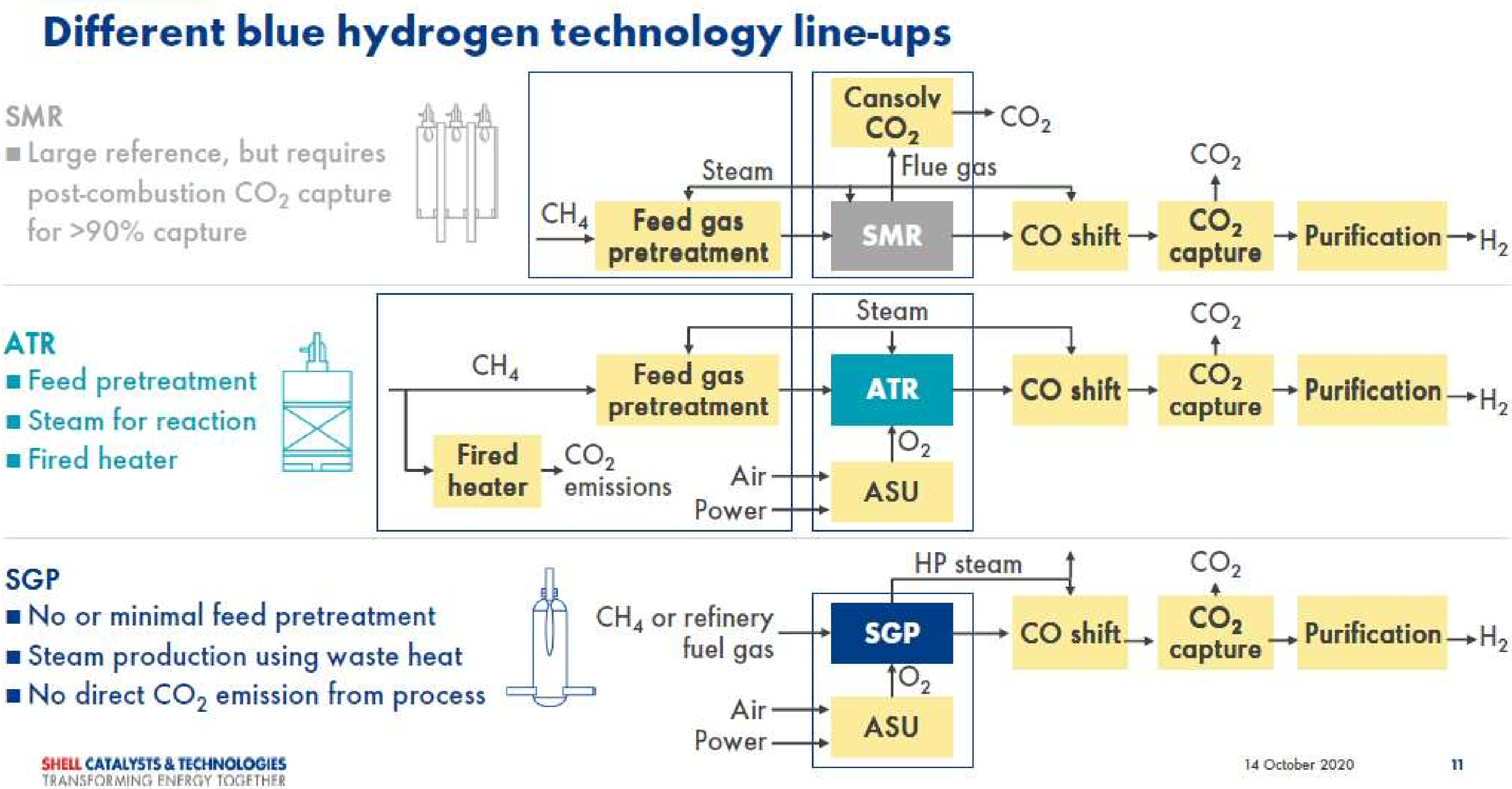


2022 Methane emissions update



- C. Bauer, K. Treyer, C. Antonini, J. Bergerson, M. Gazzani, E. Gencer, J. Gibbins, M. Mazzotti, S. T. McCoy, R. McKenna, R. Pietzcker, A. P. Ravikumar, M. C. Romano, F. Ueckerdt, J. Vente and M. van der Spek, On the climate impacts of blue hydrogen production, Sustainable Energy Fuels, 2022, 6, 66–75.https://pubs.rsc.org/en/content/articlepdf/2022/se/d1se01508g

Hydrogen Manufacture: SMR → ATR → POx



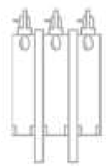
N. Liu, Increasing Blue Hydrogen Production Affordability, **Hydrocarbon Processing,** June 2021; Shell Blue Hydrogen Technology, Hydrocarbon Processing Webcast Oct 2020

Hydrogen Manufacture: SMR → ATR → POx

Which technology is best for greenfield applications?

GOOD

Steam Methane Reforming (SMR)

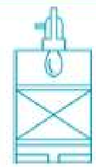


- Catalytic
- Indirect heating
- Non-oxygen based with steam
- Multi-tubular with external firing

Proven for grey hydrogen, but the alternatives may be better suited for blue hydrogen

BETTER

Auto-Thermal Reforming (ATR)

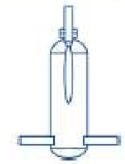


- Catalytic
- Direct heating
- Oxygen based with steam
- Refractory-lined reactor with catalyst bed

As an oxygen-based system, more cost-effective than SMR for blue hydrogen

BEST

Shell Gas POx (SGP)



- Non-catalytic
- Direct heating
- Oxygen based without steam
- Refractory-lined reactor

Offers key advantages over ATR, including, for 500 t/d hydrogen production:*

- $30 million/y lower OPEX
- 35% less power import
- 10–25% lower levelised cost of hydrogen (LCOH)

*Basis: 500 t/d of pure H_2 production (excluding inerts, CH_4, CO_2 and CO, which will also be present depending on the final purification step). Natural gas price = $396/t; demin. water = $8.4/t; power import = $86/MWh; solvent, TEG and catalyst costs based on internal quotations. H_2 discharge pressure of 72 bara; CO_2 discharge pressure of 150 bara. 95% plant availability.

SHELL CATALYSTS & TECHNOLOGIES
TRANSFORMING ENERGY TOGETHER

14 October 2020 9

N. Liu, Increasing Blue Hydrogen Production Affordability, **Hydrocarbon Processing,** June 2021; Shell Blue Hydrogen Technology, Hydrocarbon Processing Webcast Oct 2020

Global warming potential of Hydrogen (indirect)

Table 1 – Estimated global warming consequences of zero-carbon hydrogen distribution, supply and usage systems in the UK and US, making assumptions concerning the percentage leakage rate of the future hydrogen system.

	UK	US
Global warming, million tonnes CO_2 equivalent per year		
Minimum assumed leakage, 1%	0.26	1.26
Same leakage as respective natural gas network	0.6	0.6–2.7
Scale up natural gas leakage to account for H_2 energy content	1.5	1.6–6.8
Maximum assumed leakage, 100%	26	126
Current natural gas consequences	76	295–360

- Indirect Global Warming Potential due to atmospheric reactions with OH, NO
- GWP = 3.3 (<2022)
- GWP = 11 (2022)

Radical Reactions:

$OH + H_2 \rightarrow H + H2O$

$H + O2 \rightarrow HO_2$

$HO_2 + NO \rightarrow NO_2 + OH$

$NO_2 + hv \rightarrow NO + O$

$O + O_2 \rightarrow O_3$

H2 leak rate	Tg CO2/yr	% of fossil
1%	417	1.81%
10%	4167	18.12%
Fossil economy	23000	100%

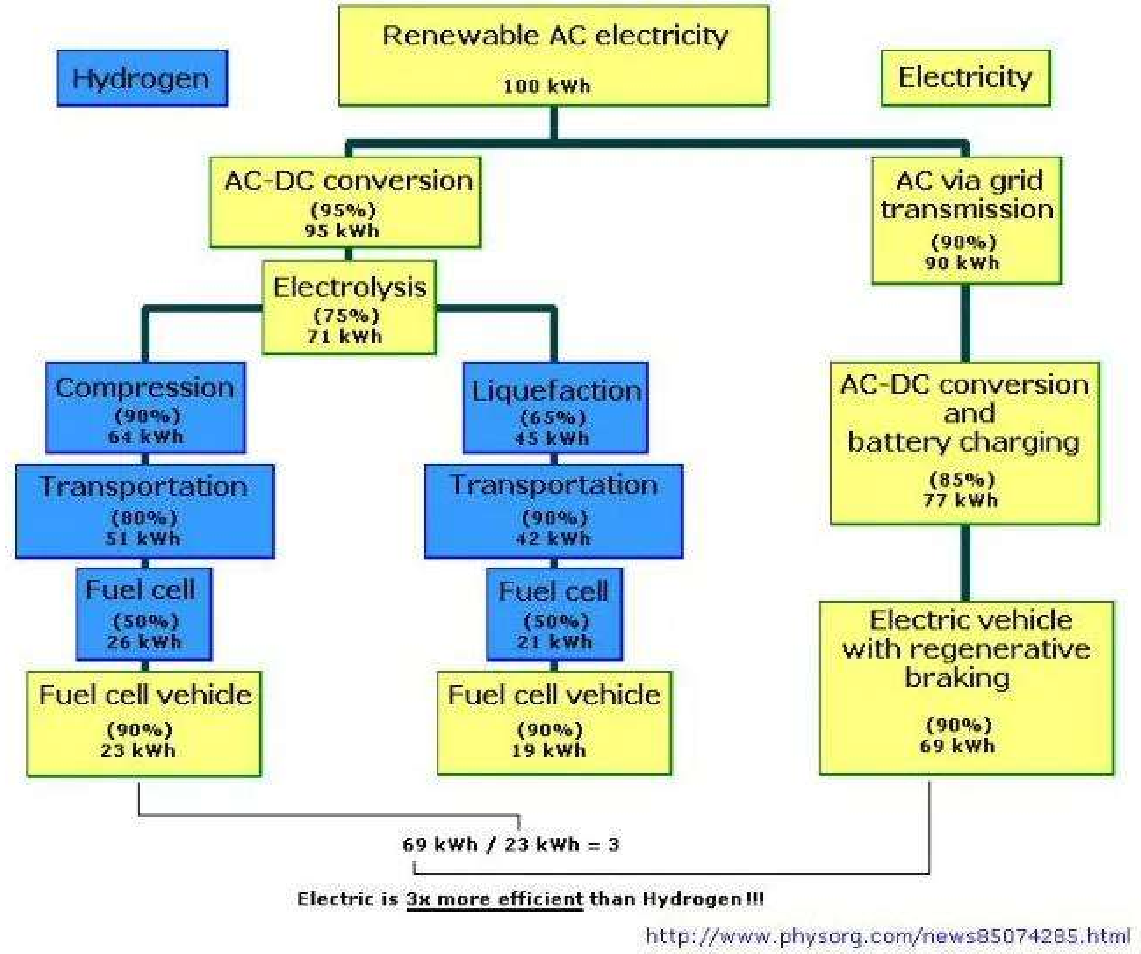
- Derwent, R. et al. (2006) "Global environmental impacts of the hydrogen economy", Int. J. Nuclear Hydrogen Production and Application 1(1): 57-67.
- R. G. Derwent, D. S. Stevenson, S. R. Utembe, M. E. Jenkin, A. H. Khan and D. E. Shallcross, Global modelling studies of hydrogen and its isotopomers using STOCHEM-CRI: Likely radiative forcing consequences of a future hydrogen economy, *International Journal of Hydrogen Energy*, 2020, **45**, 9211–9221.
- R. A. Field and R. G. Derwent, Global warming consequences of replacing natural gas with hydrogen in the domestic energy sectors of future low-carbon economies in the United Kingdom and the United States of America, *International Journal of Hydrogen Energy*, 2021, **46**, 30190–30203.
- N. Warwick, P. Griffiths, J. Keeble, A. Archibald, J. Pyle, University of Cambridge and NCAS and K. Shine, University of Reading, Atmospheric implications of increased Hydrogen use (2022) www.gov.uk/government/publications/atmospheric-implications-of-increased-hydrogen-use

Useful rules of thumb

8.8	kg-H_2/ MM Btu – lower heating value
1	Gallon of gasoline equivalent / kg-H_2
33.4	kWh / kg-H2 (LHV)

\$1/kg H_2 = \$8.80 / MM Btu gas! (LHV)
\$1/kg H_2 = \$1 / gallon gasoline or diesel equivalent (add \$2+ for distribution & dispensing)
3 cent / kWh electricity → \$1/kg H_2 at 100% efficiency

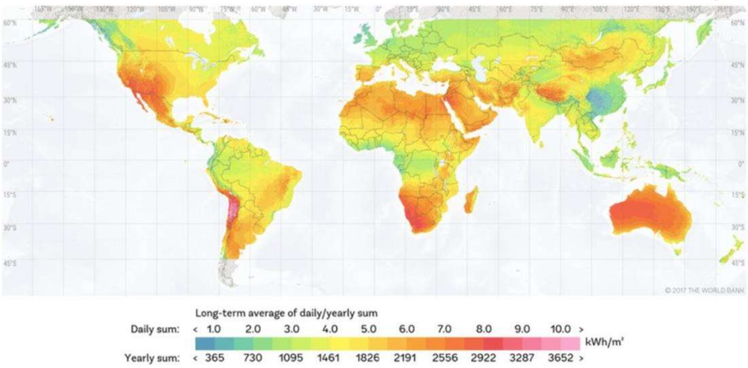
The Hydrogen economy does not make sense?



- Bossel, Ulf. "Does a Hydrogen Economy Make Sense?" *Proceedings of the IEEE*. Vol. 94, No. 10, October 2006.
- Plötz, P. Hydrogen technology is unlikely to play a major role in sustainable road transport. *Nat Electron* **5,** 8–10 (2022). https://doi.org/10.1038/s41928-021-00706-6

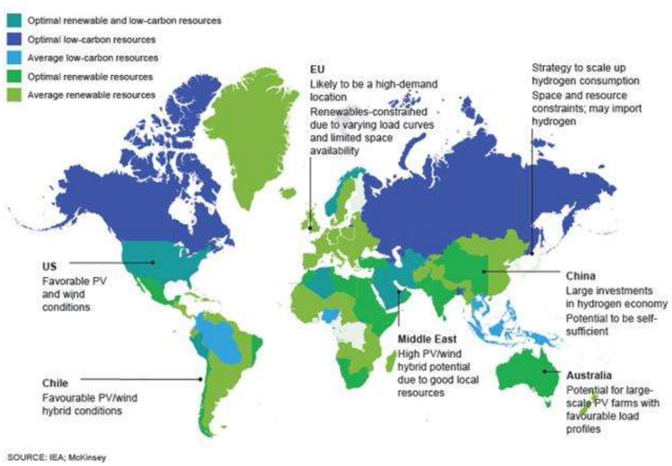
Hydrogen as Energy Vector: Transport and Storage

10X variation solar / wind intensity

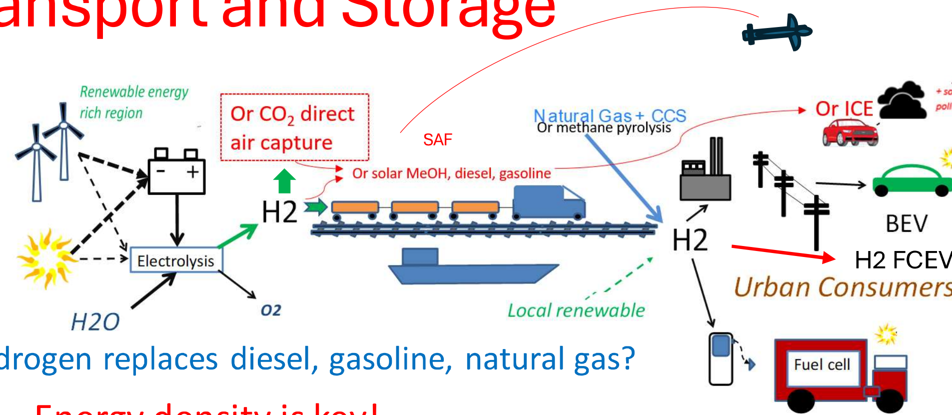


Inderwildi O, Zhang C, Wang X, Kraft M. The impact of intelligent cyber-physical systems on the decarbonization of energy. Energy Environ Sci. 2020;13(3):744-771

Renewable vs "Low Carbon" H2

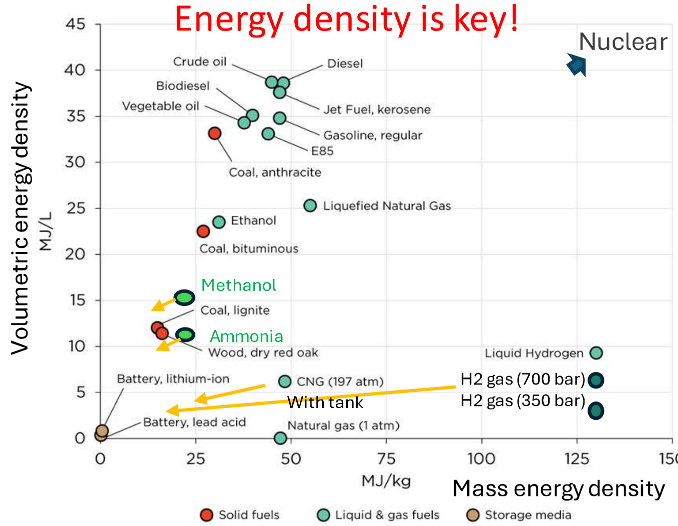


Hydrogen Council: Path to Hydrogen Competitiveness (2019)



Hydrogen replaces diesel, gasoline, natural gas?

Energy density is key!

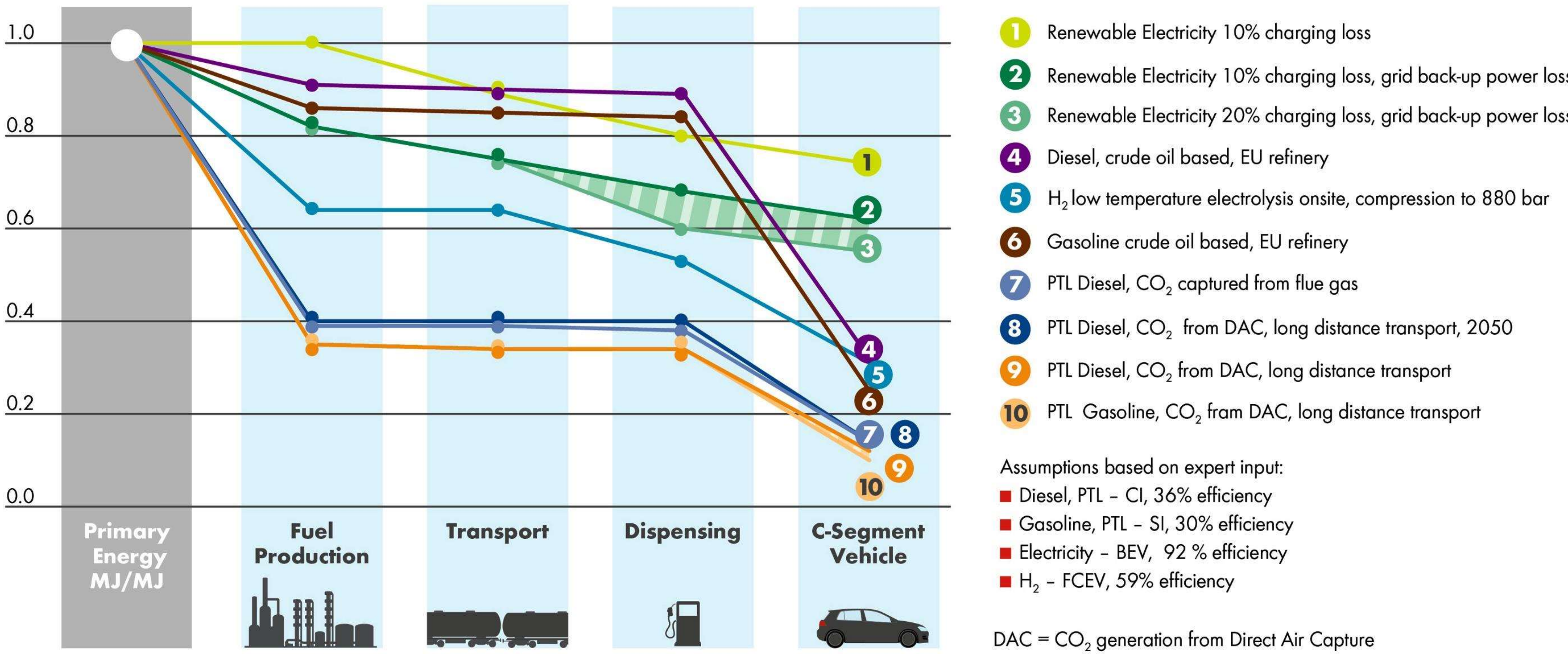


1) R. Heinberg and D. Fridley, *Our Renewable Future: Laying the path to One Hundred Precent Clean energy; 2) DNV: Comparison of Alternative Marine Fuels SEA\LNG Ltd Report No.: 2019-0567, Rev. 3 Document No.: 11C8I1KZ-1; Date: 2019-07-05*

Hydrogen FCEV:

- ❑ Rapid Refuel < 5 (20) minutes Commercial fleets
- ❑ Zero emission (H2O vapor)
- ❑ Hi range (300 mi +)

CUMULATED FUEL-POWERTRAIN EFFICIENCY FOR LIGHT DUTY VEHICLES



J. Adolf, W. Warnecke, P. Karzel, A. Kolbeck, A. Van Der Made, J. Müller-Belau, J. Powell, K. Wilbrand, L. Zimmermann, L. Sens, U. Neuling and M. Kaltschmitt, On Route to CO2-free Fuels. Hydrogen - Latest Developments in its Supply Chain and Applications in Transport, DOI:10.13140/RG.2.2.21744.58889; 'The road to sustainable fuels for zero emissions mobility: status of, and perspectives for, power-to-liquids fuels.' Paper presented at the 39th International Vienna Motor Symposium, See: https://www.concawe.eu/wp-content/uploads/Concawe-Review-28-1-web-resolution-PDF.pdf

Snapshot of Hydrogen and Fuel Cell Applications in the U.S.

Examples of Deployments

>500 MW Backup Power

>60,000 Forklifts

>3.7 GW Electrolyzers

~80 – 150 Fuel Cell Buses

~50 H_2 Retail Stations

>16,000 Fuel Cell Cars

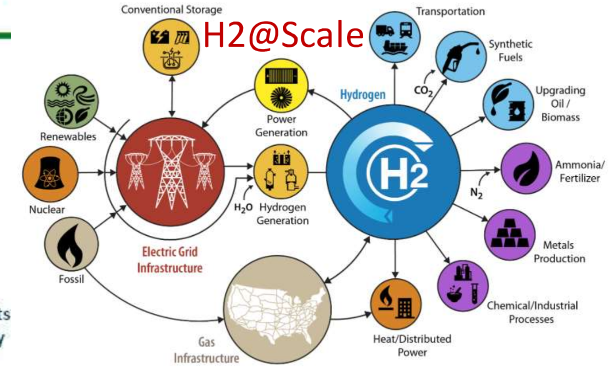
*Polymer electrolyte membrane

Major Hydrogen Production

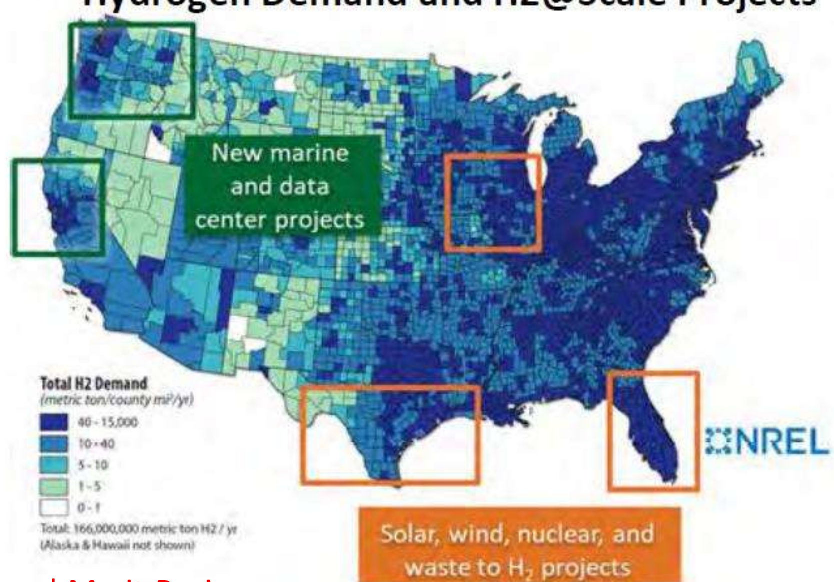
- 10 million metric tons produced annually
- More than 1,600 miles of H_2 pipeline
- World's largest H_2 storage cavern

Hydrogen Stations Plans Across States

California	Northeast	
₂00 Stations Planned California Fuel Cell Partnership Goal	12 – 20 Stations Planned	HI, OH, SC, NY, CT, MA, CO, UT, TX, MI And Others



Hydrogen Demand and H2@Scale Projects



Sunita Satyapal, 2021 & 23 June Annual Merit Reviews

Heavy duty Hydrogen Fuel Cell Trucks

What electrification of drive train eliminates:

- Engine & Transmission
- Drive Lines and Axles
- Emissions Systems
- Fluids, Tanks, Lines
- Filters
- Charge Air & Turbos

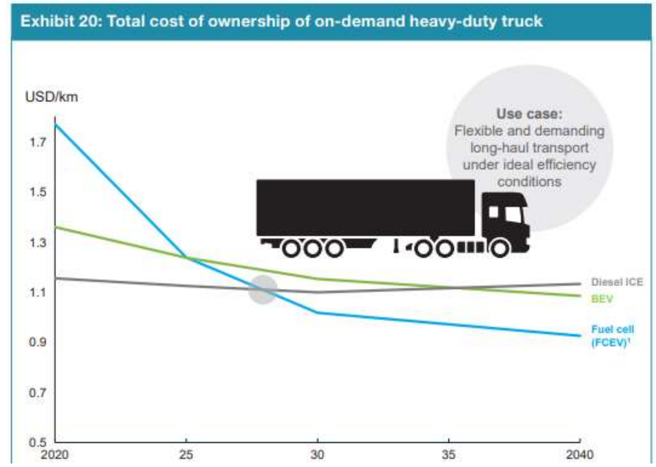
Over 7,800 lbs

Diesel Truck Subsystem	Approximate Weight (lb)
Engine & Related	2,300
Transmission & Related	810
Driveshaft Parts	230
Fuel Tank & Related	200
Rear Tandem Axle	1,200
Exhaust/Emission Systems	480
Diesel Fuel (full)	1,728
DEF	209
12V Batteries (3)	180
Cooling System	310
Other Brackets, Mounts, Cables, Components	200
Total Diesel Related	7,847

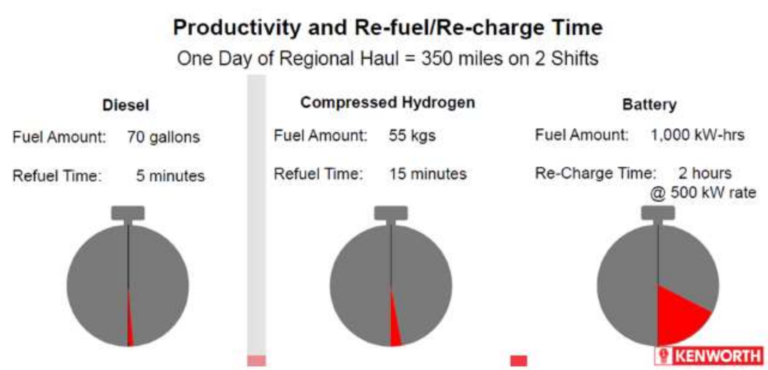
NACFE

NACFE, Guidance Report: Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors https://nacfe.org/emerging-technology/electric-trucks-2/viable-class-7-8/

•Mihelic, R., et al, "Guidance Report Electric Trucks – Where They Make Sense," North American Council for Freight Efficiency (NACFE), May 2018, https://nacfe.org/report-library/guidance-reports/



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



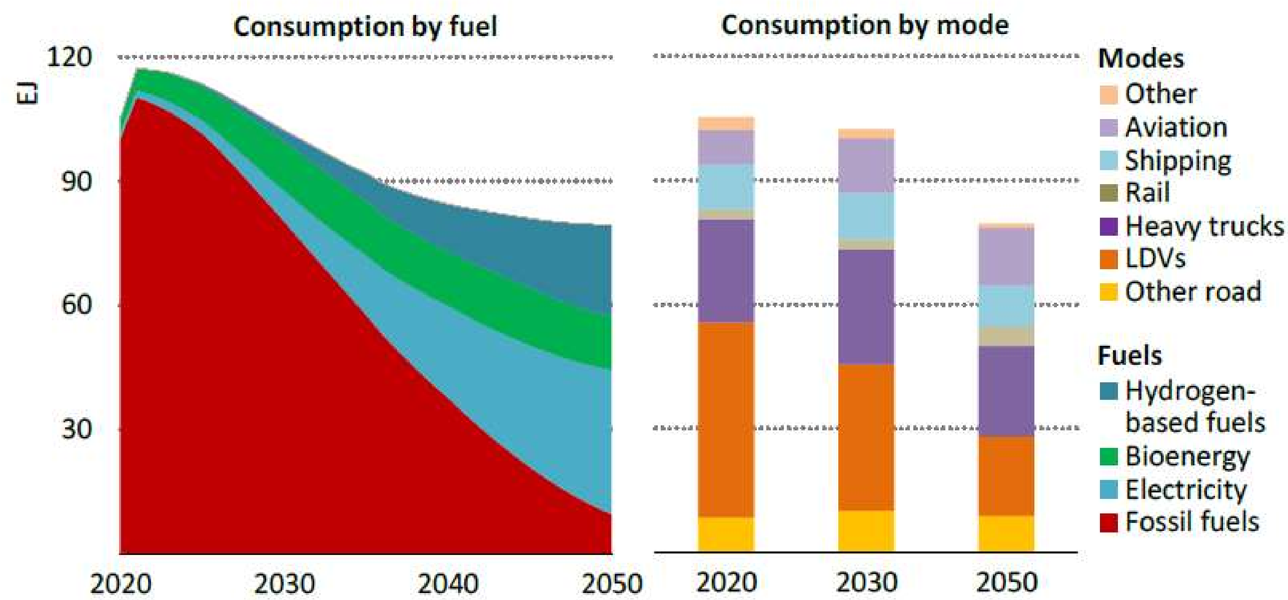
Lindgren, B., "Kenworth Electrified Powertrain," ACT EXPO 2019 presentation, May 30, 2019, https://www.gladstein.org/gna-presentations/actexpo2019presentations/

Electrify for CO2-free future

IEA NetZero by 2050:

https://www.iea.org/reports/net-zero-by-2050

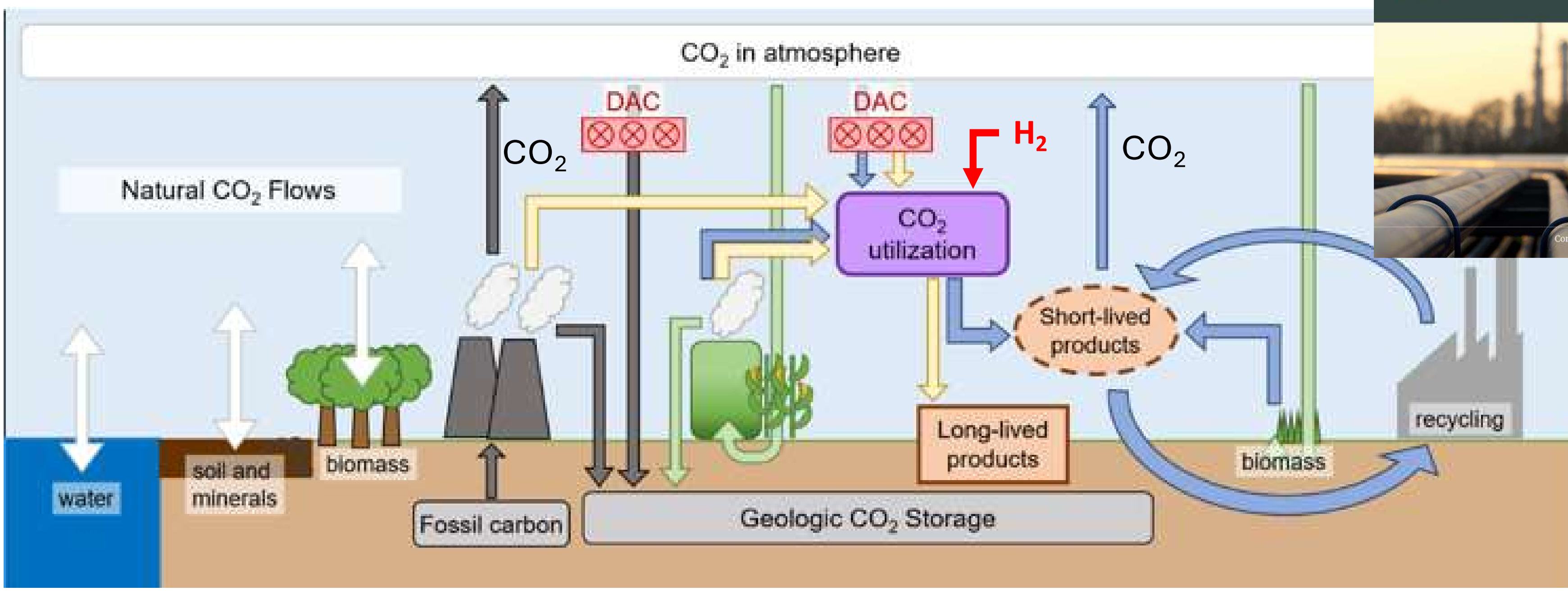
Figure 3.22 ▷ Global transport final consumption by fuel type and mode in the NZE

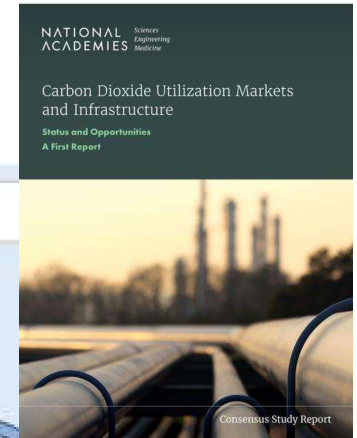


Electricity and hydrogen-based fuels account for more than 70% of transport energy demand by 2050

Note: LDVs = Light-duty vehicles; Other road = two/three wheelers and buses.

Carbon Capture Utilization & Storage (CCUS)



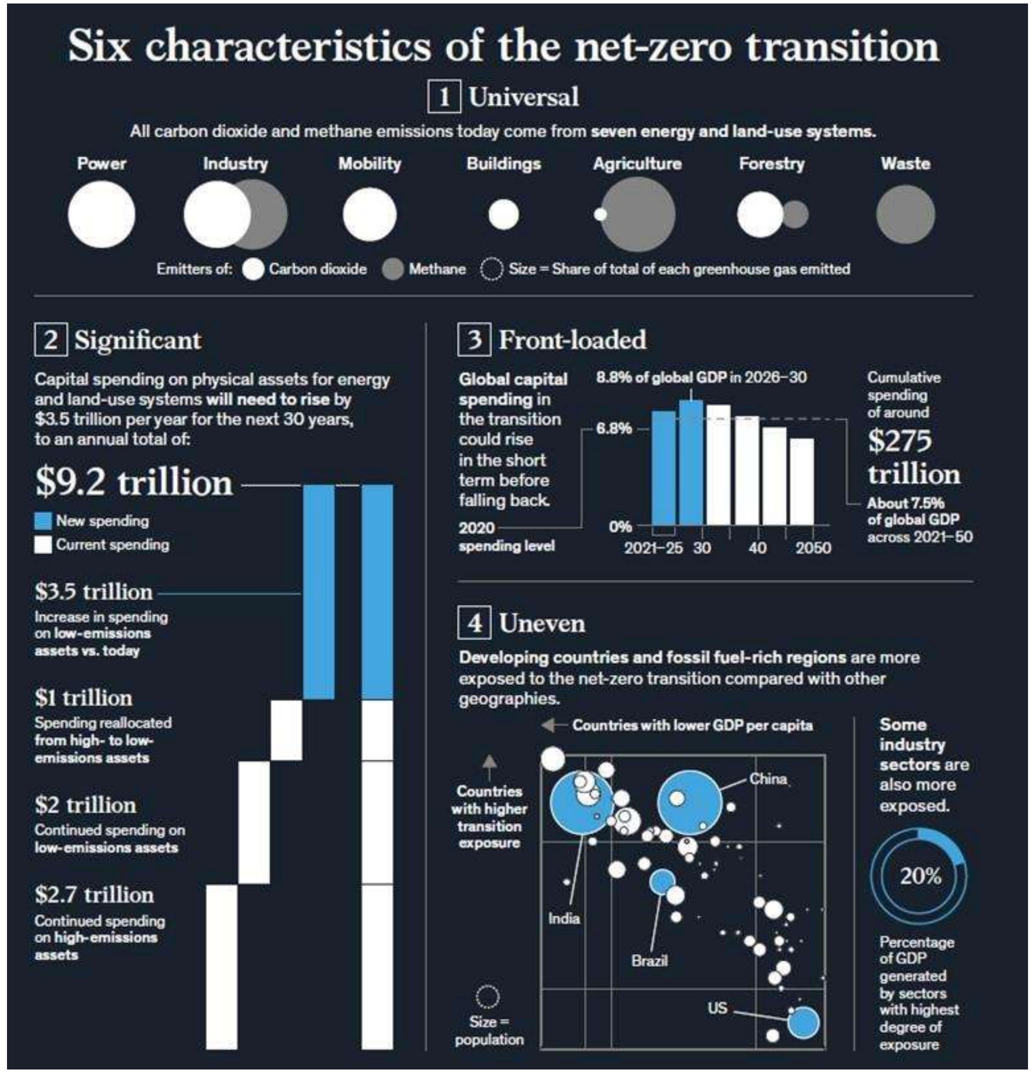


Schematic of main carbon flows in a circular carbon economy, showing sustainable pathways for the production of short- and long-lived carbon-based products as well as natural flows of carbon into and out of the atmosphere. Natural flows are white. Flows of fossil carbon and emissions are grey. Flows of biogenic carbon are green. Flows of recycled materials are blue, as are flows of carbon associated with short-lived products. Flows to be used for long-lived products are yellow. DAC = direct air capture. This schematic does not include all carbon flows that will exist in a circular carbon economy; for example, recycling could be an option for long-lived products. SOURCE: Committee generated.

National Academies of Sciences, Engineering, and Medicine. 2022. *Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26703.

How much will it cost?

- McKinsey, The net-zero transition: What it would cost, what it could bring, January 2022 https://www.mckinsey.com/capabilities/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring



Technology Session-1: Agenda

A.1 H2 Production				
		Time	Speaker	Topic
		9:15	Joe Powell (UH)	Scene Set Technology
		9:30	Kevin Topolski NREL	US H2@Scale H2 production
		9:45	Anthony Borski NEL	Green H2 / Electrolyzers
		9:55	Eric McFarland UCSB	Turquoise and Pink H2: Methane Pyrolysis & Nuclear
		10:05	Michael Wang Argonne	Greet Model LCA
		10:15	Joe Powell (UH)	Moderate Panel Q&A
		10:45	END	