A Hydrogen Economy?

John C. Bean

Outline

Vision(s) of a Hydrogen Economy
- Reactions from the Press, Environmental, Science & Industry Organizations

Today's NOT so simple Hydrogen
- From where do we now get Hydrogen?
  - White vs. Green Electrolytic vs. Gray, Brown, Black & Blue fossil-fuel-based Hydrogen
- How do we now use Hydrogen?

Tomorrow's Hydrogen
- Energy Sources vs. Energy Storage Media
- Energy conversion efficiencies of electrolysis & fuel cells vs. batteries & synthetic fuels

Climate-change-driven vs. Industry-driven versions of a Hydrogen Economy:
- Massive Electrification + Green Hydrogen vs. Gray to Blue Hydrogen + Carbon Capture
- The surprisingly stark differences between economically-driven Carbon Capture & Utilization
  - versus climate-driven Carbon Capture, Utilization and SUSTAINED Sequestration

The intrinsic energy content of Hydrogen vs. Fossil Fuels vs. Batteries vs. . . .
- plus the EFFECTIVE energy densities of differently stored & transported Hydrogen

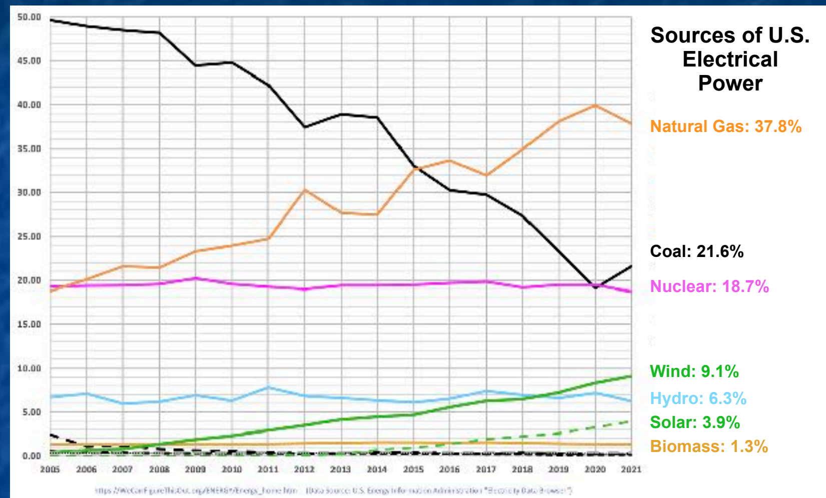
Impacts of those energy contents & densities upon future:
- Hydrogen transport and infrastructure
- Applications of Hydrogen in Heating, Electricity Generation, Cars, Trains, Ships & Planes
  - Along with energy-calculation-based comparisons to competing technologies

(Revised March 2024)

The Vision(s) of a Hydrogen Economy:

The reasoning goes something like this:

Nearly 60% of U.S. electrical power now **DEPENDS** upon CO_2 emission (37.8% + 21.6%) [1]



Nearly 100% of U.S. road, sea & air transport now **DEPENDS** upon CO_2 emission [2]

Even **electric cars** now **DEPEND** upon electricity that's 60% based on burning fossil-fuels

Nearly 100% of U.S. industrial & residential heating now **DEPENDS** upon CO_2 emission

Eliminating fossil-fuels from that huge variety of technologies will be a BIG challenge

Eliminating it fast enough to mitigate climate change might be an OVERWHELMING challenge

1) *See my webnotes:* ***U.S. Energy Production and Consumption*** *(pptx / pdf / key):*

2) *See my webnotes:* ***Energy Consumption in Transportation*** *(pptx / pdf / key)*

So instead of REPLACING those systems, why not just REPLACE their fuel?

We now exploit combustion reactions of the form: **$CX + O_2 \rightarrow CO_2$ + Byproducts + Energy**

C input comes from fossil-fuel hydrocarbons such as

gasoline, diesel fuel, coal or natural gas (NG = mostly methane)

O_2 input comes directly from the atmosphere's 21%

But their combustion then releases into the atmosphere CO_2 ,

a particularly potent & persistent Greenhouse Gas (GHG) [1]

REPLACE those combustion reactions with that of Hydrogen gas: **$H_2 + 1/2\ O_2 \rightarrow H_2O$ + Energy**

H_2 input comes from . . . well, the same place we now get it for things like balloons

O_2 input still comes from the atmosphere's 21%

But their combustion then releases only H_2O into the atmosphere [2]

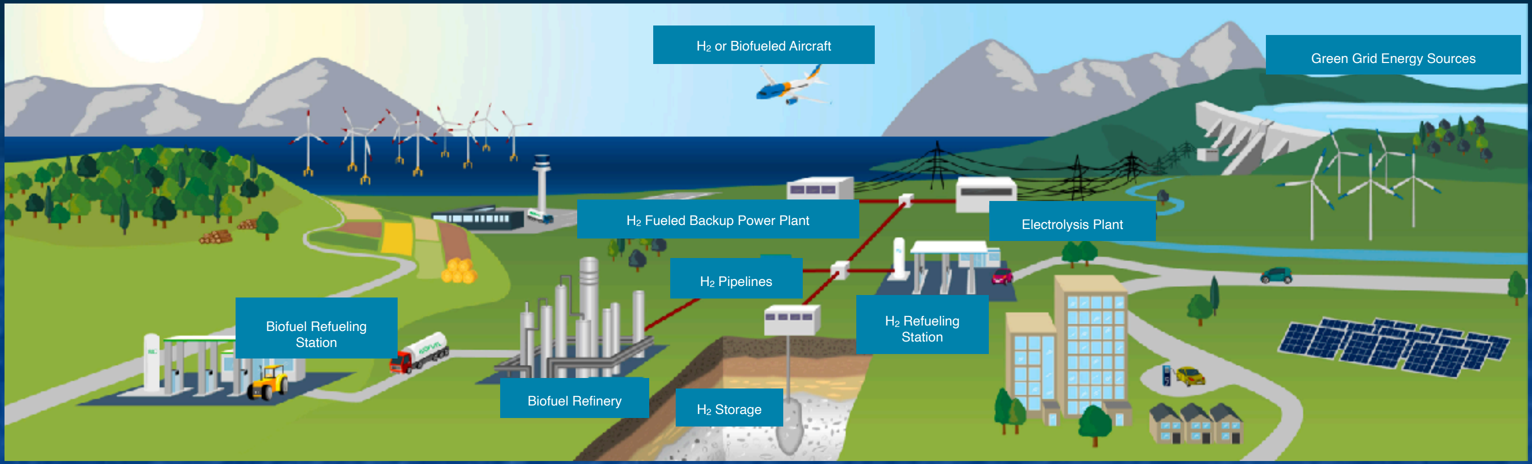
which is **already** extremely rich in H_2O vapor (e.g., clouds)

and has an environmentally friendly way of removing excess H_2O vapor (i.e., rain)

1) Aside from statistically insignificant situations where that CO_2 is now effectively & economically "sequestered" (more about this later)

2) Plus, if that combustion is very hot, compounds of oxidized atmospheric nitrogen, not now generally identified as a significant problem

Leading to depictions such as this: [1]



Visions such as these are promoted by: [2]

- Industry backed organizations including:
  - The Hydrogen Fuel Cell Partnership (formerly The California Fuel Cell Partnership)
  - The Hydrogen Council
  - The Clean Hydrogen Future Coalition
  - The Fuel Cell and Hydrogen Energy Association
- Major governmental studies, including those compiled by:
  - The European Commission
  - The U.S. Department of Energy

1) Enlarged captions added to: https://www.researchgate.net/publication/316087225_Hydrogen_Economy_for_Arab_Countries

*2) See this webnotes' **Resources Webpage** (link) for links to reports produced by these organizations (as well as cached copies)*

But that figure was decidedly lacking in detail:

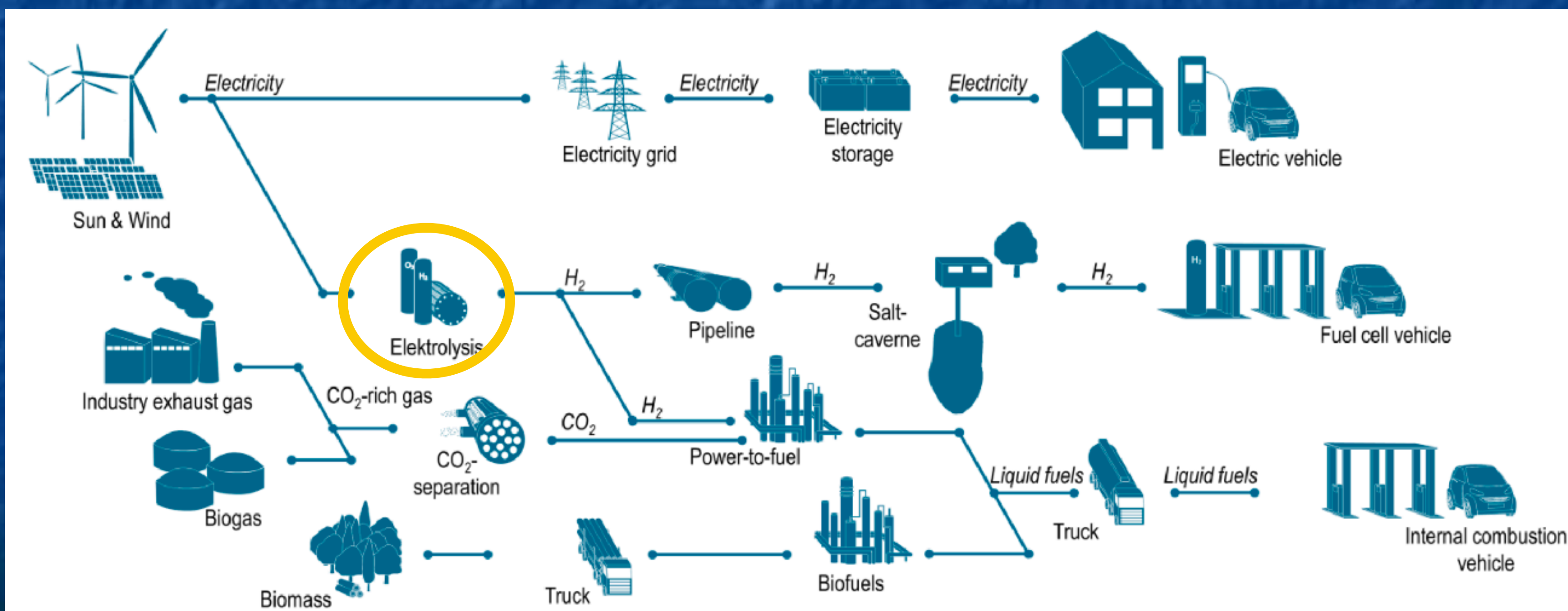
Particularly about the all-important source of the system's H_2

which all came from a small single building labeled **Electrolysis Plant:**

Another illustration offered a seemingly more technical & complete diagram: [1]

But it is also vague about the Electrolysis plant, which stands almost alone,

having only ONE familiar input (Sun & Wind Electricity) and ONE benign output (H_2)



1) Figures both found in web-posted document: https://www.researchgate.net/publication/316087225_Hydrogen_Economy_for_Arab_Countries
That figure credited as: "Renewable Hydrogen Production, Storage, Transport and Utilization for Transport, Household and Industry. Urban Power Station © Forschungszen- trum Jülich GmbH"

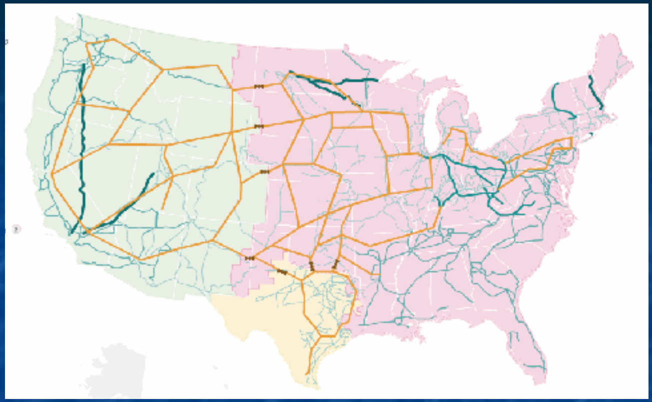
*Despite an absence of detail, the idea **seems** downright elegant in its simplicity:*

In the U.S. we **don't** build a **NEW** High Voltage DC (HVDC) Grid

as required to efficiently send electricity

FROM locations best suited for solar & wind farms

TO consumers in far distant population centers:



Map of a proposed HVDC Electrical Grid

Instead, we just send Hydrogen gas through our **EXISTING**

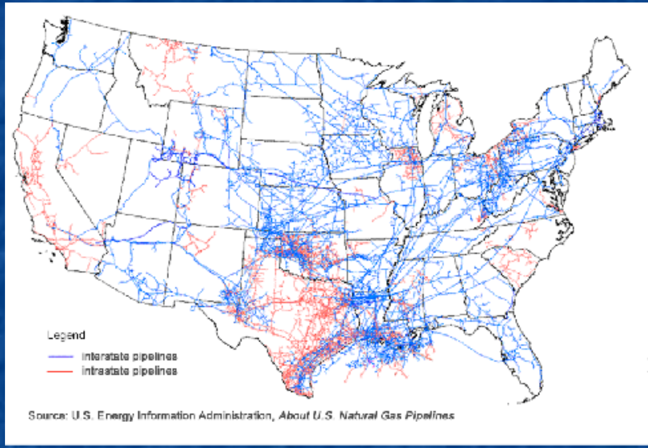
national network of natural gas pipelines:

With the added bonus that, while a HVDC Grid requires a **new**

network of wires strung between especially tall towers,

3 million miles of underground gas pipelines

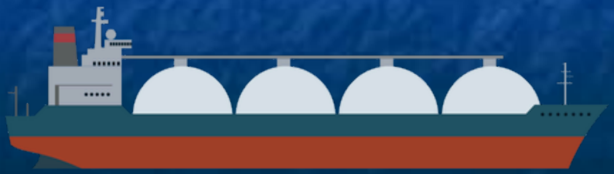
already criss-cross the the U.S. (!) [1]



Map of existing U.S. natural gas network

Similarly, over oceans, we might use versions of the tankers

already shipping huge loads of Liquified Natural Gas:



Top Map: https://infrastructureusa.org/interactive-map-visualizing-the-us-electric-grid/

Reference 1 & bottom map:

U.S. Energy Information Administration (EIA): https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php

Hydrogen might even solve the huge problem of variable solar & wind energy:

Solar and wind energy, peaking either midday or late afternoon,

won't be able to supply enough electricity in the evenings when we most need it

Meaning that dependence on solar & wind will require massive electrical energy storage

based on mostly untested or undeveloped technologies, including:

Pairs of "Pumped Storage Hydro" lakes (the only tried & well tested idea)

Huge farms of batteries, capacitors, or flywheels

Vast underground tanks/reservoirs of molten salt or compressed air

(see my noteset: **Power Cycles and Energy Storage** (pptx / pdf / key))

Instead: AT solar & wind power farms their electricity could be used to generate **Hydrogen Gas**

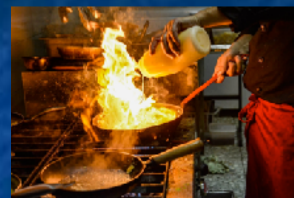
with its resulting cyclic generation then matched to the different cycles of electricity demand

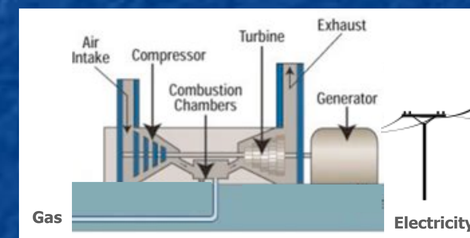
by temporarily storing that hydrogen in simple high-pressure gas tanks:

Figure: https://aoghs.org/transportation/hortonspheres/

Then, often with only minor modification of existing equipment:

H_2 could fuel the myriad burners upon which our homes, businesses & industry depend:





And if enough H_2 can be stored onboard, it could also power the combustion engines moving:

Reactions:

The doubts of Environmental & Scientific Organizations:

The Natural Resources Defense Council:

"A focus on hydrogen must not detract from other strategies and technologies that could produce much larger environmental and energy security benefits in the near term . . . It will take at least two decades before hydrogen can even begin to make a significant contribution to reducing global warming pollution, improving air quality, and reducing U.S. oil dependence" [1]

The Sierra Club

"The fossil fuel industry is hyping hydrogen of all kinds as a low-carbon replacement for all sorts of uses of fossil fuels - from powering vehicles and heavy industry to heating buildings. In reality, many hydrogen projects will only lock us in to continued fossil fuel use and additional investments in fossil fuel infrastructure" [2]

Renew Org Australia:

"Hydrogen is an inefficient option to propel a vehicle, compared to using renewable electricity via a battery . . . (Hydrogen) costs 4 to 5 times as much as a petrol equivalent . . . Hydrogen should not be allowed to distract us from the mainstream opportunity, which is wind and solar generation supported by transmission lines and energy storage" [3]

The International Renewable Energy Agency:

"Hydrogen will likely trail other strategies such as electrification of end-use sectors, and its use will target specific applications. The need for a dedicated new supply infrastructure may limit hydrogen use to certain countries that decide to follow this strategy. Therefore, hydrogen efforts should not be considered a panacea" [4]

The American Physical Society (in Physics Today):

"The gap between the present state of the art in hydrogen production, storage, and use and that needed for a competitive hydrogen economy is too wide to bridge in incremental advances. It will take fundamental breakthroughs of the kind that come only from basic research" [5]

1-5) Full links given on subsequent page

As echoed in recent Business, Popular & Technical Press Headlines:

Why are we still talking about Hydrogen?

Forbes - 6 Feb 2021 [6]

Clean Energy Superstar or Smokescreen for Fossil Fuel Use?

Washington Post - 17 March 2022 [7]

Get Tax Right or Clean Hydrogen Will be a Bigger Boondoggle than Biofuels

Washington Post - 27 April 2023 [8]

Before We Invest Billions in This Clean Fuel, Let's Make Sure It's Actually Clean

New York Times - 14 April 2023 [9]

Green Hydrogen Or Dirty Fuel? . . . Tax Credit Will Determine Industry's Future

Forbes - 17 April 2023 [10]

Synthetic Gasoline Promises Neutral Emissions - But the Math Doesn't Work

ARS Technica - 5 May 2023 (includes discussion of H_2 fuel) [11]

E-fuels - How Big a Niche Can They Carve out for Cars?

The Guardian- 5 May 2023 (includes discussion of H_2 fuel): [12]

6-12) Full links given on subsequent page

Versus the enthusiasm of established Petrochemical & Energy Companies:

As seen in their well-moneyed and sustained promotion of Hydrogen, via organizations such as:

- The Hydrogen Fuel Cell Partnership (formerly The California Fuel Cell Partnership) [13]
- The Hydrogen Council [14]
- The Clean Hydrogen Future Coalition [15]
- The Fuel Cell & Hydrogen Energy Association [16]

Which, on their homepages, proudly post their governing board & member logos including: [17-20]

Which is a virtual "Who's Who" of the world's entrenched Petrochemical & Energy Companies

13-20) Full links given on next page

Sources cited in the previous three pages:

First page:

1) https://www.nrdc.org/sites/default/files/hydrogen.pdf
2) https://www.sierraclub.org/articles/2022/01/hydrogen-future-clean-energy-or-false-solution
3) https://renew.org.au/wp-content/uploads/2019/06/HydrogenHelpOrHype02d.pdf
4) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf
5) https://physicstoday.scitation.org/doi/10.1063/1.1878333

Second page:

6) https://www.forbes.com/sites/jamesmorris/2021/02/06/why-are-we-still-talking-about-hydrogen/?sh=70b10937f044
7) https://www.washingtonpost.com/climate-solutions/2022/03/17/hydrogen-clean-energy-climate-change/
8) https://www.washingtonpost.com/opinions/2023/04/27/clean-hydrogen-tax-credit-stringent-rules/
9) https://www.nytimes.com/2023/04/14/opinion/hydrogen-fuel-tax-credit-climate-change.html?searchResultPosition=2
10) https://www.forbes.com/sites/energyinnovation/2023/04/17/green-hydrogen-or-dirty-fuel-treasury-department-rules-on-45v-tax-credit-will-determine-industrys-future/?sh=6303579ee6a1
11) https://arstechnica.com/cars/2023/05/synthetic-gasoline-promises-neutral-emissions-but-the-math-doesnt-work/
12) https://www.theguardian.com/business/2023/may/05/e-fuels-cars-aviation

Third page:

13) https://h2fcp.org/
14) https://hydrogencouncil.com/en/
15) https://cleanh2.org/
16) https://www.fchea.org/
17) https://h2fcp.org/members
18) https://hydrogencouncil.com/en/members/
19) https://cleanh2.org/
20) https://www.fchea.org/members

PLEASE ALSO NOTE: As with all of my notesets, on a companion "Resources" webpage (link), I list the sources I studied while writing that noteset (as text citations, web links, and where not "paywalled," as cached copies), as well a certain critical figures and videos (~120 such sources are already listed on this noteset's Resources webpage)

What explains the enthusiasm of well-established Petrochemical & Energy Companies?

What explains the contrasting negativity of not only Environmental & Scientific Groups but also that of the Business, Popular & Technical Press?

To understand those reactions, we must first dig more deeply into:

Today's Not So Simple Hydrogen

From where do we NOW get Hydrogen Gas?

Do we get it from natural sources?

After all, **Hydrogen atoms** are the most abundant atoms in the universe

And while Hydrogen atoms account for only about 0.14% of the Earth's crust,

a large fraction of those atoms reside in vast and readily-available bodies of water [1]

Leading one to also expect readily-available natural terrestrial sources of **Hydrogen Gas**

And, in fact, there ARE natural sources of H_2 - mostly based upon extreme high temperature

interaction of stone & water within the earth's crust & at sub-ocean hydrothermal vents [2]

Such naturally occurring H_2 has been labeled **White Hydrogen**

About which, in 2021, the "world's first" conference was held, labeling it **The New Frontier** [3]

But beyond that label, and that conference, I found essentially zero information about its use

Why? Because the H atoms of H_2 rebond so easlily to OTHER atoms (such as C & O) that

natural H_2 is incorporated into other compounds long before it can ever accumulate!

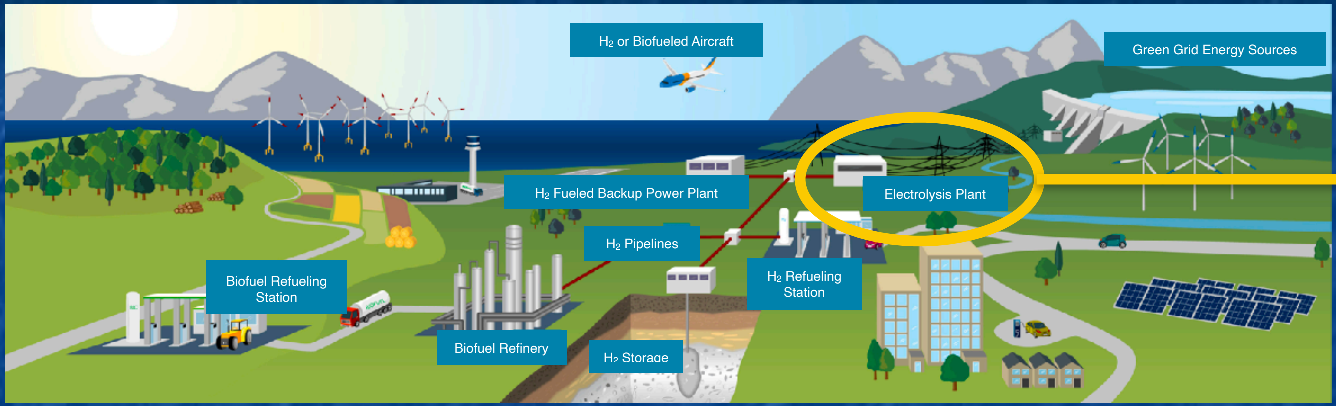
1) https://www.britannica.com/science/hydrogen

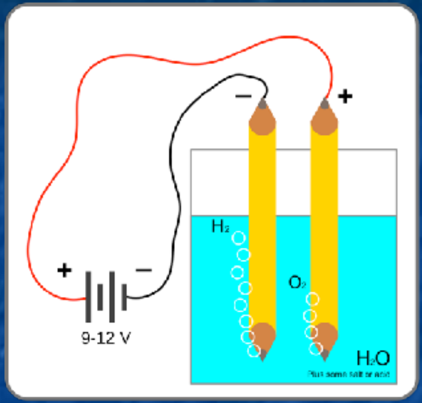
2) https://en.wikipedia.org/wiki/Natural_hydrogen

3) https://geoscientist.online/sections/unearthed/natural-hydrogen-the-new-frontier/

*So instead of **Getting** H_2 Gas we must now **Produce** H_2 Gas*

The technique suggested in the earlier "Vision" figures is **Electrolysis:**





Electrolysis applies electricity to two metal electrodes immersed water:

The negatively charged "Cathode" injects electrons into the water, liberating $H_2 + OH^-$ ions:

$$2\ H_2O\ (\textit{liquid}) + 2\ e^- \rightarrow H_2\ (\textit{gas}) + 2\ OH^-\ (\textit{in water})$$

The positively charged "Anode" takes electrons from the OH^- ions, liberating O_2 + water:

$$2\ OH^-\ (\textit{in water}) \rightarrow 1/2\ O_2\ (\textit{gas}) + H_2O\ (\textit{liquid}) + 2\ e^-$$

Yielding an overall **$H_2 + O_2$ Gas Production Reaction**:

$$2\ H_2O\ (\textit{liquid}) + \text{Electrical Energy Input} \rightarrow 2\ H_2\ (\textit{gas}) + O_2\ (\textit{gas})$$

Left figure: Enlarged captions added to: https://www.researchgate.net/publication/316087225_Hydrogen_Economy_for_Arab_Countries
Right figure: https://en.wikipedia.org/wiki/Electrolysis_of_water

Characteristics of today's "Electrolytic" production of Hydrogen Gas

Drawing from sources including International Energy Agency (IEA) [1] reports [2, 3]

And International Renewable Energy Agency (IRENA) [4] reports [5, 6]

- Today's Electrolysis electrodes require exotic materials such as Platinum, Titanium and Gold [7-9]

- Latent energy content of H_2 fuel produced vs. the Electrical Energy needed to produce it:

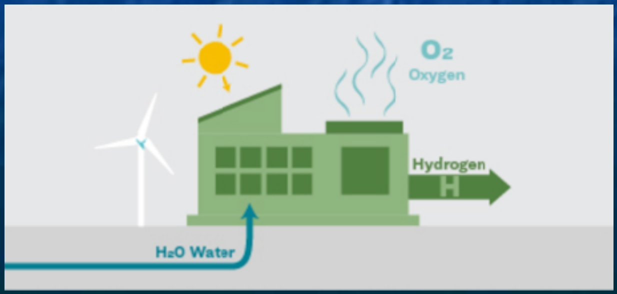
For **Electrolysis**: H_2 Energy Output / Electrical Energy Input = **64 - 68%** [6]

- Only 4% of world H_2 gas is now produced using Electrolysis [5, 6, 10]

Only **0.03%** of world H_2 gas is now produced by Electrolysis using Renewable Electricity [11]

(i.e., Electricity derived from Wind, Solar, Hydro, Biomass AND Nuclear)

ONLY THAT 0.03% of today's worldwide H_2 gas qualifies as **Green Hydrogen**



[12]

Sources cited on the previous page:

International Energy Agency (IEA:

1) https://www.iea.org/

2) https://www.iea.org/reports/the-future-of-hydrogen

3) https://www.iea.org/reports/global-hydrogen-review-2021

International Renewal Energy Agency (IRENA):

4) https://www.irena.org/

5) https://www.irena.org/Energy-Transition/Technology/Hydrogen

6) Page 20 in: https://www.irena.org/Publications/2018/Sep/Hydrogen-from-renewable-power

Addition Information about Electrolysis of Water:

7) https://en.wikipedia.org/wiki/Electrolysis_of_water

8) https://en.wikipedia.org/wiki/Alkaline_water_electrolysis

9) https://en.wikipedia.org/wiki/Proton_exchange_membrane_electrolysis

10) https://en.wikipedia.org/wiki/Electrolysis_of_water

11) Page 109 in: https://www.iea.org/reports/global-hydrogen-review-2021

Figure (from the Sierra Club):

12) https://www.sierraclub.org/articles/2022/01/hydrogen-future-clean-energy-or-false-solution

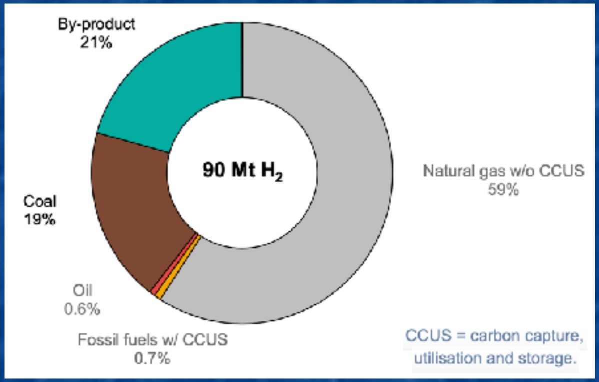
Then from where does the ***remaining 96%*** *of today's Hydrogen Gas come?*

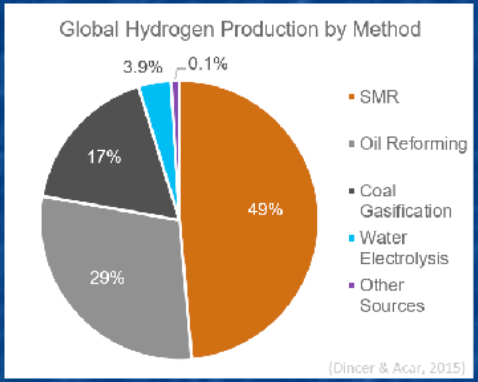
Consistent breakdowns are surprisingly hard to find:

IRENA's "Overview" states: "almost 47% of the global hydrogen production is from natural gas, 27% from coal, 22% from oil (as by-product) and only around 4% comes from electrolysis" [1]

Vs. figure from a 2020 International Energy Agency (IEA) report, at left [2]

Vs. figure from Wikipedia [3] citing publication locked behind publisher's (Elsevier) paywall, at right [4]





	IRENA:	IEA:	Wikipedia:	**Range:**
Natural Gas SMR *	47%	59.7%	49%	**47 - 59.7%**
Coal *	27%	19%	17%	**17 - 27%**
Oil Byproduct *	22%	21%	29%	**22 - 29%**
Electrolysis #	~ 4%	(~ 0%)	3.9%	**~ 0 - 4%**

* Virtually ALL w/o carbon capture

\# Virtually ALL now using non-renewable Electricity

1) https://www.irena.org/Energy-Transition/Technology/Hydrogen

2) Page 108 in: https://www.iea.org/reports/global-hydrogen-review-2021

3) https://en.wikipedia.org/wiki/Steam_reforming - citing as its source:

4) https://www.sciencedirect.com/science/article/abs/pii/S0360319914034119

Steam Methane Reforming (SMR): *~ 50-60% of today's worldwide Hydrogen Gas*

Though a U.S. DOE source states that it accounts for **95% of the United States'** H_2 gas [1, 2]

The Methane source? Gas wells, often injecting high-pressure fracking chemicals,

and sometimes burning off ("flaring") unwanted gas at the well site (as seen in left photo):

Steam Methane Reforming (SMR) plants (right photo) exploit two chemical reactions: [3]

One "reforming" methane: $CH_4 + H_2O + (206\ kJ / mol) \leftrightarrow CO + 3\ H_2$

A second "reforming" the CO byproduct: $CO + H_2O \leftrightarrow CO_2 + H_2 + (41\ kJ / mol)$

Yielding the net reaction: $CH_4 + 2\ H_2O + (165\ kJ / mol) \leftrightarrow CO_2 + 4\ H_2$

Inputs: Heat (1100 ºC) **CH_4 H_2O**

Outputs: CO_2 4 H_2

Energy balance? Approximate values in kJ/mol: [4] CH_4 (890) + Heat (165) = 1055 → 4 x H_2 (286) = 1144

SMR strips oxygen from H_2O to "burn" CH_4's carbon, thereby liberating H_2 from both CH_4 & H_2O

1) Published paper now locked behind an American Chemical Society paywall: https://pubs.acs.org/doi/pdf/10.1021/acs.est.8b06197

2) https://www.osti.gov/pages/biblio/1546962 3) https://en.wikipedia.org/wiki/Steam_reforming 4) https://en.wikipedia.org/wiki/Heat_of_combustion

Left Figure: https://www.bizjournals.com/denver/news/2020/10/29/colorado-oil-natural-gas-flaring-emissions-cogcc.html

Right Figure: https://www.hydrogenproduction-plant.com/sale-12437032-steam-methane-reforming-hydrogen-generation-plant-purity-up-to-99-999-v-v.html

Coal Gasification: *~ 20-30% of today's worldwide Hydrogen Gas*

Gasification Plants (photo at left) use different types of coal, often grouped and labled as:

Black Coal, including **bituminous**, **sub-bituminous** & **anthracite** varieties (center)

OR **Brown Coal**, the lower grade **lignite** variety derived from decayed peat (right) [2, 3]

Black Hydrogen is produced from **Black Coals** (which are richer in C), via the reactions [1]

3 C (in that coal) + O_2 + H_2O (steam) + (intense energy) $\leftrightarrow$ H_2 + 3 CO

with that CO byproduct (again) processed to yield additional H_2 via:

CO + H_2O (steam) $\leftrightarrow$ CO_2 + H_2 + (41 kJ / mol)

Brown Hydrogen is produced from **Brown Coal** (poorer in C, but richer in H_2O) that can instead be produced by slightly altered reactions from which added steam is omitted

1) https://en.wikipedia.org/wiki/Coal_gasification
Left & Center Figures: https://bettermeetsreality.com/brown-coal-vs-black-coal-comparison-differences-emissions-more/
Right Figure: https://www.phxequip.com/plant.107/coke-and-coal-gasification-plant-2-200-tpd.aspx

Liquid Petroleum Refining: *~ 20-30% of today's worldwide Hydrogen Gas*

That refining, parts of which are also called **Catalytic Reforming,** [1]

occurs in the huge worldwide complex of oil refineries [2] that feed our fossil-fuel economies:

But despite the substantial quantity of H_2 generated in such refineries,

Hydrogen Gas is a mere byproduct of processes actually

focused on the much more massive production of liquid fossil-fuels & chemicals

1) https://en.wikipedia.org/wiki/Catalytic_reforming *2) https://en.wikipedia.org/wiki/Oil_refinery*

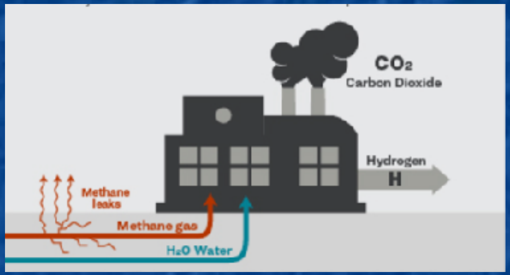
Photo source: https://creakhousenews.blogspot.com/2020/04/inside-louisianas-horrifying-cancer.html

*Summarizing the answer to: "From where do we **now** get Hydrogen Gas?"*

50-60% Steam Methane Reforming

Using: $CH_4 + H_2O \rightarrow CO_2 + H_2$

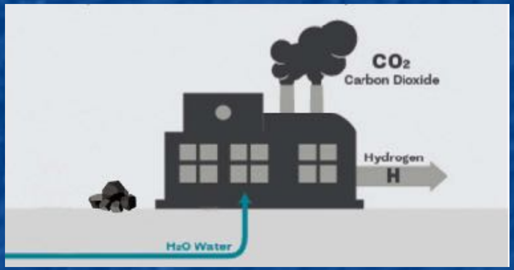
Gray Hydrogen



20-30% Coal Gasification:

Using: Coal + $O_2 + H_2O \rightarrow CO_2 + H_2$

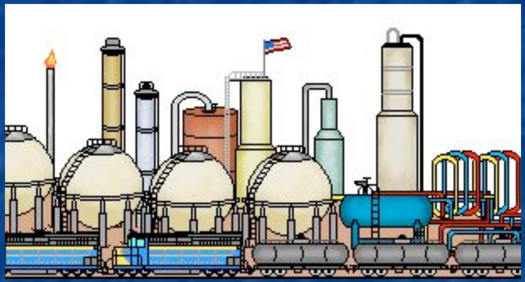
Brown or **Black Hydrogen**



20-30% Oil Refining:

Using many GHG-emitting reactions

Grayish Hydrogen



Recurring theme in all three H_2 production processes:

C bonds to O that was stripped from $H_2O \rightarrow$ GHG **CO_2** + **H_2 / H_2**

Echoing the process of fossil-fuel burning:

C bonds to O that was stripped from $O_2 \rightarrow$ GHG **CO_2**

Making all three of the H_2 processes (~ 96% of today's H_2) contributors to global warming

Left Figure: https://www.sierraclub.org/articles/2022/01/hydrogen-future-clean-energy-or-false-solution

Center Figure: My altered version of Left Figure

Right Figure: http://clipart-library.com/refinery-cliparts.html

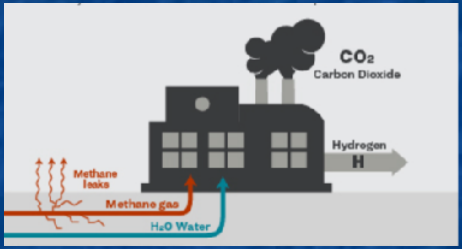
*But **Gray Hydrogen**'s dependence on Methane has an additional **hidden** impact:*

Natural Gas's ~ 75% Methane is a much more potent Greenhouse Gas than CO_2 (~ 25-30X)

Which is WHY wells sometimes burn off their excess NG, converting it into less harmful CO_2

But Natural Gas infrastructure is **massively & pervasively LEAKY**

as noted at the left of the Sierra Club's **Gray Hydrogen** illustration:



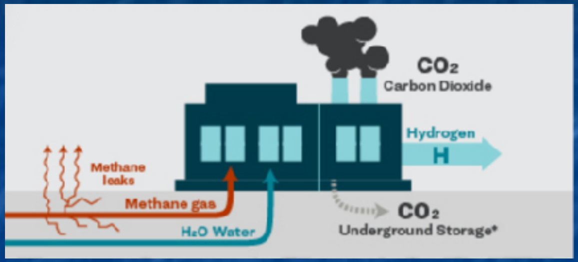
According to the **U.S. Energy Information Administration (EIA):** "Oil and gas operations worldwide emitted just over 70 Mt of methane into the atmosphere in 2020. Converted into equivalent amounts of CO_2 . . . these methane emissions are comparable to the total energy-related emissions of the European Union" [1]

As documented in this excellent TV news report originating in West Texas Oil Country (click): [2]

1) https://www.iea.org/reports/methane-tracker-2021　　*2) https://www.youtube.com/watch?v=DE1Jvc6U5gI*

"But what about **Blue Hydrogen**?"

Blue Hydrogen = Gray Hydrogen + Carbon Capture, Utilization & Storage (CCUS)



But according to a 2019 report from the **International Renewal Energy Agency (IRENA):** [1]

"Overall, less than 0.7% of current hydrogen production is from renewables or from fossil fuel plants equipped with CCUS" [2]

Meaning that **Blue Hydrogen** plays almost **ZERO** role in TODAY's hydrogen production

Making Blue Hydrogen irrelevant to the my first question:

From where do we NOW get Hydrogen Gas?

Bringing us to my second question:

1) https://www.irena.org
2) The Future of Hydrogen - IRENA 2019: https://www.iea.org/reports/the-future-of-hydrogen
Figure: https://www.sierraclub.org/articles/2022/01/hydrogen-future-clean-energy-or-false-solution

How do we now USE Hydrogen Gas?

One International Energy Administration (IEA) report broke down 2019 world use of H_2 as: [1]

33% for oil refining

27% for production of ammonia

11% for production of methanol

3% for chemical reduction of the iron ore used in steel production

But the uses of the **remaining 26%** were not enumerated

Another IEA report put 2021 world H_2 production at ~ **97 Mega tonnes (Mt)**, [2]

Its breakdown of major uses was similar to the 2019 report, but it went on to note that:

H_2 **use in road transportation had increased 60%** over the preceding year,

including a **60X** (!) increase in heavy-duty hydrogen-powered trucks

But that still brought net use in transportation to only **30 kilo tons → 0.03%** [3]

Similarly underwhelming was H_2 **use in buildings and electrical power generation,**

both of which were quickly dismissed using the same word: **"negligible"** [4, 5]

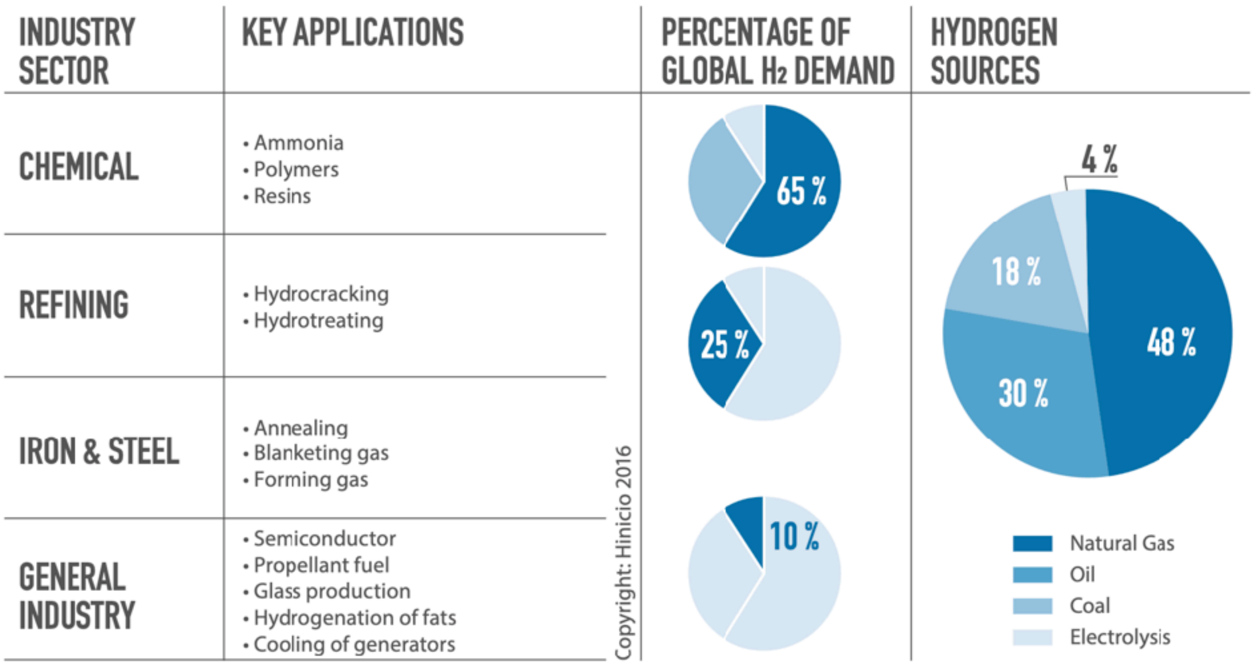
1) Page 89 in: https://www.iea.org/reports/the-future-of-hydrogen

2) Page 18 in: https://www.iea.org/reports/global-hydrogen-review-2022 3) Ibid., page 40 4) Ibid., page 57 5) Ibid., page 64

To more concisely answer the same question, IRENA offered this figure:

From the IRENA report "Hydrogen from Renewable Power:" [1]

Figure 4: Global hydrogen demand and production sources

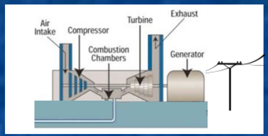


Source: IRENA based on FCH JU (2016).[3]

Which, using rounded numbers, is entirely consistent with the preceding page's IEA factoids

1) https://www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power

Meaning that right NOW Hydrogen has virtually ZERO impact on ANY of these:



But in the discussion of Hydrogen Economy Vision(s)

THESE were identified as the PRIME TARGETS for H_2 supplanting Fossil Fuels

Meaning that:

Far from being based upon an already tried, tested and now readily scalable fuel,

a "Hydrogen Economy" is still very much ONLY a Vision

(i.e., an extrapolation based upon only severely limited experience or proven technology)

*(What software engineers sometimes label **vaporware**)*

USING what we've learned about Today's Hydrogen to help define viable possibilities for

Tomorrow's Hydrogen

Perhaps the KEY thing we have learned:

Mother Nature put energy into **Fossil Fuels** allowing us to now use them as **ENERGY SOURCES**

But **WE** must put energy into creating **H_2 Gas** making it instead an **ENERGY STORAGE MEDIUM**

Which makes Hydrogen's direct competition NOT Fossil Fuels

but instead **OTHER Energy Storage Media** - most particularly: **BATTERIES**

Further, while full use of **Energy Sources** requires only **ONE** process - For Fossil Fuels:

Energy Release during Consumption via Combustion:

$CX + O_2 \rightarrow CO_2 + Energy_{output}$ + **Byproducts** (made up of C + O + constituents of X)

Full use of **Energy Storage Media** involves **TWO** linked processes - In one Hydrogen scenario:

Energy Investment during Synthesis via SMR:

$2\ HX + Y + Energy_{input} \rightarrow H_2$ + **Byproducts** (made up H + constituents of X & Y)

Energy Return during Consumption via Combustion:

$H_2 + 1/2\ O_2 \rightarrow H_2O + Energy_{output}$ where $Energy_{output} < Energy_{input}$ (often MUCH less)

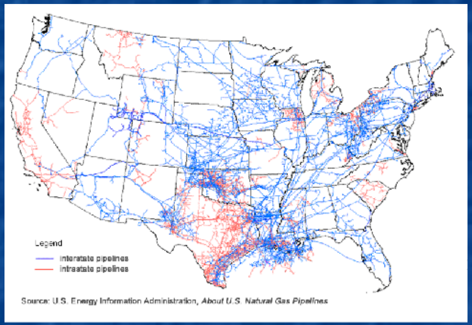
Those distinctions mean that:

While an ENERGY SOURCE's key figure of merit is **$\text{Energy}_{\text{output}}$**

An ENERGY STORAGE MEDIUM's key figure of merit is **$\text{Energy}_{\text{efficiency}}$ = $\text{Energy}_{\text{output}}$ / $\text{Energy}_{\text{input}}$**

Also very important are its: **Energy Density per Mass** and **Energy Density per Volume**

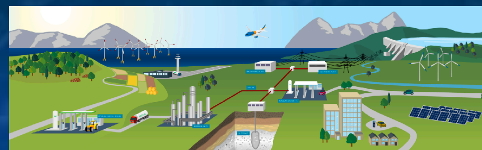
Because high **Energy Density per Volume** makes it much more effective in these:



And because high **Energy Density per Mass** is absolutely IMPERATIVE in these:

Which Process Pairings would optimize H_2 as an Energy Storage Medium?

Here Environmentalist & Petrochemical / Energy Industry **Vision(s) begin to radically diverge**



vs.

The Climate Driven Choice is to focus strongly on the use of:

1) **Electrolysis** powered by Green Electricity to produce Green Hydrogen

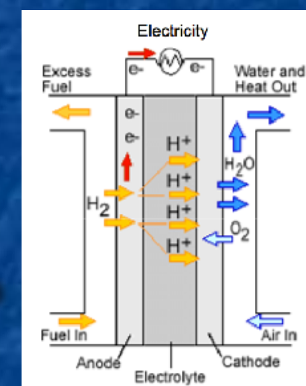
which, we learned earlier, uses exotic materials such as Platinum, Titanium and Gold

Yielding: **H_2 Energy$_{out}$ / Electrical Energy$_{in}$** = **64 - 68% ~ 66%** [1]

2) **Fuel Cells** consuming that Green Hydrogen to return Green Electricity

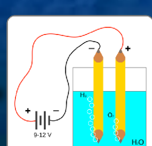
These based on similar but reversed electrochemical reactions

Yielding: **Electrical Energy$_{out}$ / H_2 Energy$_{in}$** of = **40 - 60% ~ 50%** [2, 3]



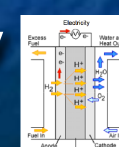
Combined they yield a **Cumulative Energy Efficiency** of (64-68%) x (40-60%):

Electricity →



"Round Trip" Electrolysis to Fuel Cell Energy Efficiency

Electricity$_{out}$ / Electricity$_{in}$ = 26 - 41% ~ 33%



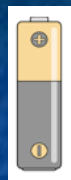
→ ***Electricity***

1) Page 20 in: https://www.irena.org/Publications/2018/Sep/Hydrogen-from-renewable-power
2) https://en.wikipedia.org/wiki/Fuel_cell
3) https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

But for storing electricity, Li Batteries are much more energy efficient:

Li Batteries use a **SINGLE TECHNOLOGY** (running first one way and then the other) to produce:

Electricity →



"Round Trip" Battery in / Battery out Energy Efficiency

$Electricity_{out}$ / $Electricity_{in}$ = 83 - 93% ~ 88% [1-3]

→ **Electricity**

Making the paring of Electrolysis & Fuel Cells only ~ 44% as energy efficient as Batteries alone

Then, in electric cars ~ 75% of Electricity Storage Medium's Energy is delivered to the vehicle's wheels: [4]

Battery Electric Vehicle: $Electricity\ Energy_{in}$ / $Wheel\ Energy_{out}$: (75%)(88%) ~ **66%**

Electrolysis / Fuel Cell Vehicle: $Electricity\ Energy_{in}$ / $Wheel\ Energy_{out}$: (75%)(33%) ~ **25%**

What if Electrolytic H_2 were instead burned in a car's internal combustion (IC) engine?

Taking into account that earlier Electrolytic synthesis of H_2 was only ~ 66% energy efficient

But assuming Internal Combustion engines burn Fossil Fuels or H_2 with same energy efficiency,

then deliver energy thru transmission & drivetrain to wheels with same 13-20% efficiency: [4]

Fossil Fueled IC Vehicle: $Wheel\ Energy_{out}$ / $Fuel\ Energy_{in}$ ~ 13-20%

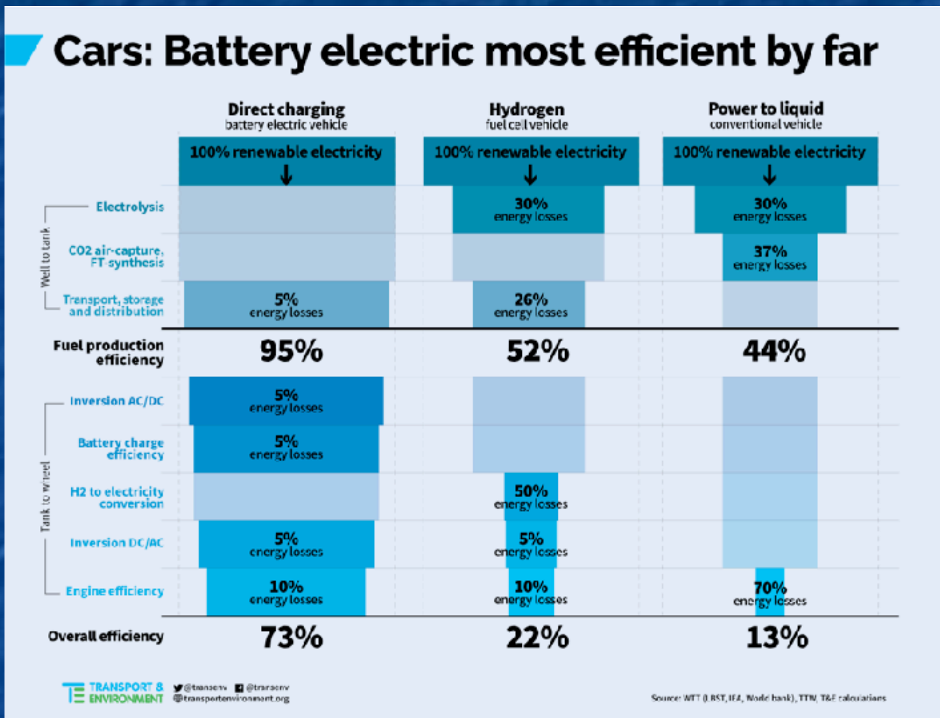
Electrolytic H_2 fueled IC Vehicle: $Wheel\ Energy_{out}$ / $Electricity\ Energy_{in}$ = (66%)(13-20%) ~ 7-13%

1) https://atb.nrel.gov/electricity/2022/commercial_battery_storage 2) https://en.wikipedia.org/wiki/Comparison_of_commercial_battery_types
3) https://www.irena.org/-/media/Files/IRENA/Agency/Events/2017/Mar/15/2017_Kairies_Battery_Cost_and_Performance_01.pdf
*4) For a more comprehensive discussion, see my noteset: **Green(er) Cars & Trucks** (pptx / pdf / key)*

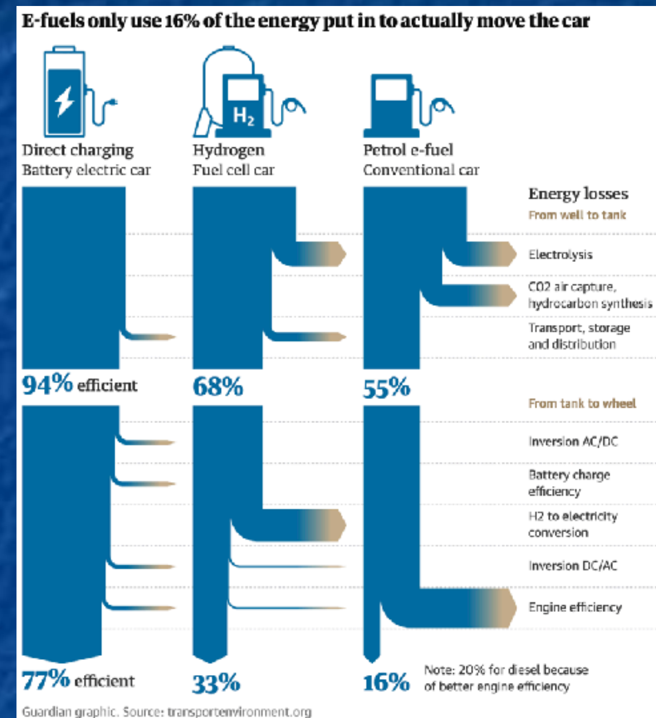
A variety of reports, drawing on other data sources, reach near identical conclusions:

Including even more damning numbers for synthetic fuel / "e-fuel" vehicles (at right of their figures):

From a 2020 **CleanTechnica** article [1]



From a 2023 **Guardian** article [2]



Plus a 2021 report in the business publication Forbes (cited early in this noteset) estimating:

73% for Battery Electric Vehicles (BEVs) vs. **23%** for Fuel Cell Electric Vehicles (FCEVs) [3]

(My BEV result was smaller because I used studies giving 83-93% Battery Round Trip Energy Efficiency vs. the 95 & 94% above)

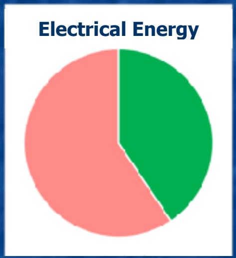
1) https://cleantechnica.com/2020/06/10/this-stunning-chart-shows-why-battery-electric-vehicles-win/
2) https://www.theguardian.com/business/2023/may/05/e-fuels-cars-aviation
3) https://www.forbes.com/sites/jamesmorris/2021/02/06/why-are-we-still-talking-about-hydrogen/?sh=620907267f04

*But **ANY FORM** of complete Electrification **will require VASTLY more Electricity:***

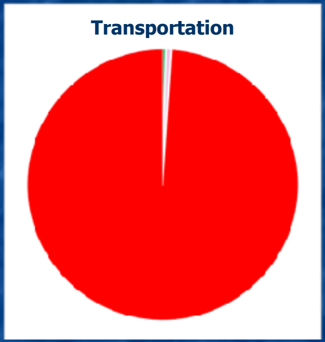
These charts (with areas scaled in proportion to energies represented) depict: [1, 2]

2021 U.S. **Electrical Energy Supply** (Pink = GHG-linked / Green = Non-GHG linked)

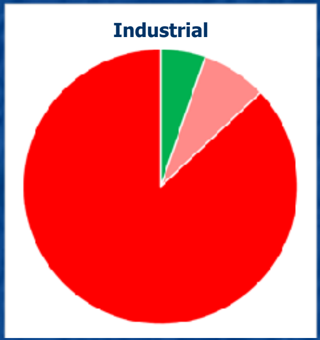
2021 U.S. **Total Energy Consumption** by category (Red = GHG-linked Non-Electrical)



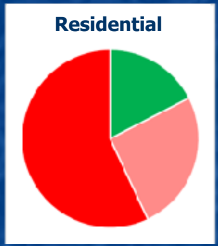
3.78 QW-h



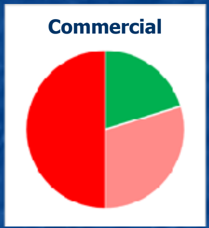
7.88 QW-h



7.59 QW-h



3.39 QW-h



2.67 QW-h

From which, in my noteset **U.S. Energy Production and Consumption,** I calculated that: [1]

Eliminating GHG-Electricity ALONE would require **2.5X** more Green Electricity

Also eliminating other GHG-linked Energy Consumption would require **7-12X** Green Electricity!

*1) **U.S. Energy Production and Consumption** (pptx / pdf / key)* *2) Q = Quadrillion = 10^{15} = 1,000,000,000,000,000*

To stimulate such a VAST expansion of U.S. clean Electrical Power Capacity . . .

A Biden Administration-proposed, Congressionally-approved, but not yet implemented

45V Tax Plan **LINKS** H_2 R&D and infrastructure tax credits to three requirements:

1) Hydrogen plants must be powered by NEW clean electrical power plants (wind, solar, hydro . . .)

2) Hydrogen plants must be located close to those NEW clean electricity plants

Eliminating need for long-distance High Voltage DC electrical transmission lines

3) Hydrogen plant output must follow the natural generation cycles of the coupled electricity plants

E.G., if coupled to only new local solar + wind power plants, Electrolytic H_2 production would typically ramp up with the rising sun, and fall with the diminishing evening winds

This **45V Tax Plan**, implemented WITH those requirements stimulated these earlier headlines:

"Get Tax Right or Clean Hydrogen will be a Bigger Boondoggle than Biofuels" - Washington Post [7]

"Before We Invest Billions in this Clean Fuel, Let's Make Sure It's Actually Clean" - New York Times [8]

"Green Hydrogen Or Dirty Fuel? . . . Tax Credit Will Determine Industry's Future" - Forbes [9]

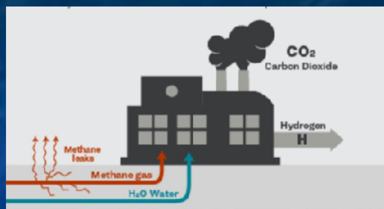
7) https://www.washingtonpost.com/opinions/2023/04/27/clean-hydrogen-tax-credit-stringent-rules/

8) https://www.nytimes.com/2023/04/14/opinion/hydrogen-fuel-tax-credit-climate-change.html?searchResultPosition=2

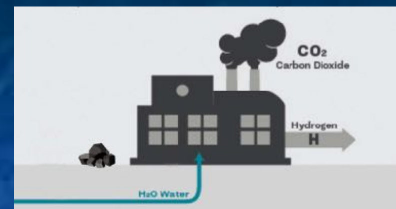
9) https://www.forbes.com/sites/energyinnovation/2023/04/17/green-hydro...s-on-45v-tax-credit-will-determine-industrys-future/?sh=34ced0ffd226

***WITH** those requirements, few if any existing U.S. H_2 plants could qualify*

Not 50-60% using Steam Methane Reforming



Not 20-30% using Coal Gasification:



Not 20-30% using Oil Refining:

The strongest candidates for a share of the multi-billion-dollar 45V Tax Plan credits are instead:

The ~ 1% of plants now using H_2 Electrolysis powered by green electricity

The ~ 3% of plants now using H_2 Electrolysis powered by NON-green electricity

Though both could qualify ONLY if their existing or new green electricity suppliers were local

Which has led to massive Petrochemical / Energy Industry pushback & lobbying

Up to and apparently including the formation of the aforementioned Clean Hydrogen Future Council

Which was founded in 2021, exactly as the 45V Tax Plan was being formulated

Unlike the Hydrogen Fuel Cell Partnership, Hydrogen Council & Fuel Cell and Hydrogen Energy Assoc.

which have all released lengthy Vision or Roadmap statements:

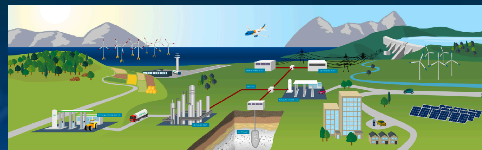
The Clean Hydrogen Future Coalition (CHFC) has published only a short position statement

entirely concerned with ways in which **all three** 45V Tax Plan eligibility requirements

could be relaxed to **benefit the remaining 96% of existing GHG-linked H_2 suppliers** [1]

1) https://cleanh2.org/wp-content/uploads/CHFC-Position-Statement-on-use-of-RECs-for-45V-Implementation-April-2023.pdf

Brushing aside the GHFC's tax-lobbying, what ELSE is industry arguing for?

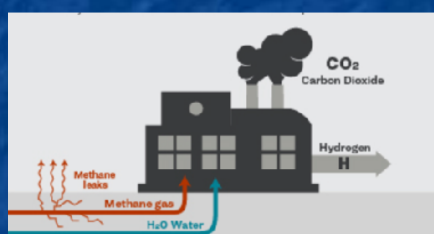


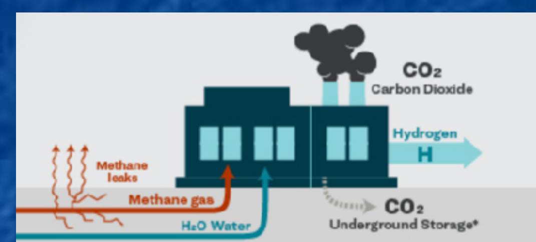
vs.

Their visions of a Hydrogen Economy are NOT based on green-electricity-driven Electrolytic H_2

They instead envisage continued reliance on Steam Methane Reforming which, it must be acknowledged, DOES NOT require VAST Green-Electricity expansion

But rather than just maintaining "business as usual," under which existing SMR plants would continue to release massive amounts of Greenhouse Gas CO_2, they foresee a shift from **Gray Hydrogen** SMR plants to **Blue Hydrogen** SMR Plants





Which differ only in adding **Carbon Capture, Utilization and Sequestration (CCUS)**

(or as it was promoted in the last decade's arguments for coal-powered electricity, just CCS)

A three page review of why Carbon Capture is desirable: [1]

Our garden greenhouses become warmer because,

while their glass ceilings pass sunlight of all visible colors,

inside those greenhouses that absorbed **visible light** (VIS) begins to warm things

causing them to emit increasing amounts of invisible **infrared light** (IR)

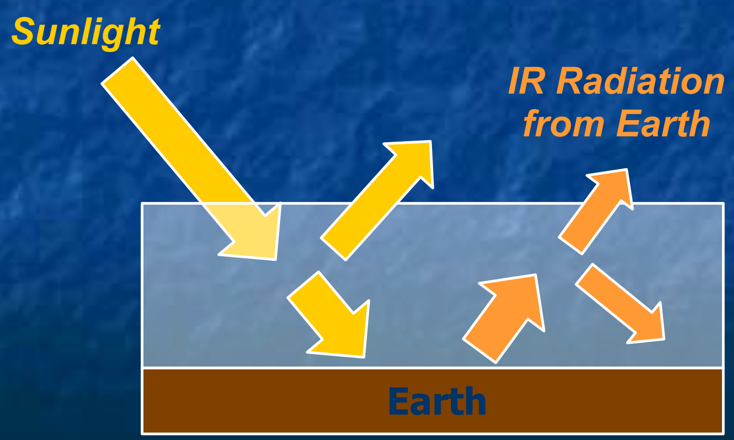
most of which CANNOT pass back through glass and is thus trapped inside

CO_2 and CH_4 are labeled Greenhouse Gases (GHG's) because in our atmosphere

they mimic greenhouse glass by interacting / interfering very little with **visible light**'s passage

while absorbing **infrared light** trying to come back up from the ground

And even if they DO re-emit that IR, much of it is sent Back down to the ground:



1) For a more complete discussion, see my noteset: ***Greenhouse Effect, Carbon Footprint & Sequestration*** *(pptx / pdf / key)*

So to be a Greenhouse Gas, that gas must strongly absorb / emit Infrared Light

Perhaps surprisingly, the DOMINANT GHG in the Earth's atmosphere is **WATER VAPOR**

It is water vapor's GHG action that kept our planet from becoming a frozen (Mars-like) rock,

letting it instead climb to temperatures hospitable to living organisms such as ourselves

Adding a new gas that absorbs / emits **SIMILAR infrared colors** makes very little difference

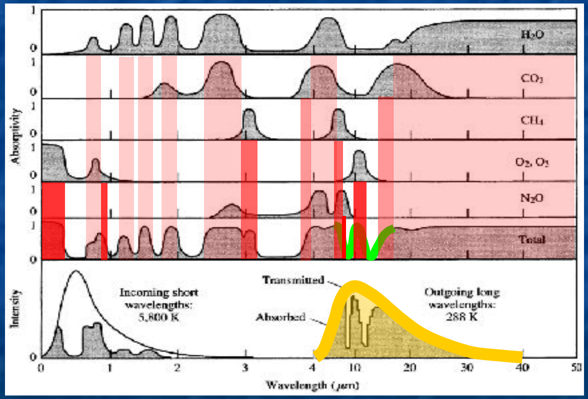
because its added effect is swamped by water vapor's already much stronger effect

But adding a new gas that absorbs / emits **DIFFERENT infrared colors** makes a lot of difference

because it is as if the slight cooling effect of a previously open **small greenhouse window**

is suddenly lost after that small window is closed, heating the Greenhouse even further

Which is why my more COMPLETE examination of the Greenhouse Effect quickly devolved into a complex examination of gases' absorption in both the infrared and solar visible light ranges: [1]



CO_2 and CH_4 are among the WORST ACTORS at closing down our atmosphere's windows!

1) For a more complete discussion, see my noteset: ***Greenhouse Effect, Carbon Footprint & Sequestration*** *(pptx / pdf / key)*

CO_2 & CH_4 concentrations are thus extremely important - but so is their persistence:

By this I mean how long (on average) a Greenhouse Gas molecule **stays** in the atmosphere

before being **converted** into something else (which may or may not also be a GHG)

or **removed** from the atmosphere (by photosynthesizing plants, absorbing oceans, etc.)

To reverse Global Warming we must not only STOP ADDING new GHG's to the atmosphere

Which is the goal of so-called **Net Zero** / **Carbon Neutrality** initiatives [1]

We must also lower EXISTING record-breaking GHG levels

But while inventors now dream of our pulling GHGs right out of the atmosphere,

a practical, literally worldwide process is still far, far beyond our reach

So we must WAIT for natural processes to pull today's GHGs out of the atmosphere,

and while we are waiting, sequester (i.e., hold) any newly manufactured GHG's

And how LONG must we wait while sequestering any new GHG's?

For about as long as today's GHG's persist

Here CO_2 is again one of the worst actors, persisting for CENTURIES [2]

1) https://en.wikipedia.org/wiki/Carbon_neutrality

2) See for example the EPA's Overview of Greenhouse Gases: :https://www.epa.gov/ghgemissions/overview-greenhouse-gases

So we must not only CAPTURE but then HOLD any new GHG's for CENTURIES

In the twenty-teens supporters of coal-powered electrical power insisted that

coal's atmospheric damage could be eliminated by Carbon Capture & Sequestration (CCS),

to be accomplished by pumping the CO_2 down into abandoned gas and oil wells

For which there turned out to be (at least) three major problems:

1) Analyses indicating CCS would add at least 50% to the cost of coal-based electricity

which was **already** the most expensive large source of U.S. electrical power [1]

2) The resulting fact that virtually no one would build a full-scale CCS-equipped coal plant

3) Skepticism that "**Pumping CO_2 down a hole and then walking away**"

could actually work for the centuries required to curtail global warming

Skepticism was fueled by the petrochemical industry's long history of gas and oil leaks

ESPECIALLY from abandoned / disused wells

As graphically described in the earlier video:

Skepticism was then validated by the petrochemical industry's 2015-2016 demonstration:

1) *See my noteset:* ***Power Plant Economics: Analysis Techniques & Data*** (pptx / pdf / key)

The massive 111 day leak from the Porter Ranch / Aliso Canyon Natural Gas storage plant:

Timeline and public impacts as reported by television station KCAL 9 - CBS LA (click to play): [1]

1) https://www.youtube.com/watch?v=EdGIpKi-A_E

The long list of NG storage plant flaws cited in the official California report:

From a **Root Cause Analysis** ordered by the California Public Utilities Commission (CPUC) and Department of Conservation's Division of Oil, Gas & Geothermal Resources (DOGGR): [1, 2]

*1) CPUC & DOGGR announcement of Root Cause Analysis to be performed by **Blade Energy Partners**:*
https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M292/K947/292947433.PDF
2) Video summary of that study released by Blade Energy Partners: https://www.youtube.com/watch?v=Z3D1DvqBcgU

A decade later, CCUS is now proposed to clean up SMR production of H_2

CCUS adds a "U" to CCS yielding: Carbon Capture, **Utilization** and Sequestration

This rebranding is an obvious effort to distance such proposals from earlier failures

Nevertheless, addition of "Utilization" **could** have major real world significance:

Gas molecules are really good at slithering out of even well-built containers [1]

Holes in the dirt are NOT well-built containers & over centuries they're miserable containers [2]

But **IF** "Utilization" converts CO_2 gas into **stable weather-resistant solids,** CCUS **might** just work

Do proposed CCUS techniques include viable means of stably solidifying carbon?

If yes: Can use of those CCUS techs grow fast enough to blunt climate change?

For answers, I first identified nominally unbiased reports about projected CCUS capabilities:

As offered by **Wikipedia**, [3] two **International Energy Agency** (IEA) reports, [4, 5]

a **McKinsey & Co**. study [6] and the U.S. **Government Accountability Office** (GAO) [7]

Which then needed to be measured against data on the levels of human GHG generation:

As provided by both the **International Energy Agency** (IEA) [8] and **OurWorldinData.org** [9]

1) Speaking from an entire scientific career spent managing gases
2) Speaking from a childhood spent above the San Andreas Fault
3) https://en.wikipedia.org/wiki/Carbon_capture_and_utilization
4) https://www.iea.org/reports/about-ccus
5) https://www.iea.org/reports/carbon-capture-utilisation-and-storage-2
6) https://www.mckinsey.com/industries/oil-and-gas/our-insights/scaling-the-ccus-industry-to-achieve-net-zero-emissions
7) https://www.gao.gov/products/gao-22-105274
8) https://www.iea.org/reports/co2-emissions-in-2022
9) https://ourworldindata.org/co2-emissions

I was immediately struck by those source's lack of interest in Sequestration

Particularly in the Wikipeida write-up (which even omitted "Sequestration" from its title), [3]

but also in the two International Energy Agency papers [4, 5]

Their strong focus was instead on **resource & economic opportunities** offered by **CCU (w/o the S)**

Specifically, CCU was seen as a potential source of carbon fuels and feedstocks

that would sidestep the need for new fossil-fuel sources

Which would be done by recycling the CO_2 combustion product of past Fossil Fuel burning

back into new carbon, available for new fuels and new feedstocks

This **would** address concerns that we are in danger of running out of new Fossil Fuels

and/or (at least eventually) might even become a cheaper way of acquiring new carbon

But Wikipedia placed **no emphasis on the CCU applications offering longer-lived Utilization**

Further, it argued (with minimal support) that CCU could produce lower GHG emissions

than today's direct petrochemical synthesis of Fossil fuels and feedstocks

Despite noting that breaking captured CO_2 back apart into usable carbon will require

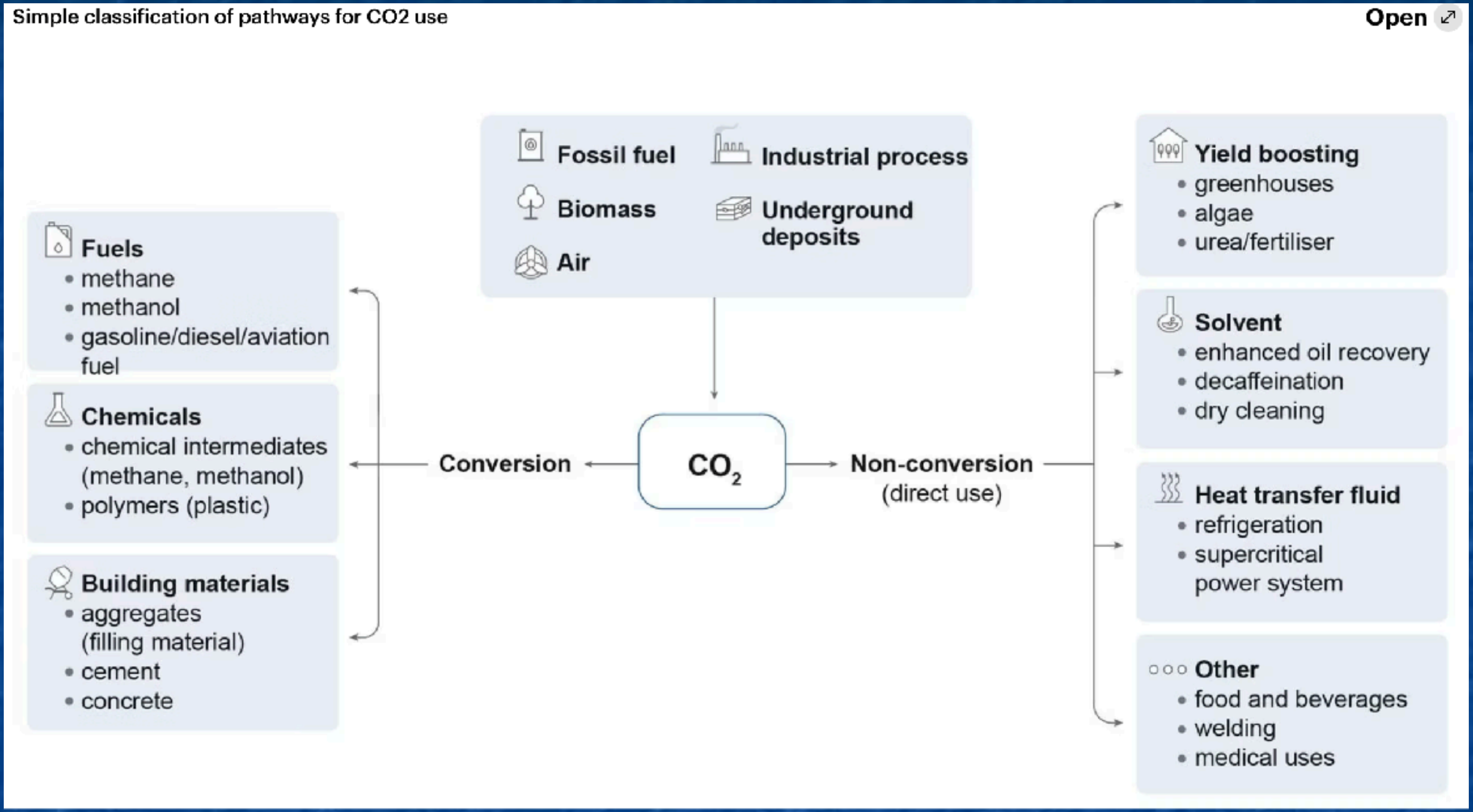
intense energy input - which (today) implies comparably large **additional GHG releases**

3) https://en.wikipedia.org/wiki/Carbon_capture_and_utilization

4) https://www.iea.org/reports/about-ccus   *5) https://www.iea.org/reports/carbon-capture-utilisation-and-storage-2*

The IEA described Capture & Utilization in even greater detail [4, 5]

Using this summary figure in one report (with a title downgrading "Utilization" into mere "Use"): [4]



But outdoing Wikipedia, these two IEA reports **did not even mention** which of these uses would delay GHG atmospheric re-emission for the longest periods of time!

4) https://www.iea.org/reports/about-ccus

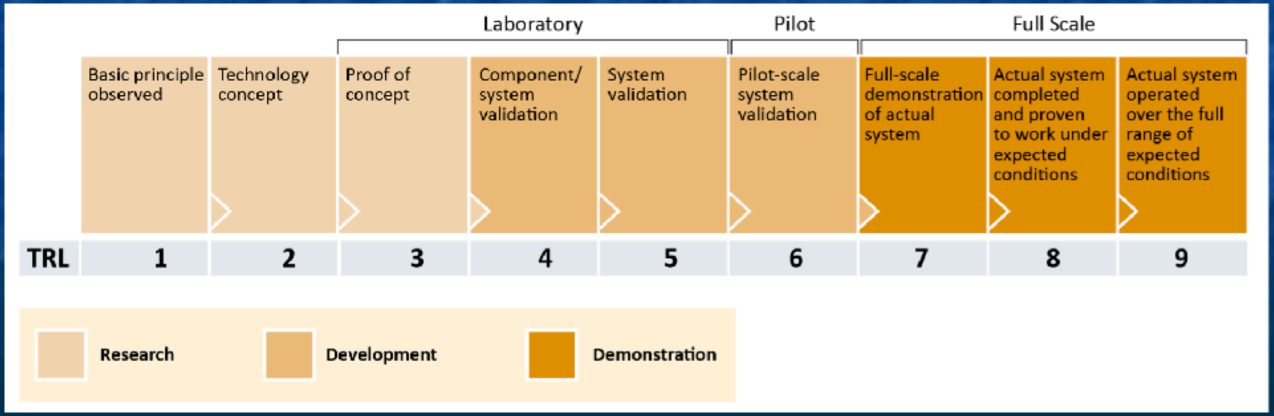
5) https://www.iea.org/reports/carbon-capture-utilisation-and-storage-2

ONLY the GAO confronted the need to Utilize or Sequester carbon for CENTURIES

After listing possible roles for CCUS, the GAO immediately responded with the statement: [7]

> **"In all of these roles for CCUS, the amount of CO_2 reduced or removed will depend on what happens to the captured CO_2. Geologic storage is generally considered permanent (millions of years), as is conversion into certain products, such as concrete.**
>
> **Other CO_2 utilization products only retain CO_2 for amounts of time that may be short (days to years) or moderate (decades to centuries), after which the CO_2 is released to the atmosphere"**

For CCUS techniques, the GAO then defined a scale of **Technology Readiness Level (TRL)**:



7) https://www.gao.gov/products/gao-22-105274

The GAO then proceeded through a detailed analysis of CCUS technologies

Summarized here by CCUS "pathway" groups:

Within each pathway, technologies were next scored based on answers to 4 critical questions:

- **Is cost lower than conventional tech?**
- **Is CO_2 retained for > 100 years?**
- **Could it capture > 1000 Mt CO_2 by 2050?** [1]
- **Is its Technology Readiness Level > 8?**

From which they identified the leading prospects:

Table 8: Comparison of selected carbon dioxide (CO_2)-based products

Product category	Is the cost to produce the CO_2-based product currently less than the selling price of conventional?	Is CO_2 retained for >100 years?	Could CO_2 utilization potential be >1000 million metric tons by 2050?	Is the maximum TRL ≥ 8?
Synthetic mineral aggregates	X	✓	–	✓
CO_2-cured concrete	✓	✓	✓	✓
Commodity chemicals (methanol)	X	X	X	✓
Fuels	X	X	✓	✓
Polymers	✓	—	X	✓

Legend: ✓ = yes, X = no, — = studies are inconsistent

"Check" = Yes **"X" = No** **" -" = Maybe**

Table 7: Summary of selected carbon dioxide (CO_2) conversion pathways

Conversion pathway	What it can make	Strengths	Limitations	Status
Mineral carbonation	Mineral aggregates, cured concrete	Permanent CO_2 storage Low energy requirements Can directly use CO_2 waste gas streams	Slow reaction rate Needs careful control of reaction conditions, e.g., pH and water content	Early stages of commercialization to fully commercialized
Hydrogenation	Fuels (e.g., methane, diesel, gasoline, aviation fuel); commodity chemicals (e.g., methanol, ethanol, formic acid)	Produces a large array of products with large market potentials High product yield	Energy intensive; needs low-carbon energy and clean hydrogen to achieve net CO_2 reduction Short CO_2 retention time in products	Methanol and methane are commercialized, many other applications are pilot scale to early stages of commercialization
Electrochemistry	Carbon monoxide, syngas, methanol, formic acid	Produces a large array of products Cost-effective carbon monoxide production	Energy intensive; needs low-carbon energy to achieve net CO_2 reduction Short CO_2 retention time in products	Research phase to early stages of commercialization
Co-polymerization	Polycarbonates, polyols	Moderate CO_2 retention time in products Moderate energy requirements High value materials	Still relies on fossil fuel-based feedstocks Polyol production is small scale compared to conventional More research needed for other polymer types	Fully commercialized
Microbial conversion	Photosynthetic microbes (e.g., algae) can make biofuel, animal feed, nutraceuticals Nonphotosynthetic microbes (e.g., bacteria) can make ethanol, isopropanol, acetone, methane	Photosynthetic microbes can produce high-value products Both microbe types can directly use CO_2 waste gas streams	Photosynthetic: Resource-intensive cultivation and processing Nonphotosynthetic: Needs hydrogen for more carbon-efficient reactions, oxygen can be toxic to some microbes	Some photo-synthetic microbe products and nonphotosynthetic ethanol production are fully commercialized; otherwise, production is research phase to pilot scale

*1) To ensure climate change impact, I assume this means 1000 Mt of **ANNUAL** CO_2 capture by 2050, not cumulative capture by 2050*

Based on those four questions, the three high-scoring prospects were:

CO_2 Cured Concrete - Already satisfying 4 out of 4 criteria

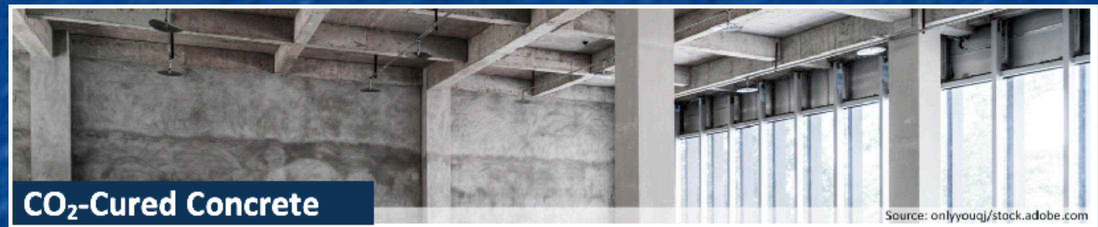
Synthetic Mineral Aggregates & **Polymers** - Maybe satisfying 3 of 4 (and eventually 4 of 4?)

For those three leading prospects, the GAO summarized their analyses of each as follows:

CO_2-Cured Concrete (4 out of 4):

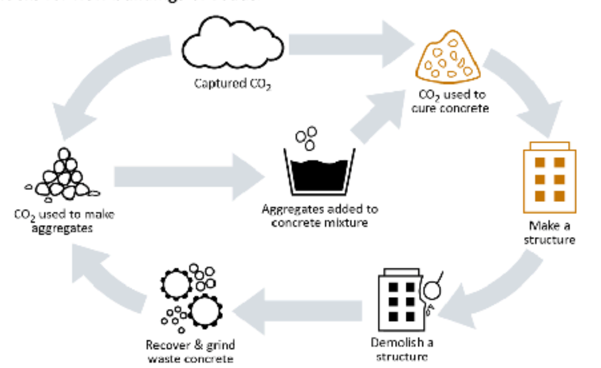
Reading as if liquid concrete is just foamed via injection of GHG gases, which are then trapped as the concrete solidifies into shapes such as blocks, bricks, pavers . . .

But other sources clarify that the key process feature is carefully controlling both pressure and temperature during solidification ("curing") which then leads to the injected CO_2's carbon being incorporated into thermodynamically stable solid calcium carbonate compounds *



CO_2-cured concrete retains CO_2 for millions of years and may be price competitive with conventional concrete. Concrete is a mixture of aggregates, cement, and water. The curing process converts cement into interlocking crystals which bind the elements of concrete together. Though CO_2 can be mixed directly with traditional cements in a concrete mixer, fully CO_2-cured concrete uses non-traditional cements that are cured in CO_2 chambers as precast concrete blocks. This process can use flue gas directly, which simplifies both carbon capture and utilization. Furthermore, some demonstrations have shown that CO_2-cured concrete is stronger than traditional concrete.

According to trade groups, a circular economy for concrete is a key step towards CO_2 emissions reduction in the building industry. For example, CO_2 captured from cement manufacturing facilities could cure precast concrete blocks for new buildings or roads.



Challenges

- Usually uses nontraditional cements, which may not be allowed under current prescriptive building standards.
- Fully CO_2-cured concrete is currently only available as precast concrete products, which is a small portion of the global concrete market (approximately 30 percent).
- Quantification of CO_2 benefits for CO_2-cured concrete is difficult, and independent life cycle assessments have not confirmed that it results in an overall net reduction in emissions.

** See for instance: https://theconstructor.org/concrete/curing-concrete-carbon-dioxide/39587/*

Continuing:

Synthetic Mineral Aggregates (3 out of 4):

Here, instead of driving carbon to bind with solidifying concrete, it is driven to react with already solid "aggregates" (i.e., small stones) of either natural rocks or waste solids.

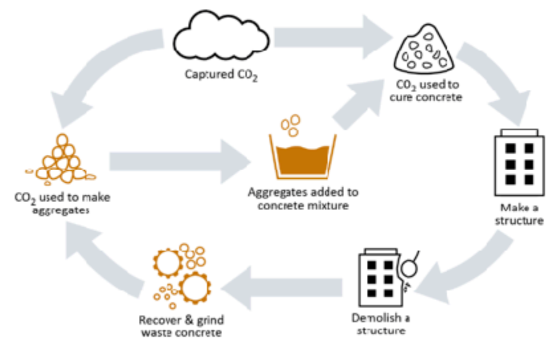
Desirably, those waste solids could include fly ash (from coal burning), slag (from steel making) & dust (from cement making) which could then be used as the aggregates that must be added to cement to make concrete or tars to make asphalt

Synthetic Mineral Aggregates

Source: JENOCHE/stock.adobe.com

Synthetic mineral aggregates—human-made versions of natural materials such as chalk or limestone— could provide a revenue generating way to store large quantities of CO_2 for millions of years. Most mineral aggregates currently come from mines, and a recent scientific article estimated that the global annual market was 45 billion metric tons in 2020. One primary use is in concrete, which is 60 to 80 percent mineral aggregate. Synthetic aggregates are made by mineral carbonation and can provide essentially permanent storage of CO_2 from either flue gas or pure CO_2 streams. They can also serve as disposal for other industrial wastes, such as fly ash, steel slag, and cement kiln dust.

According to trade groups, a circular economy for concrete is a key step towards CO_2 emissions reduction in the building industry. For example, CO_2 captured from cement manufacturing facilities could create synthetic aggregates or could recarbonate concrete waste for recycled aggregates.



Challenges

- Availability of the waste materials currently used as feedstocks, such as fly ash or steel slag, may decline if levels of coal mining, coal-fired power generation, or primary steel production decrease.
- May not be cost-competitive with mined or recycled aggregates.
- May not always mitigate more CO_2 emissions than other aggregate types. For example, CO_2 emissions from transporting synthetic aggregates to a construction site might be higher than CO_2 emissions from producing recycled aggregates from construction waste.

Polymers (3 out of 4) - a.k.a. plastic & rubber

Problematic in that, while they can incorporate GHG carbon, their natural deterioration could re-release it too quickly (< 100 years) thereby ALSO contributing to our growing problems with micro-plastic ocean (and land?) pollution

Polymers

Source: ink drop/stock.adobe.com

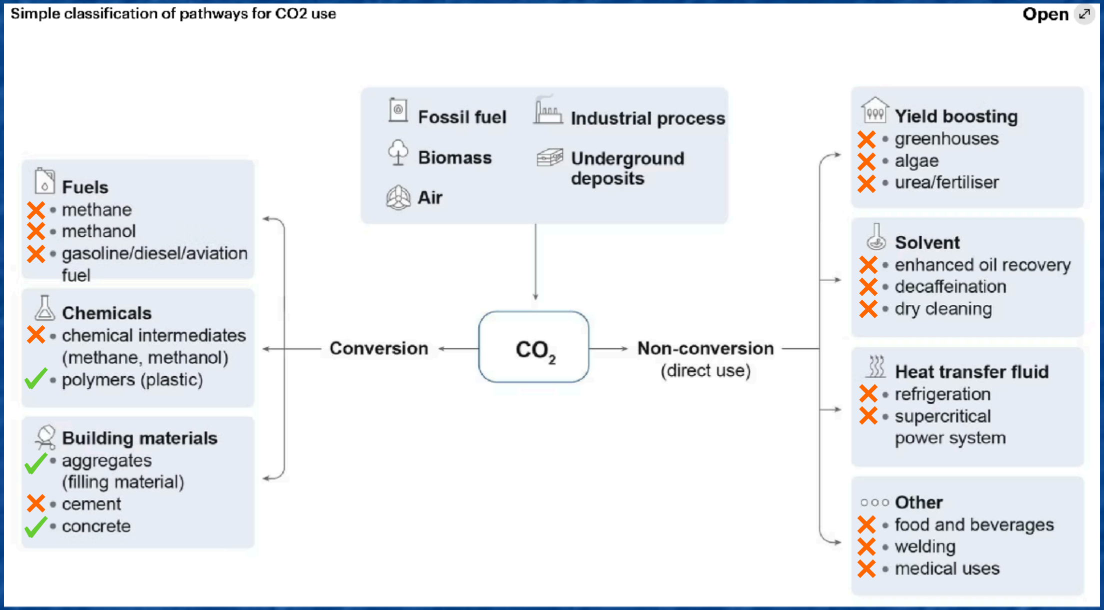
CO_2-based polymers are at commercial scale, cost less to make than the selling price of conventional, and can retain CO_2 for tens to hundreds of years. Polymers are the basis of many modern materials, including plastics, foams, and resins. For polymers such as polyols and polycarbonates, it is possible to replace some fossil fuel-based feedstock with CO_2 during manufacture. CO_2-based polyols are currently used in the production of polyurethane, which in turn is used to make products such as foam mattresses, low-impact sports floors, and foams for cars. CO_2-based polycarbonate production is also safer than conventional polycarbonate production because it avoids the use of a toxic chemical.

Yielding only three possibly viable ***Utilization*** *candidates (one with major downsides)*

Thus, returning to the first of my two earlier CCUS questions:

"Do proposed CCUS techniques include viable means of stably solidifying carbon?"

The answer appears to be **"Yes, but only for 2-3 out of dozens of suggested technologies"**



As seen above in my added GAO scoring of the earlier IEA figure about Utilization technologies

So the citizen editors of Wikipedia's CCU page got it right - listings such as this **actually** describe:

Economically relevant Carbon Capture & Utilization (CCU) - But NOT more challenging

Climate relevant Carbon Capture, Utilization and SUSTAINED Sequestration

for which I will now coin and carefully use the distinguishing acronym: **CCUSS**

Can use of these CCUSS techs grow fast enough to blunt climate change?

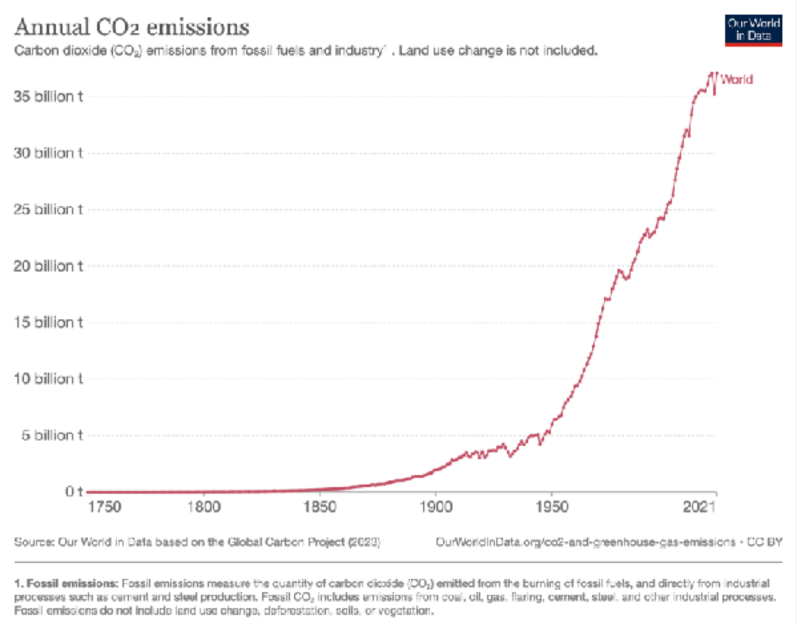
To blunt climate change we must eliminate - or at least slash - human GHG emissions:

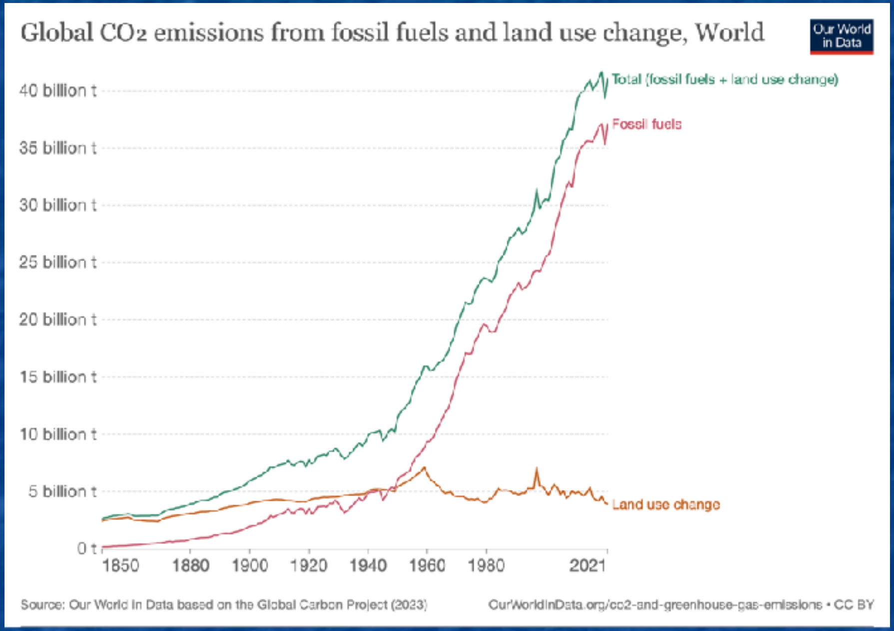
Which according to multiple sources have followed this historical trend: [8, 9]

Direct Human GHG Emissions

Effective Human GHG Emissions

(including human land-use effects such as elimination of wetlands and deforestation)





Meaning that, barring other dramatic and thus far absent reductions in CO_2 emissions,

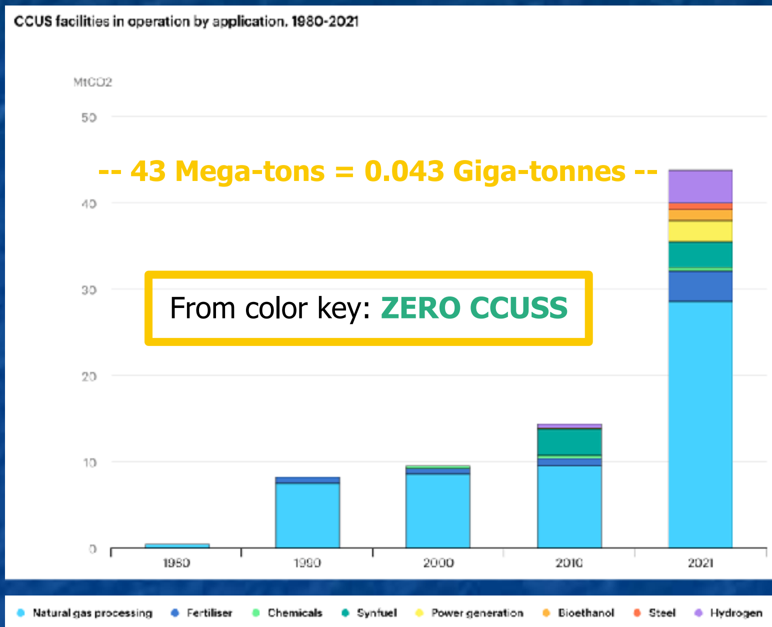
CCUSS would have to capture (or slash) ~ 40 billion t (40 Giga tonnes) of CO_2 per year

8) https://www.iea.org/reports/co2-emissions-in-2022 *9) https://ourworldindata.org/co2-emissions*

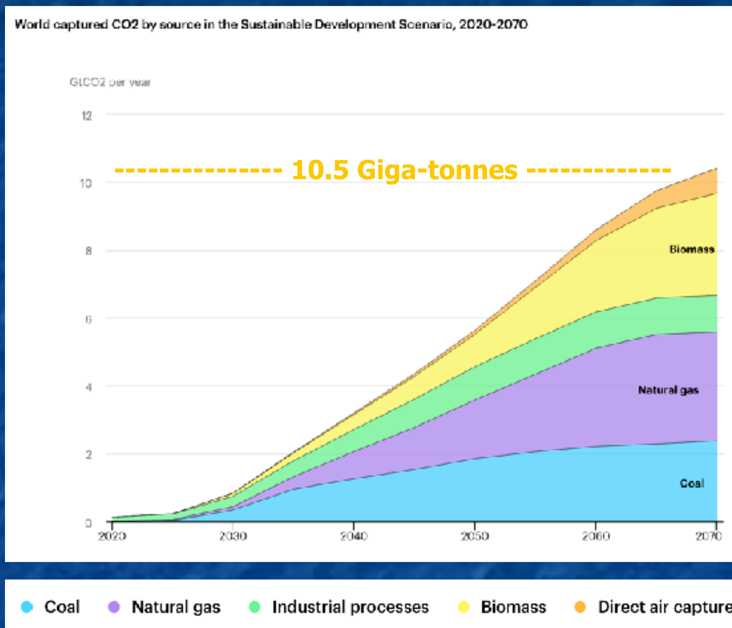
*How much CO_2 **might** CCUSS be able to capture?*

According to the International Energy Agency study (of what was overwhelmingly ONLY CCU): [4]

Annual CCU CO_2 Capture to 2021:



Scenario of Future CCU CO_2 Capture:



Today's human GHG emissions:	40 Giga tonnes / year	= target
2021's actual CCU CO_2 capture:	0.043 Giga-tonnes / year	1/930 x target
Versus (hockey stick like) IEA projections of		
2030 CCU CO_2 capture:	0.7 Giga-tonnes / year	1/57 x target
2040 CCU CO_2 capture:	2.9 Giga-tonnes / year	1/15 x target
2050 CCU CO_2 capture:	5.7 Giga-tonnes / year	1/7 x target

4) My orange notes added to figures from: https://www.iea.org/reports/about-ccus

But could the IEA be underestimating the true potential of Carbon Capture ?

Have any other credible sources projected the impact of carbon capture on GHG emissions?

I identified one other study, a synopsis of which was released by McKinsey & Company

An organization Wikipedia describes as being far from a green bastion:

"(It is) the oldest and largest of the "Big Three" management consultancies (MBB), the world's most prestigious strategy consulting firms (focusing) on the finances and operations of their clients."

In their report entitled: **Scaling the CCUS Industry to Achieve Net Zero Emissions** [6]

McKinsey chose a target for annual carbon capture of **4.2 Giga-tonnes** of CO_2 by 2050

Which is very close to the preceding slide's IEA projection of **5.3 Giga-tonnes** of CO_2 by 2050

To achieve that goal, McKinsey concluded (color NOT added):

"CCUS uptake needs to grow 120 times over by 2050 for countries to achieve their net-zero commitments"

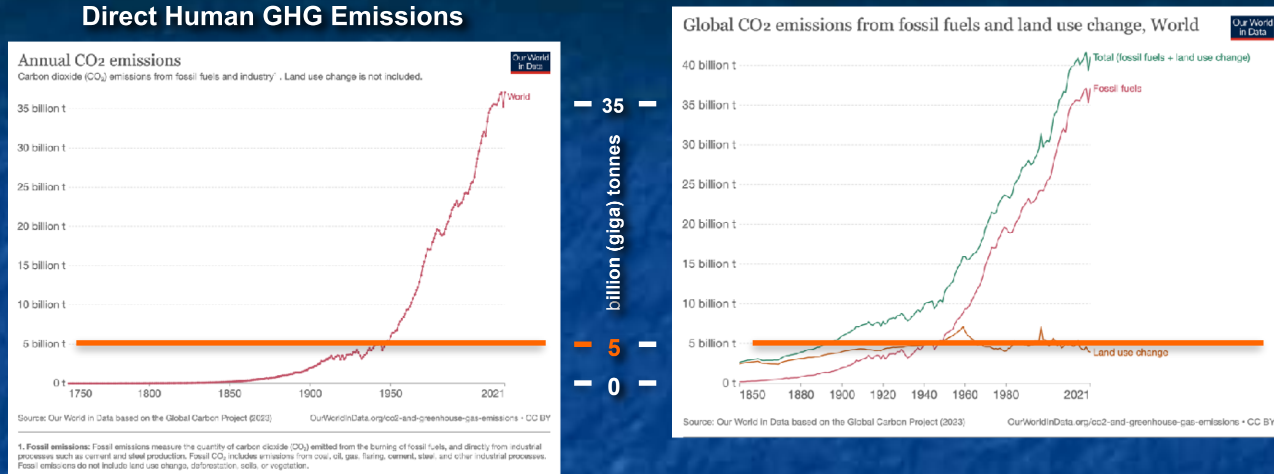
Almost identical to IEA's: (2050 projected 5.7 Gt/yr) / (2021 actual 0.043 Gt/yr) = **133 times**

Implying McKinsey was ALSO ignoring the the hugely important distinction between economically relevant (but mostly climate irrelevant) "CCUS" and climate relevant **CCUSS**

6) https://www.mckinsey.com/industries/oil-and-gas/our-insights/scaling-the-ccus-industry-to-achieve-net-zero-emissions

Further, is a 2050 goal of capturing only 4.4 - 5.3 Giga-tonnes of CO_2 enough?

Direct Human GHG Emissions | **Effective Human GHG Emissions**



Centuries of human CO_2 emission have raised its atmospheric concentration to an unprecedented level,

now driving global warming faster than even the more pessimistic model predictions of a decade ago

Now, even if we immediately stopped emitting ANY MORE CO_2,

it would take a century or more for already airborne CO_2 to naturally fade away

So we'll instead continue our CO_2 emissions but, over the next 25 years, trim them by < 15%?

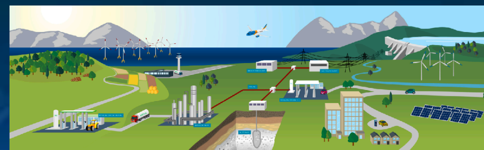
I'll stick with my earlier statement that we'll likely need to **slash** our existing emissions, meaning that a

"Business as Usual + CCUSS Scenario" requires ~ 7X more **CCUSS** than IEA & McKinsey target

So instead of an already credibility-straining **120X to 133X** growth from the 2021 CCUS level,

the net required **CCUSS** growth would be more like 7 x (120X to 130X) ~ **900X**

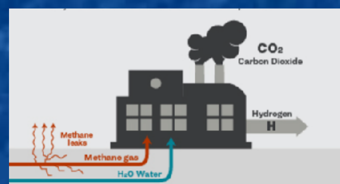
I opened this section by contrasting Climate vs. Industry driven Visions of a Hydrogen Economy



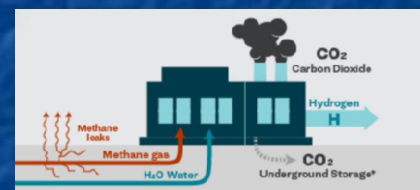
vs.

The **first part of the Industry-driven Vision** was that Hydrogen would continue to be supplied by Steam Methane Reforming of Methane (SMR), but via plants migrating from CO_2 release to CCUS

Gray Hydrogen



Blue Hydrogen



Which lead me to then ask:

"Do proposed CCUS techniques include viable means of stably solidifying carbon?"

For which the answer appears to be: **Yes, but only for 2-3 out of dozens of suggested technologies**

"Can use of those CCUS techs grow fast enough to blunt climate change?"

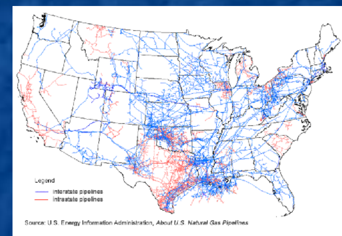
For which the answer from the last few pages appears to be:

If one projects (radical, unprecedented, implausible?) 120-900X growth of CCUSS by 2050

Bringing me ***almost*** *to the second and third parts of* ***Hydrogen Economy Visions:***

Part 2) Hydrogen Gas could be shipped via existing Natural Gas infrastructure

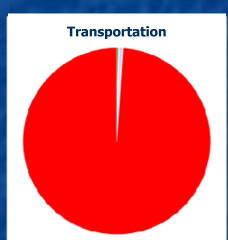
including the existing 3 million miles of buried U.S. Natural Gas Pipelines



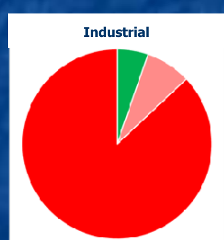
Part 3) Once delivered, Hydrogen Gas's portability would then accommodate myriad applications

Especially in the U.S.'s largest energy consumption sector of Transportation

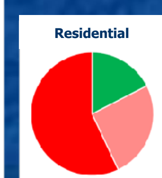
Where it might even meet the extreme challenge of GHG-free long-distance flight



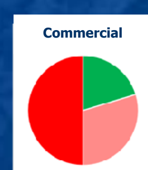
7.88 QW-h



7.59 QW-h



3.39 QW-h



2.67 QW-h

"Bringing me ***almost****"* because some extremely important questions must first be addressed:

How much Energy does H_2 contain / How much energy can it transport?

And how does H_2's stored energy compare to that of other Energy Storage Media?

I've sought out tabulations of Energy Density,[1-2] and data on single Energy Storage Media [3]

Energy / Mass data are fairly easy to find, but ***effective*** values depend upon containers

Energy / Volume data can be difficult to find and, for gases, values depend upon pressure

For a particular Medium, a cited energy density value typically spans a range of about 10%

Variation is due in part to many Media not being uniquely defined, for instance:

Fossil-fuel gasoline, diesel, jet fuel & natural gas are in fact complex chemical mixtures

which can vary by source, or by deliberate efforts to tweak their energy content

Similarly, Li ion batteries & Li metal batteries each come in many different formulations

Given my intent of exploring possibilities (and the continuing improvement of new technologies),

in the table that follows I've tended to select higher values reported by responsible sources

Further, in that table, to make comparisons easier, I've also added two columns providing

the ratio of a medium's Energy / Mass and Energy / Volume to those values for Gasoline

1) https://en.wikipedia.org/wiki/Energy_density *2) https://en.wikipedia.org/wiki/Energy_density_Extended_Reference_Table*

*3) See sources in the "Energetics of Hydrogen & Competing Energy Storage Media " section of my **Resources** webpage (link)*

In table form, including my data on many additional Energy Storage Media:

Increasing Energy per Mass →

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen Gas (H_2) at 20°C	150 Atm. gas *	142	39.4	**3.1**	1.79	0.50	**0.05219**
	1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Methane Gas at 15°C	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
	1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
	1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Fat	Animal or Vegetable	37	10.3	**0.80**	34	9.4	**0.99**
Coal	Anthracite or Bituminous	30	8.3	**0.65**	38	10.6	**1.11**
Carbohydrates	Including Sugars	17	4.7	**0.37**			
Ammonia	Liquid	16.9	4.7	**0.36**	11.5	3.2	**0.336**
Protein		16.8	4.7	**0.36**			
Wood		16.2	4.5	**0.35**	13	3.6	**0.380**
TNT		4.61	1.3	**0.10**	6.92	1.9	**0.202**
Gun Powder		3	0.8	**0.065**			
Lithium (Mn) Metal Battery		1.01	0.28	**0.022**	2.09	0.6	**0.061**
Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**
Flywheel		0.50	0.14	**0.011**			
Alkaline Battery		0.59	0.16	**0.013**	1.43	0.40	**0.042**
Nickel Metal Hydride Battery		0.40	0.11	**0.0086**	1.55	0.43	**0.045**
Lead Acid Battery		0.14	0.039	**0.0030**	0.36	0.10	**0.011**
Super Capacitor		0.020	0.006	**0.0004**	0.050	0.014	**0.0015**
Capacitor		0.002	0.001	**0.00004**			

** Effective Energy / Mass is as much as 100 times smaller for high-pressure gas in heavy tanks*

Table source: https://WeCanFigureThisOut.org/ENERGY/Energy_home.htm

*Hydrogen compared to today's **most important** Energy Storage Media:*

	Substance	Specifics:	Energy / Mass: MJ / kg	Energy / Mass: kW-h / kg	Energy / Mass: Ratio to Gasoline	Energy / Volume: MJ / liter	Energy / Volume: kW-h / liter	Energy / Volume: Ratio to Gasoline	
Hydrogen:	**Hydrogen Gas (H_2) at 20°C**	150 Atm. gas *	142	39.4	**3.1**	1.79	0.50	**0.05219**	**1/20 th**
		1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**	**1/3000 th**
Fossil Fuels:	**Methane Gas at 15°C**	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**	
		1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**	
	Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**	
		1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**	
	Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**	
	Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**	
	Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**	
	Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**	
New Batteries:	**Lithium (Mn) Metal Battery**		1.01	0.28	**0.022**	2.09	0.6	**0.061**	
	Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**	
Old Batteries:	**Alkaline Battery**		0.59	0.16	**0.013**	1.43	0.40	**0.042**	
	Nickel Metal Hydride Battery		0.40	0.11	**0.0086**	1.55	0.43	**0.045**	
	Lead Acid Battery		0.14	0.039	**0.0030**	0.36	0.10	**0.011**	

H_2 Energy per MASS is ~ 3X that of Gasoline / Diesel / Jet fuel

At 150 Atm. pressure [1] H_2 Energy per VOLUME is ~ 1/20 that of Gasoline / Diesel / Jet fuel

At 100 Atm. pressure [2] H_2 Energy per VOLUME is ~ 1/30 that of Gasoline / Diesel / Jet fuel

At 1 Atm. pressure H_2 Energy per VOLUME is ~ 1/3000 that of Gasoline / Diesel / Jet fuel

At any pressure H_2 Energy per VOLUME is ~ 1/3 that of Natural Gas at the same pressure

1) ~ Upper pressure range of common "class 1" compressed-gas cylinders

2) ~ Pressure in NG pipelines: https://homeupward.com/what-is-the-psi-of-natural-gas-in-a-home/ OR https://www.nrel.gov/docs/fy13osti/51995.pdf

*But **high pressurization of H_2** requires a very strong & **heavy** container:*

The most common high-pressure container is a "Class 1" steel gas cylinder: [1]

Which can contain gases at up to ~ 150 atmospheres of pressure [2]

And hold up to ~ 50 liters of that gas within the cylinder's ~ 50-85 kg body

But that reduces pressurized Hydrogen's effective Energy Density per Mass:

From the table: 150 Atm. Hydrogen's intrinsic Energy Density = 39.4 kW-h/kg

But while 50 liters of 150 Atm. H_2 weighs = 50 x 0.0126 kg/l = 0.63 kg

the weight of the cylinder needed to **contain** that H_2 = 50-85 kg

Hydrogen's EFFECTIVE Energy Density / Mass when contained in a gas cylinder:

≤ [0.63 / (0.63+50)] x 39.4 kW-h/kg = **1.24% of its intrinsic value**: 39.4 kW-h/kg → **0.49 kW-h/kg**

For CONTAINED 150 Atm. Hydrogen, the CORRECTED top of the table would instead be:

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
	1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**

1) https://en.wikipedia.org/wiki/Gas_cylinder *2) Hence my use of 150 Atm. in the preceding table*

Container weight correction has HUGE downsides for a Hydrogen Economy:

Before: H_2 easily surpassed the Energy / Mass of ALL common fossil-fuels,
while maintaining Energy / Volume only ~ 3X smaller than Natural Gas

After: H_2 Energy / Mass plummets below fossil-fuels, to almost as low as Lithium Batteries
Placing H_2 in direct competition with the already-mature technology of those batteries

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
	1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Methane Gas at 15°C	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
	1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
	1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Fat	Animal or Vegetable	37	10.3	**0.80**	34	9.4	**0.99**
Coal	Anthracite or Bituminous	30	8.3	**0.65**	38	10.6	**1.11**
Carbohydrates	Including Sugars	17	4.7	**0.37**			
Ammonia	Liquid	16.9	4.7	**0.36**	11.5	3.2	**0.336**
Protein		16.8	4.7	**0.36**			
Wood		16.2	4.5	**0.35**	13	3.6	**0.380**
TNT		4.61	1.3	**0.10**	6.92	1.9	**0.202**
Gun Powder		3	0.8	**0.065**			
Lithium (Mn) Metal Battery		1.01	0.28	**0.022**	2.09	0.6	**0.061**
Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**
Flywheel		0.50	0.14	**0.011**			
Alkaline Battery		0.59	0.16	**0.013**	1.43	0.40	**0.042**
Nickel Metal Hydride Battery		0.40	0.11	**0.0086**	1.55	0.43	**0.045**
Lead Acid Battery		0.14	0.039	**0.0030**	0.36	0.10	**0.011**
Super Capacitor		0.020	0.006	**0.0004**	0.050	0.014	**0.0015**
Capacitor		0.002	0.001	**0.00004**			

** Effective Energy / Mass is as much as 100 times smaller for high-pressure gas in heavy tanks*

Table source: https://WeCanFigureThisOut.org/ENERGY/Energy_home.htm

(use up & down keys to identify the data linked to each statement)

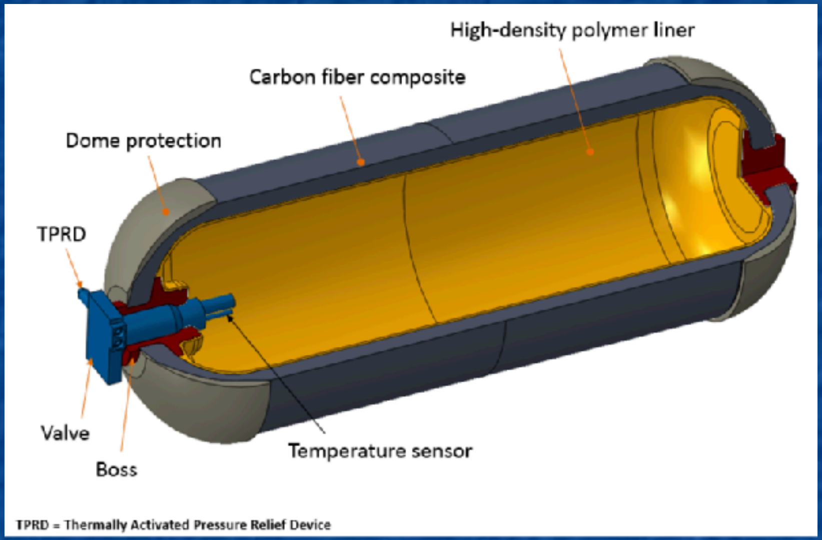
What about using entirely new types of high pressure Hydrogen gas containers?

Above, based on conventional steel gas cylinders, I calculated:

(Mass of stored 150 Atm. H_2) / (Mass of that stored H_2 + gas cylinder) = **1.24%**

But for vehicle applications, the U.S. DOE is funding research into high-tech containers including

350 Atm. & 700 Atm. versions of this: [1]



Their goals for (H_2 mass) / ("System mass") ratio are **4.5%** for 2020, and **6.5%** "eventually"

The DOE reported one lab approaching the 2020 goal having attained a ratio of **4.2%**

For that 700 Atm. Argonne National Lab unit, System energy / System mass = **1.4 kW-h / kg**

Which IS far better than the value I calculated for 150 Atm. steel cylinders: **0.49 kW-h / kg**

But still HUGELY short of H_2's (often misleadingly cited) intrinsic value of **39.4 kW-h / kg**

1) https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage

Then why not just liquify Hydrogen?

After all, the ease of liquifying **Propane** vastly increases its energy density and portability,

and liquifying **Natural Gas** is what makes its huge shipments possible:

When a fuel is driven from gas to liquid, its molecules ABRUPTLY huddle 1000's of times closer,

giving that liquid a very desirable 1000's of times more energy per volume!

How does one force such a transition? Decrease temperature (T) and / or increase pressure (P)

But getting practical, we need to know exactly which combinations of T & P force this transition

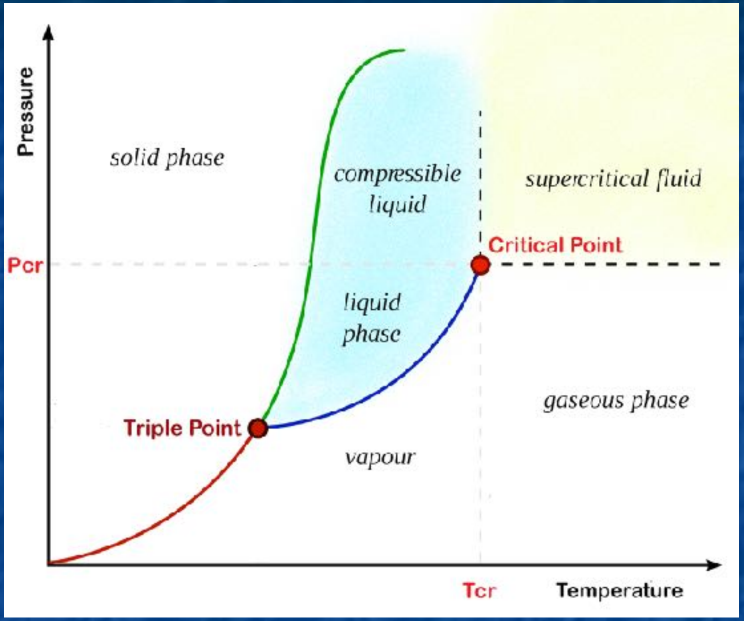
And getting really practical, we need to compare these for a variety of candidate fuels

Scientists plot a substance's Temperature & Pressure behavior in:

Left figure: https://www.ferrellgas.com/tank-talk/blog-articles/how-to-paint-a-propane-tank/
Center figure: https://blog.masterappliance.com/discover-these-8-professional-uses-for-a-propane-torch/
Right figure: https://gcaptain.com/new-lng-terminals-get-smaller/

"Phase Diagrams"

Where pressure increases upward, and temperature increases rightward: [1]



Our everyday experience falls in the diagram's center,

where the blue line plots T & P combinations where

vapor and liquid coexist in equilibrium

(= the substance's "Vapor Pressure Curve")

At lesser T's and greater P's everything becomes liquid

At greater T's and lesser P's everything becomes vapor

But at higher Temperatures things get weird:

There is a **Critical Point** above & right of which a normal dense liquid **DOES NOT** form

Instead, there is **Supercritical Fluid (SF)** [2] which is described as a strange high temperature state

with properties **gradually shifting** from gas-like to liquid-like moving up & right in the diagram

By NOT abruptly densifying, SF's offer no abrupt energy storage or transport advantage,

leading us to seek T & P combinations below & left of the Critical Point = (T_{cr}, P_{cr})

1) This is my modified / simplified version of a figure from: https://en.wikipedia.org/wiki/Phase_diagram

2) https://en.wikipedia.org/wiki/Supercritical_fluid

Comparing liquid Hydrogen with other liquid energy fuel contenders:

Drawing from the Phase Diagrams of Ammonia, Propane, Methane and Hydrogen: [1-3]

	Ammonia	**Propane**	**Methane**	**Hydrogen**
Critical Temperature (T_c)	132.4 ºC	96.7 ºC	-82.6 ºC	-240 ºC
Critical Pressure (P_c)	111 Atm.	42 Atm.	46 Atm.	13 Atm
Vapor Pressure of 25 ºC liquid	9.9 Atm.	9.9 Atm.	(N/A)	(N/A)
Temperature for 1 Atm. Vapor Pressure	-33 ºC	-43 ºC	-162 ºC	-253 ºC

Critical temperatures for **Ammonia** (132.4 ºC) & **Propane** (96.7 ºC) are far above 25 ºC meaning they are liquid in 25 ºC containers able to withstand their modest 9.9 Atm. vapor pressures

Or to use lighter/cheaper 1 Atm. tanks, they'd be cooled to -33 ºC and -43 ºC respectively

But to liquify the **Methane** in Natural Gas it MUST be refrigerated below its **-82.6 ºC** T_c

Or to use lighter/cheaper 1 Atm. pressure tanks, on today's LNG ships it is cooled to -162 ºC [2]

Liquifying **Hydrogen** requires refrigeration below **-240 ºC = 33º above Absolute Zero**

Or to use 1 Atm. tanks, it must be cooled to **-253 ºC = 20º above Absolute Zero** [3]

1) https://www.engineeringtoolbox.com/gas-critical-temperature-pressure-d_161.html

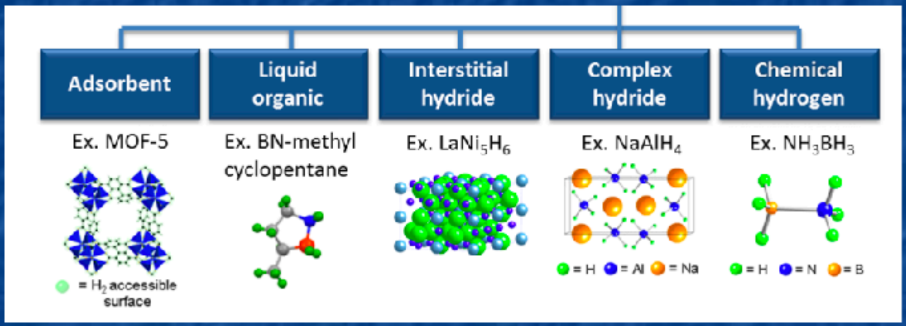
2) https://en.wikipedia.org/wiki/Liquefied_natural_gas *3) https://lcn.people.uic.edu/classes/che205s17/docs/che205s17_reading_02a.pdf*

*But there might be a final **wildcard** way to densely store Hydrogen:*

REVERSIBLY bond large numbers of H to certain complex molecules,

or drive H into the crevices of especially porous materials,

or into even the small spaces between the bonded atoms of special solids: [1]



Plans & results from a U.S. DOE research initiative on "Materials-based Hydrogen Storage:" [2]

	H_2 Mass / System Mass	System Energy / Mass	System Energy / Volume
2020 Goal:	4.5%	1.5 kW-h / kg	1.0 kW-h / l
Ultimate Goal:	6.5%	2.2 kW-h / kg	1.7 kW-h / l
$NaAlH_4$ results:	1.2%	0.4 kW-h / kg	0.4 kW-h / l
MOF-5 results:	3.8%	1.3 kW-h / kg	0.7 kW-h / l
Chemical hydrogen results:	4.6%	1.5 kW-h / kg	1.3 kW-h / l

The best per volume energy density achieved is only ~ 3X better than:

H_2 in 150 Atm. gas cylinder	1.24%	0.49 kW-h / kg	0.495 kW-h / l

1) Figure from: https://www.energy.gov/eere/fuelcells/hydrogen-storage *2) https://www.energy.gov/eere/fuelcells/materials-based-hydrogen-storage*

FINALLY *getting to the second and third parts of* ***Hydrogen Economy Visions:***

But armed with all of that **Energetics Information,**

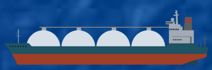
and now using it to analyze the full real-world consequences of:

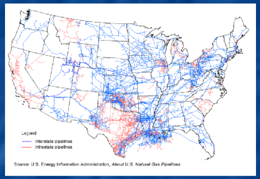
This Reality MEETING These Visions

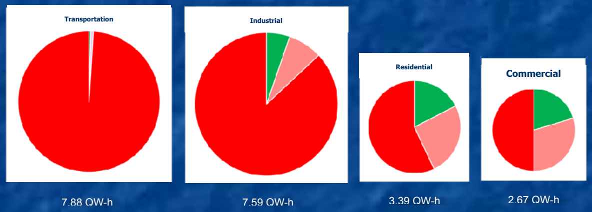
Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
	1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Methane Gas at 15°C	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
	1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
	1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Fat	Animal or Vegetable	37	10.3	**0.80**	34	9.4	**0.99**
Coal	Anthracite or Bituminous	30	8.3	**0.65**	38	10.6	**1.11**
Carbohydrates	Including Sugars	17	4.7	**0.37**			
Ammonia	Liquid	16.9	4.7	**0.36**	11.5	3.2	**0.336**
Protein		16.8	4.7	**0.36**			
Wood		16.2	4.5	**0.35**	13	3.6	**0.380**
TNT		4.61	1.3	**0.10**	6.92	1.9	**0.202**
Gun Powder		3	0.8	**0.065**			
Lithium (Mn) Metal Battery		1.01	0.28	**0.022**	2.09	0.6	**0.061**
Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**
Flywheel		0.50	0.14	**0.011**			
Alkaline Battery		0.59	0.16	**0.013**	1.43	0.40	**0.042**
Nickel Metal Hydride Battery		0.40	0.11	**0.0086**	1.55	0.43	**0.045**
Lead Acid Battery		0.14	0.039	**0.0030**	0.36	0.10	**0.011**
Super Capacitor		0.020	0.006	**0.0004**	0.050	0.014	**0.0015**
Capacitor		0.002	0.001	**0.00004**			

** Effective Energy / Mass is as much as 100 times smaller for high-pressure gas in heavy tanks*

Table source: https://WeCanFigureThisOut.org/ENERGY/Energy_home.htm







The second part of Hydrogen Economy Visions concerned ***TRANSPORT of H_2***

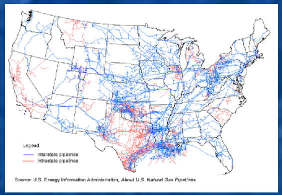
For which "Liquifying Hydrogen requires refrigeration below -240 ºC = 33º above Absolute Zero"

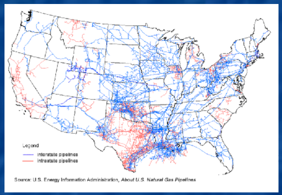
and "To use 1 Atm. tanks, it must be cooled to -253 ºC = 20º above Absolute Zero"

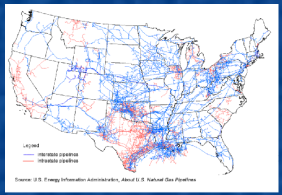
very likely rule out practical / economic seaborne transport of liquified H_2:

As my "At any pressure H_2 Energy per VOLUME is ~ 1/3 that of Natural Gas"

means replacing Natural Gas with H_2 would require 3X our present day pipeline capacity





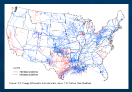


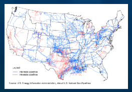
While "At 100 Atm. pressure H_2 Energy per VOLUME is 1/30 that of Gasoline / Diesel / Jet fuel"

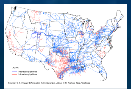
suggests that for H_2 from centralized SMR / CCUS plants to ALSO replace liquid fossil fuels,

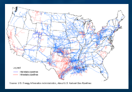
(which IS part of Industry's alleged Vision), our huge **fossil fuel** pipeline network

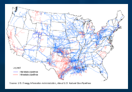
would also have to be replaced by even HUGER additional H_2 pipeline capacity [1]

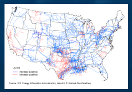












+ ? ? ?

1) I did not try to estimate HOW MUCH more H_2 pipeline capacity would be required to replace the existing U.S. liquid fossil fuel pipeline network because, among other factors, gases at 100 atmospheres almost certainly flow though pipes very differently than liquid fossil fuels (which if now pumped at much lower pressures would also use pipelines of significantly different design)

*But some industry-backed Visions would only **DILUTE** pipeline Natural Gas with H_2*

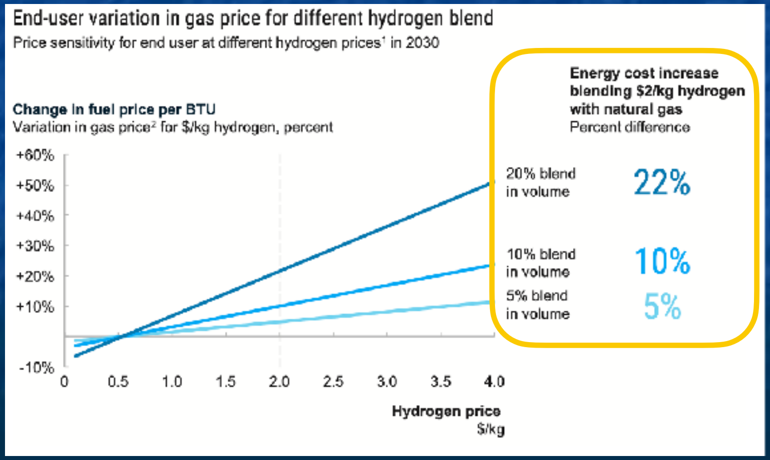
As in the Fuel Cell & Hydrogen Energy Association: **Road Map to a U.S. Hydrogen Economy** [1]

> "Companies can blend low percentages of hydrogen into **existing natural gas networks** without the need for major changes in infrastructure or new home appliances. In the US gas network today, blending levels should be safe within a range of 4 to 5 percent . . . Various studies show blending levels limited at 5 to 30 percent by volume without appliance upgrade" [1]

But again recalling my: "At any pressure H_2 Energy per VOLUME is ~ 1/3 that of Natural Gas"

if H_2 were added to Natural Gas at volume fractions of:	3%	5%	20%	30%
Its energy contribution to the gas mixture would then be:	1%	1.7%	7%	10%

Which, despite reduction in NG's share, would increase mixture's cost in proportion to H_2 share: [1]



1) Pages 29-31 in: https://www.fchea.org/us-hydrogen-study   *Yellow box added to figure*

Then why even bother to make such minor changes? A disturbing precedent:

Gasohol (gasoline diluted with ≤ 10% methanol)

Which once ***seemed*** like it might be a climate-friendly change, but turned out to yield equivalent or *higher* GHG emissions while causing major environmental & worldwide economic damage (associated with the required massive cultivation of water & fertilizer-hungry corn) [1]

But which continues on thanks to political leverage of embedded farming & industry interests

Well aware of that precedent, many now see the proposed use of weakly H_2 diluted Natural Gas as a way of **Greenwashing** business-almost-as-usual operation of the Natural Gas Industry

Among those criticisms (cited in the introduction of this noteset):

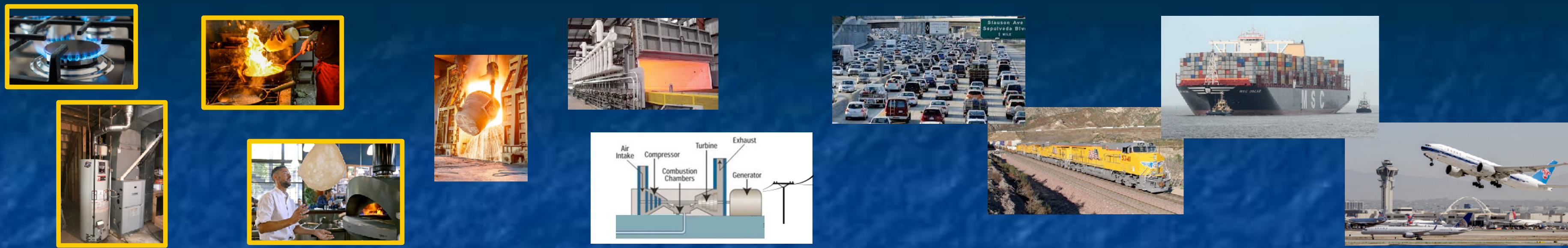
The Sierra Club: "The fossil fuel industry is hyping hydrogen of all kinds as a low-carbon replacement for all sorts of uses of fossil fuels - from powering vehicles and heavy industry to heating buildings. In reality, many hydrogen projects will only lock us in to continued fossil fuel use and additional investments in fossil fuel infrastructure" [2]

Washington Post: Clean Energy Superstar or Smokescreen or Fossil Fuel Use? (2022) [7]

Get Tax Right or Clean Hydrogen Will be a Bigger Boondoggle than Biofuels (2023) [8]

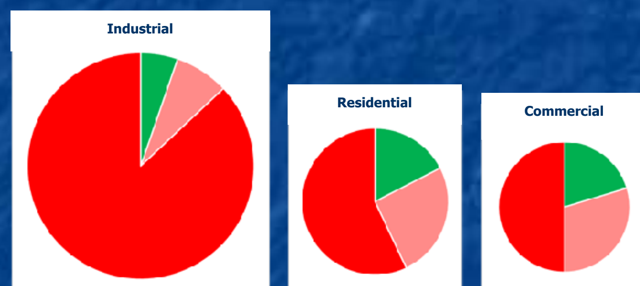
1) See my noteset: **Biomass and Biofuels** (pptx / pdf / key) 2) https://www.sierraclub.org/articles/2022/01/hydrogen-future-clean-energy-or-false-solution
7) https://www.washingtonpost.com/climate-solutions/2022/03/17/hydrogen-clean-energy-climate-change/
8) https://www.washingtonpost.com/opinions/2023/04/27/clean-hydrogen-tax-credit-stringent-rules/

*The third & final part of Hydrogen Economy Visions concerned **Applications of H_2***



Left of center icons depict Residential, Commercial & Industrial **HEATING**

which is **the major contributor** to the red parts of these types of U.S. Energy Consumption:



7.59 QW-h   3.39 QW-h   2.67 QW-h

The leftmost 4 icons depict **Residential & Commercial HEATING**, mostly gas furnaces & ovens

With fairly minor changes furnaces / ovens **could** indeed be converted to burn Hydrogen fuel

But recalling my "At any pressure H_2 Energy per VOLUME is ~ 1/3 that of Natural Gas"

H_2 furnaces & ovens would require 3X the gas to heat as well as Natural Gas units

But for ***Residential & Commercial HEATING*** *there's often an immensely a better solution:*

HEAT PUMPS which, rather than converting their input electrical energy directly into heat,

instead use that energy to compel a liquid to expand and evaporate (absorbing heat) **outside**,

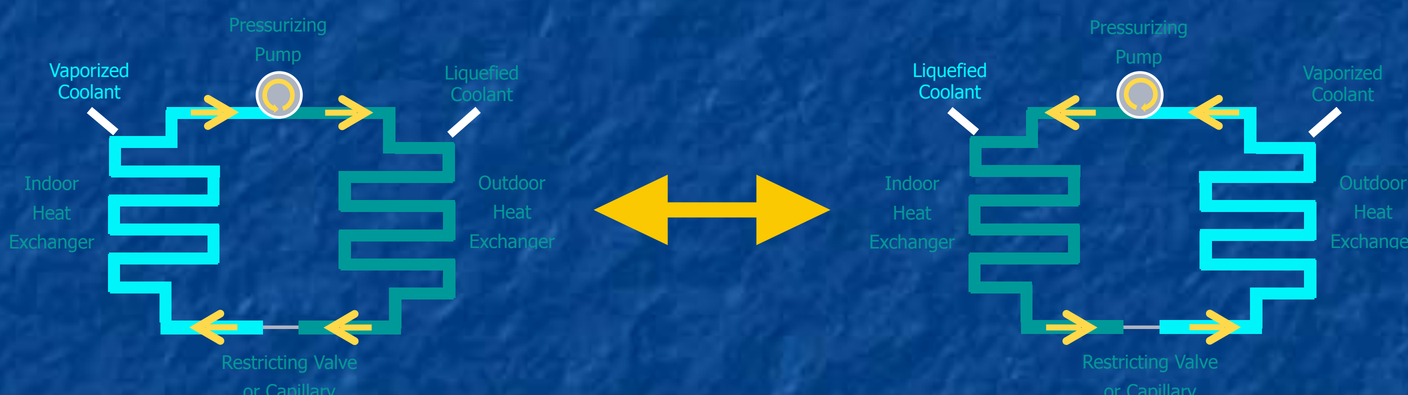
and then compel the resulting vapor to compress and condense (releasing heat) **inside**,

thereby effectively "pumping" heat from **outside** to **inside**

Which can actually be 300% energy efficient (delivering 3X the heat energy per energy expended)

and which can be reversed, at the flick of a switch, to pull heat from **inside** to **outside**

thereby running as invented by Willis Carrier to produce AIR CONDITIONING [1, 2]



But Heat Pump efficiency drops as difference between **inside** & **outside** temperature increases

making them unsuitable for room air heating or cooling in extreme climates, or for the

extreme heating done in other types of commercial non-room-air furnaces & burners

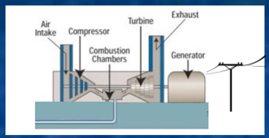
1) https://www.smithsonianmag.com/smithsonian-institution/unexpected-history-air-conditioner-180972108/ 2) https://en.wikipedia.org/wiki/Willis_Carrier
3) Figure and further detail in my noteset: ***Energy Consumption in Housing*** *(pptx / pdf / key)*

*The 5th and 6th icons instead depicted **Industrial Heating***












Most of that heat is now produced with electric heaters or GHG-emitting Natural Gas burners,

because non-air industrial heating is mostly to temperatures beyond the reach of Heat Pumps

Here H_2 could be substituted for Natural Gas, but having 1/3 the intrinsic heat energy / volume,

3X the H_2 volume of the Natural Gas it supplanted would again be required

If that H_2 came from Green Electricity driven Electrolysis, it would eliminate GHG emissions

But going even father back in this noteset:

> For **Electrolysis**: H_2 Energy Output / Electrical Energy Input = **64 - 68%** [6]

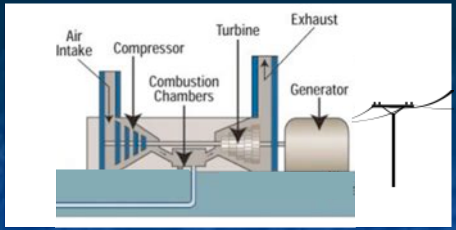
Meaning 1.5 times **more heat** would come from heaters powered **directly** by Green Electricity

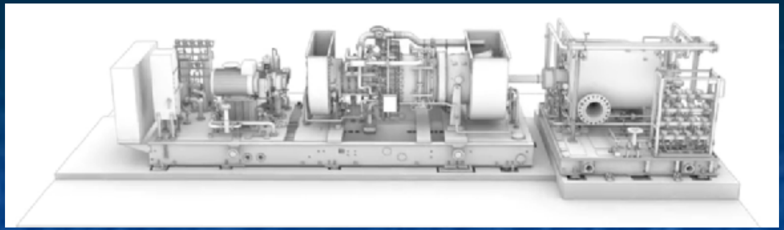
While the final alternative of SMR / CCUSS generated GHG-free H_2

would work ONLY if CCUSS were fully employed, versus:

industry Visions of partially applying only partially (now minimally) effective "CCUS"

The 7th icon depicted gas-powered generation of electricity

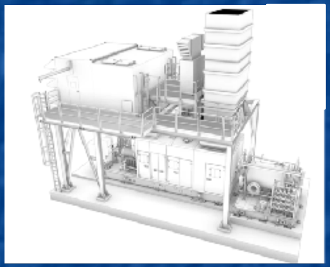




And did a good job of representing a **real** Open Cycle Gas Turbine (OCGT) power plant (at right) [1]

Which, even with its covers and catwalks fully in place

can still be remarkably simple and compact:



But using GHG-free electricity to Electrolyze water into H_2,

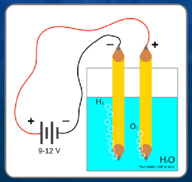
and then using that H_2 to fuel a turbine to drive a generator to re-generate electricity

would really only make sense in a single, **but possibly very important**, situation:

As a buffer used to marry the natural cycles of wind & solar electricity generation

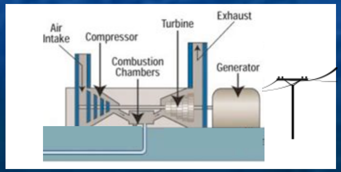
with the significantly different human cycles of electricity consumption:

Electricity →



→ ***H_2*** →

→ ***H_2*** →



→ ***Electricity***

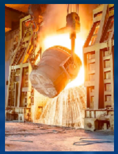
*1) For more detail, se my noteset: **Fossil Fuels** (pptx / pdf / key)*

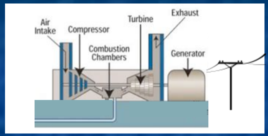
OCGT photos (used in that noteset) were clipped from video at: https://www.youtube.com/watch?v=OkfqUSBdN8M

Bringing us to the final (and largest) category of U.S. Energy consumption: ***Transportation***












The leftmost transportation icon depicts road travel in **Cars and Trucks**

But I've already discussed calculations of H_2 Fuel Cell Vehicle energy efficiencies: **22-33%**

which are far inferior to those of Battery Electric Vehicles: **66-77%**

But there are recurring claims that **Fuel Cell Vehicles might at least offer superior range**

Which IS critical in long distance trucking & and some delivery truck applications,

and is at least perceived to be critical in many personal vehicle purchasing decisions

So setting aside efficiencies, let's see if my energy data support claims of superior FCEV range

I'll try to compare the range of my own car (a small "mature" gasoline-fueled crossover-SUV)

with that of its possible Fuel Cell or Battery Electric Vehicle replacements (FCEV / BEV)

My car now has or now gets:

53 liter (14 gal) fuel tank   9.4 highway km / liter (22 mpg)   500 km (310 mile) range

Drawing on my earlier discussion of comparative energetics:

By excerpting its table, including its calculation for pressurized H_2 in standard steel cylinders

	Substance		Energy / Mass			Energy / Volume		
		Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen:	Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
		1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Fossil Fuels:	**Methane Gas at 15°C**	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
		1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
	Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
		1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
	Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
	Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
	Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
	Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Batteries:	**Lithium (Mn) Metal Battery**		1.01	0.28	**0.022**	2.09	0.6	**0.061**
	Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**

Then ignoring the likely small weight of my car's thin sheet metal gas tank itself,

its gasoline-filled **53 liter** tank must weigh ~ (53 l) (0.001 m^3/l)(755 kg/m^3) = **39.3 kg**

Which, from the table, says it contains ~ (39.3 kg)(**12.9** kW-h/kg) = **507 kW-h of fuel energy**

But having an internal combustion engine + automatic transmission + 4 wheel drivetrain,

no more than 20% of that fuel energy is ultimately transferred to the wheels = **101.4 kW-h**

We now need to compare that energy with the energy H_2 Fuel Cells or Lithium Batteries might provide

But how will the quantity of Hydrogen Tanks or Batteries likely be constrained?

By matching the **53 liter VOLUME** of my gasoline tank OR by matching its ~ **39.3 kg MASS**?

It will likely be some subtle vehicle-type-dependent combination of BOTH - So I will calculate BOTH

*First calculating ranges as constrained by fuel storage **VOLUME**:*

	Substance	Specifics:	Energy / Mass MJ / kg	Energy / Mass kW-h / kg	Energy / Mass Ratio to Gasoline	Energy / Volume MJ / liter	Energy / Volume kW-h / liter	Energy / Volume Ratio to Gasoline
Hydrogen:	Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
		1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Fossil Fuels:	**Methane Gas at 15°C**	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
		1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
	Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
		1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
	Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
	Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
	Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
	Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Batteries:	**Lithium (Mn) Metal Battery**		1.01	0.28	**0.022**	2.09	0.6	**0.061**
	Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**

From earlier, my gasoline internal combustion engine + automatic transmission + 4 wheel drivetrain car

now uses **53 liters of gasoline** to deliver to its wheels ~ **101.4 kW-h**

Versus **53 liters of Lithium ION Batteries** providing ~ (53 l)(**1.00** kW-h/l) = **53.0 kW-h**

of which, as in all electric vehicles ~ 75% makes it to the wheels: (53.0)(.75) = **39.8 kW-h**

Which is 39.2% that of the fossil fueled vehicle

Versus **53 liters of 150 Atm. H_2** in steel cylinders containing (53 l)(**0.50** kW-h/l) = **26.5 kW-h**

of energy input to Fuel Cells which would output about 50% as much electrical energy

of which, as in all electric vehicles ~ 75% makes it to the wheels: (26.5)(0.5)(0.75) = **9.93 kW-h**

Which is 9.8% that of the fossil fueled vehicle

Or assuming that research **does** ultimately produce practical **700 Atm.** H_2 storage tanks

which would increase H_2 storage per volume by ~ 5X, yielding instead (5)(9.84) = **49.2 kW-h**

Which is 49.0% that of the fossil fueled vehicle

*Then calculating ranges as constrained by fuel storage **MASS**:*

	Substance	Specifics:	Energy / Mass			Energy / Volume		
			MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen:	**Hydrogen Gas (H_2) at 20°C**	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
		1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Fossil Fuels:	**Methane Gas at 15°C**	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
		1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
	Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
		1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
	Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
	Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
	Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
	Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Batteries:	**Lithium (Mn) Metal Battery**		1.01	0.28	**0.022**	2.09	0.6	**0.061**
	Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**

From earlier, my gasoline internal combustion engine + automatic transmission + 4 wheel drivetrain car

now uses **39.9 kg of gasoline** to deliver to its wheels ~ **101.4 kW-h**

Versus **33.9 kg of Lithium ION Batteries** providing ~ (33.9 kg)(0.20 kW-h/kg) = **6.78 kW-h**

of which, as in all electric vehicles ~ 75% makes it to the wheels: (**6.78**) (0.75)= **5.09 kW-h**

Which is 5.0% that of the fossil fueled vehicle

Versus **33.9 kg of H_2 in steel cylinders** containing (33.9)(0.50 kW-h/kg) = **17.0 kW-h**

of energy input to Fuel Cells which would output about 50% as much electrical energy

of which, as in all electric vehicles ~ 75% makes it to the wheels: (17.0)(0.5)(0.75) = **6.36 kW-h**

Which is 6.27% that of the fossil fueled vehicle

Or assuming that research **does** ultimately boost (H_2 mass) / (Storage System Mass) from 1.24% to 6.5%

that (6.5 / 1.25) = 5.2X improvement would boost H_2 energy to wheels from 6.23 kW-h to **32.4 kW-h**

Which is 32.6% that of the fossil fueled vehicle

*Finally, calculating both for possible future use of **Lithium METAL** batteries*

	Substance		Energy / Mass			Energy / Volume		
		Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen:	Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
		1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Fossil Fuels:	**Methane Gas at 15°C**	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
		1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
	Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
		1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
	Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
	Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
	Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
	Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Batteries:	**Lithium (Mn) Metal Battery**		1.01	0.28	**0.022**	2.09	0.6	**0.061**
	Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**

From earlier, my gasoline internal combustion engine + automatic transmission + 4 wheel drivetrain car now uses **53 liters of gasoline** to deliver to its wheels ~ **101.4 kW-h**

VOLUME CONSTRAINED:

53 liters of Lithium METAL Batteries provide ~ (53 l)(**0.6** kW-h/l) = **31.8 kW-h**

of which, as in all electric vehicles ~ 75% makes it to the wheels: (31.8)(.75) = **23.9 kW-h**

Which is 23.5% that of the fossil fueled vehicle

MASS CONSTRAINED:

33.9 kg of Lithium METAL Batteries provide ~ (33.9 kg)(**0.28** kW-h/kg) = **9.49 kW-h**

of which, as in all electric vehicles ~ 75% makes it to the wheels: (9.49) (0.75)= **7.12 kW-h**

Which is 7.0% that of the fossil fueled vehicle

Comparing those possibly confusing arrays of results:

Expressing BEV & FCEV energy-to-wheels as percentage of Fossil Fuel vehicle energy-to-wheels:

	Volume Constrained:		Mass Constrained:	
	BEV	FCEV	BEV	FCEV
Today's Li Ion Batteries & **Today's** H_2 Tanks:	39.2%	9.8%	5.0%	6.27%
Today's Li Ion Batteries & **Tomorrow's** H_2 Tanks:	39.2%	49.0%	5.0%	32.6%
Tomorrow's Li Metal Battery & **Tomorrow's** H_2 Tanks:	25.3%	49.0%	7.0%	32.6%

When I compare **today's** BEV with **today's** FCEV:

VOLUME constrained BEV range is ~ 3X longer than FCEV range

MASS constrained ranges are both much lower, but near identical

The comparison of BEVs using **TODAY's** Batteries with FCEVs using **TOMORROW's** H_2 Tanks

is instead a **very misleading and inappropriate** apples-to-oranges comparison

But when I compare **tomorrow's** BEV using a projected more robust & safer Li Metal Battery with

tomorrow's FCEV using U.S. DOE projected new Hydrogen Storage Tank technology:

Projected VOLUME & MASS constrained FCEVs improve much more strongly than BEVs

producing FCEV Ranges that (as claimed) would be much longer than BEV ranges

(undoubtedly why the U.S. DOE is pushing its underlying Hydrogen storage research programs)

Repeating a bit to make sure ALL of my EV calculations are put into perspective:

First, do not let those **Range** calculations obscure my earlier calculation,

and its corroboration by no less than three other respected sources,

that BEVs are at least 2-3X more **Energy Efficient** than H_2 FCEVs

BEVs will thus require substantially less expansion of our Green Electricity Grid

and require us, as individuals, to spend far less on powering them up

Second, contrary to claims, my Range calculations based on **current technologies**

indicated ~ 4X superior BEV ranges under Volume constraints

versus near equal BEV and FCEV ranges under Mass constraints

Third, only when I assumed that U.S. DOE Hydrogen storage programs are fully successful

could claims of superior across-the-board FCEV ranges find any validation

Finally, even if research falls short, with current technology unconstrained by Volume or Mass

BEVs could MATCH fossil-fuel vehicle range if batteries were 2.5X larger in volume

FCEVs could MATCH fossil-fuel vehicle range if H_2 Tanks were 10X larger in mass

Bringing us to this would-be H_2 application:

Regarding efforts to reduce GHG emissions from trains, I found three informative sources:

From the International Rail Journal: "Europe Leads the Charge to Replace Diesel Traction" [1]

From RailNet.com [2] - which thoughtfully analyzed a study on:

U.S. rail electrification from the Lawrence Laboratory National Lab, UCLA & UC Berkeley [3]

For me, these contained two surprises and one reminder:

The first surprise was that overhead electrification of Europe's trains is **not** nearly complete

It was instead pointed out that while **mainline** passenger & freight rail was largely electrified,

low **branch line** traffic often fails to support the cost of overhead electric line installation

Leading to intense discussion, including about possible **Battery or H_2 Fuel Cell engines** [1]

But, while ongoing, discussion seemed to be leaning toward addition of **battery tenders**

which are cars packed with batteries trailing existing mainline electric engines

to which those engines can switch when on unelectrified branch lines [2]

1) https://www.railjournal.com/opinion/europe-leads-charge-replace-diesel-traction/

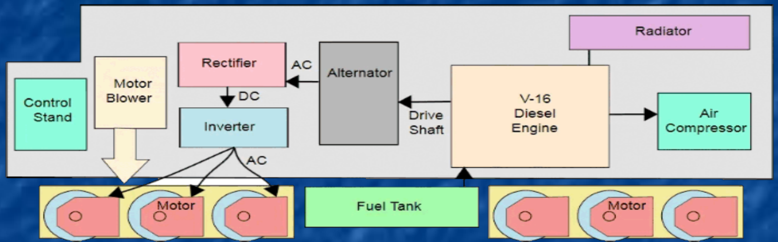
2) https://dieselnet.com/news/2021/12berkeley.php *3) https://www.nature.com/articles/s41560-021-00915-5.pdf*

The reminder:

For ~70 years virtually all rail engines - including U.S. engines - have been partially electric

As in the icon image's engine which has wheels driven directly by electric motors,

powered from the main body of the engine by diesel-engine-driven electric generators:



*The **second** surprise:*

Despite the much, much longer distances traveled by U.S. freight trains,

not only **fully electrical**, but even **battery electric** engines are being seriously discussed

This based on the fact that while a train may travel ~ 700 miles per day, there are stops during

that day to replace crews (or even change out engines to deal with different upcoming terrain)

Advocates argue that Battery electric engines could be recharged during these stops OR that

already recharged engines could be swapped in - both using only **existing** infrastructure [3]

U.S. rail operators are still unconvinced but, again, the relative maturity of battery technology

seems to have undercut consideration of less developed options, such as **H_2 Fuel Cells** [2]

Figure: https://commons.wikimedia.org/wiki/File:DieselElectricLocomotiveSchematic.svg

2) https://dieselnet.com/news/2021/12berkeley.php *3) https://www.nature.com/articles/s41560-021-00915-5.pdf*

And then on to this would-be H_2 application:

In my noteset about **Energy Consumption in Transportation** (pptx / pdf / key)

I spend over forty pages discussing ways of lowering the carbon footprint of Shipping

Summarizing that discussion VERY briefly (emphasizing parts relevant to Hydrogen):

For simpler ideas, the estimated percentage CO_2 emission reductions are disappointingly minor

Moving from higher toward lower impact ideas, highlights include:

Speed reduction (8.5%), Hull Cleaning (4.8%), Wind Power (2.4%), Solar Power (0.1%) [1]

I therefore constructed a model of a possible large (Panama Canal limited) Battery Electric Ship,

but while that model showed that such a BES might be **technically** feasible, matching

the Range of Fossil-Fuel counterparts required Li Batteries costing ~ 6.3 billion dollars

Explaining the shipping industry search for extremely high energy density but climate-friendly fuels

Essentially, something with near fossil-fuel energy density, but without the carbon

1) Page 10 : https://theicct.org/sites/default/files/publications/ICCT_GHGfromships_jun2011.pdf

Per my table, pressurized-H_2 is NOT the obvious Fossil-Fuel replacement

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
	1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Ammonia	Liquid	16.9	4.7	**0.36**	11.5	3.2	**0.336**

But lower in the table, **Ammonia** has Energy/Mass = 4.7 kW-h / kg, Energy/Vol. = 3.2 kW-h / l

Which is more than 1/3 that of fossil-fuels (and 7-10X times better than pressurized H_2)

Even more striking is that while liquifying **H_2** requires temperatures below **-240 ºC**

Ammonia only requires cooling below **-33.3 ºC**, and will remain liquid at **room temperature**

if held in a tank capable of withstanding its **9.9 Atm.** room temperature vapor pressure

But paralleling H_2:

NH_3 is also now generated via energy-intensive, heavily GHG-emitting chemical processes

Which would have to be replaced by Green Electricity powered **Electrolytic Synthesis**

And continuing that parallel:

While Green NH_3 could then cleanly fuel Internal Combustion Engines

The environmentally preferred use would to fuel **NH_3 Fuel Cells** producing Electricity

But due to its much higher energy density AND much higher boiling point . . .

Ammonia Fuel Cell powered test ships ARE under construction:

As funded by the **European Union's fourteen nation ShipFC project,** [1]

the "Viking Energy" is scheduled for sea trials late in 2023, [2]

propelled by NH_3 Solid Oxide Fuel Cells generating 2 MW of electricity

With a 2020: "Study of Alternative Ship Propulsion System(s) Fueled by Ammonia . . ." [1]

concluding that Ammonia powered alternatives to fossil-fueled diesel ships would:

Require 1.6 - 2.3 times the volume

Be 1.4 - 1.6 times heavier

Have a total life cycle cost 3.5 - 5.2 times larger

But could reduce GHG emissions by 83.7 - 92.1%

1) https://www.prototech.no/news/2020/01/23/prototech-awarded-contract-to-supply-2mw-zero-emission-ammonia-fuel-cell-module/
2) https://www.prototech.no *3) https://www.mdpi.com/2077-1312/8/3/183/htm*

And finally to this would-be H_2 application:

In my noteset about **Energy Consumption in Transportation** (pptx / pdf / key) I also

spend over twenty-four pages discussing ways of lowering the carbon footprint of Aircraft

But its most Hydrogen (and Battery) relevant section is an analysis I made of a typical airliner

In particular, for different Boeing 777 models with maximum ranges of 10,000 to 16,000 km

For which Wikipedia had a webpage that supplied these data: [1]

Boeing 777 specifications

Variants	Initial[184]		Long-range[144]	
Model	**777-200/200ER**	**777-300**	**777-300ER**	**777-200LR/777F**
Range[175]	5,240 nmi / 9,700 km[d][171] 200ER: 7,065 nmi / 13,080 km[e]	6,030 nmi / 11,165 km[f][171]	7,370 nmi / 13,649 km[g]	8,555 nmi / 15,843 km[h] 777F: 4,970 nmi / 9,200 km[i]
Max Takeoff Weight	545,000 lb / 247,200 kg 200ER: 656,000 lb / 297,550 kg	660,000 lb / 299,370 kg	775,000 lb / 351,533 kg	766,000 lb / 347,452 kg 777F: 766,800 lb / 347,815 kg
Empty Weight	299,550 lb / 135,850 kg 200ER: 304,500 lb / 138,100 kg	353,800 lb / 160,530 kg	370,000 lb / 167,829 kg	320,000 lb / 145,150 kg 777F: 318,300 lb / 144,379 kg
Fuel capacity	31,000 US gal / 117,340 L / 207,700 lb / 94,240 kg 200ER/300: 45,220 US gal / 171,171 L / 302,270 lb / 137,460 kg		47,890 US gal / 181,283 L / 320,863 lb / 145,538 kg	

1) With two expanded acronyms, excerpted from main table at: https://en.wikipedia.org/wiki/Boeing_777

Thus, for a flight approaching the aircraft's full range:

Load weight (Passengers + Cargo) = (Max. Takeoff weight) - (Empty weight) - (Max. Fuel weight):

Aircraft Model's Range:	10,000 km	11,000 km	13600 km	16,000 km
Max takeoff Wt (=100%):	247200 kg	299370 kg	351533 kg	347452 kg
Aircraft Empty Wt:	135850 kg **~ 55%**	160530 kg **~ 54%**	167829 kg **~ 48%**	145150 kg **~ 42%**
Max Full Fuel Load Wt:	94240 kg **~ 38%**	94240 kg **~ 32%**	145538 kg **~ 41%**	145538 kg **~ 42%**
→ Passenger + Cargo Wt =	17110 kg **~ 7%**	44600 kg **~15%**	38166 kg **~ 11%**	56764 kg **~ 16%**

Leading to the conclusion that **for a typical, fully loaded, transcontinental or transoceanic flight:**

Load Weight is approximately ~ 3/4 Fuel versus 1/4 (Passengers + Cargo) [1]

If Fuel Weight increased by 33%, Passenger + Cargo weight would have to be cut to ZERO

If Fuel Weight increased by only 10%, Passenger + Cargo Weight would have to be cut by 30%

But flight income is PAID by and thus proportional to Passenger + Cargo Weight

33% Heavier Fuel → ZERO Income

10% Heavier Fuel → 1/3 drop in Income (likely yielding **Negative Profit)**

Smaller increases in Fuel Weight could still bankrupt today's low-profit-margin Aircraft Industry

1) Explaining modern air travel's HUGE CARBON FOOTPRINT:

*For each **1 kg** of body & luggage weight you add to a flight, ~ 3 **kg** of hydrocarbon fuel must be loaded and then burned into Greenhouse Gases*

Returning (for a final time) to my Energetics Table:

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen Gas (H_2) at 20°C	150 Atm. gas in tank	1.76	0.5	0.038	1.79	0.50	**0.05219**
	1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Methane Gas at 15°C	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
	1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
	1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Fat	Animal or Vegetable	37	10.3	**0.80**	34	9.4	**0.99**
Coal	Anthracite or Bituminous	30	8.3	**0.65**	38	10.6	**1.11**
Carbohydrates	Including Sugars	17	4.7	**0.37**			
Ammonia	Liquid	16.9	4.7	**0.36**	11.5	3.2	**0.336**
Protein		16.8	4.7	**0.36**			
Wood		16.2	4.5	**0.35**	13	3.6	**0.380**
TNT		4.61	1.3	**0.10**	6.92	1.9	**0.202**
Gun Powder		3	0.8	**0.065**			
Lithium (Mn) Metal Battery		1.01	0.28	**0.022**	2.09	0.6	**0.061**
Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**

Below H_2 (with Energy / Mass plummeting in its pressurized and thus necessarily heavy tanks)

Below all of the Fossil-Fuels AND Fat (which, biofuel or not, would surely choke a Jet engine)

EVERYTHING ELSE IN THE TABLE HAS ENERGY / MASS < 1/2 THAT OF JET FUEL

meaning planes would need MORE THAN twice the weight of those other "fuels"

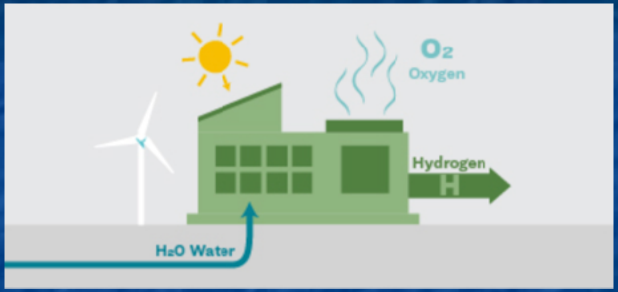
Income-generating Green Flight thus REQUIRES new fossil-fuel-like synthetic fuels,

(achievable only by investing much **more** energy & money into their chemical synthesis)

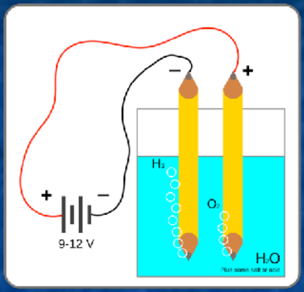
Summary & Conclusions

Part I: Hydrogen Sources

Climate Driven Choice: Green-electricity-powered water Electrolysis



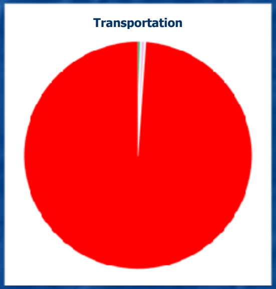
= ***Electricity*** →



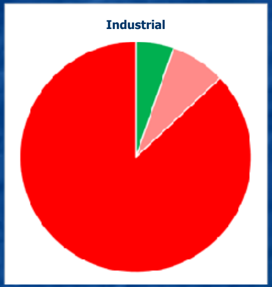
→ ***Hydrogen Gas***

Now accounting for only an almost negligible "~ 0.03% of today's H_2 production"

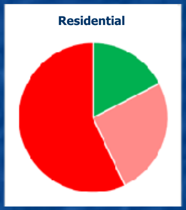
For electrolyzed H_2 to displace U.S. use of Fossil Fuels (red & pink parts of pie charts), Total U.S. Green Electricity production would have to increase by ~ 7 to 12 times



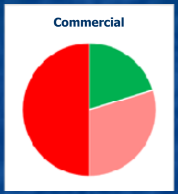
7.88 QW-h



7.59 QW-h



3.39 QW-h



2.67 QW-h

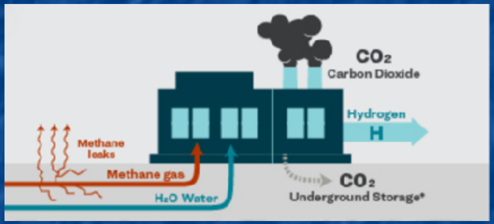
= THE SAME CHALLENGE CONFRONTING **ALL** ELECTRIFICATION SCHEMES

(including those dependent upon batteries)

Part I: Hydrogen Sources (cont'd)

Industry Driven Choice: H_2 gas synthesized via its separation from Fossil Fuels

Most particularly, by high-energy-investment Steam Reforming of Methane (SMR), with a claim that the GHG CO_2 byproduct of reforming would EVENTUALLY be captured



Contrary to 2019 report that:

"Overall, less than 0.7% of current hydrogen production

is from renewables or from fossil fuel plants equipped with CCUS"

But even more alarming (to me): The accepted meanings of "EVENTUALLY" and "CCUS"

"EVENTUALLY" because the broadly accepted goal is to increase the level of CO_2 capture to <15% of today's level of human CO_2 emissions, and doing that **only** by the year 2050

An apparently weak and likely climate-ineffective goal nevertheless widely calculated to still require a **120-133X** increase of today's level of carbon capture

Versus COMPLETE CO_2 capture instead requiring an almost ~ 1000X increase

Then hugely compounded by insights into the use of the acronym "CCUS"

Which, expanded into Carbon Capture, Utilization & Sequestration,

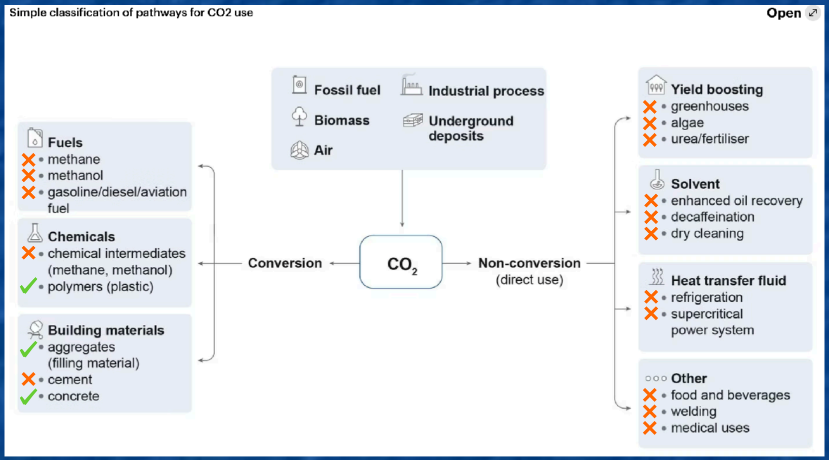
is popularly believed to mean carbon capture capable of blunting Global Warming

Instead, "CCUS" is being broadly applied to describe carbon capture

driven almost entirely by economic exploitation, rather than by suppression of warming

Economic exploitation involves carbon capture for days, months, years or perhaps decades

vs. suppression of global warming which instead requires CO_2 capture for a century or longer



Rated by the U.S. GAO: Only a very small subset of today's "CCUS" technologies actually qualify as climate-relevant Carbon, Capture, Utilization and SUSTAINED Sequestration

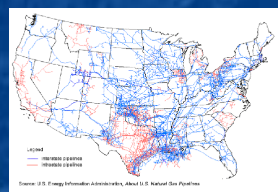
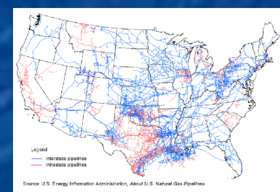
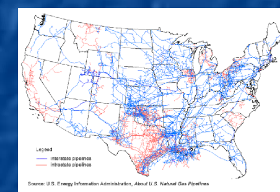
Part II: Transportation of Hydrogen

Climate-Driven & Industry-Driven Visions both assume H_2 transport

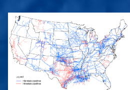
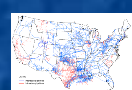
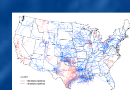
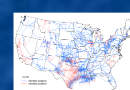
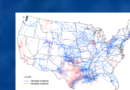
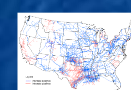
from its point-of-synthesis to its point-of-use via existing or similar infrastructure

But based on simple, direct, and unambiguous energy data and calculations:

H_2's 3X lower energy / volume means replacing NG will require 3X more pipeline capacity:

While 30X lower energy / volume of pressurized H_2 **gas** means replacing **liquid** Fossil Fuels will require VASTLY more pipeline capacity, as well as very different types of pipelines:







+ ? ? ?

While considerably more complex "Phase Diagram" science indicated that shipment of liquified H_2 would require such extreme low temperatures (**-240 to -253º C**) as to almost certainly rule out such transport:

Part III: Applications of H_2

Which I will summarize even **more** quickly because it was topic of the preceding section:

Heating:

H_2 combustion could replace Fossil Fuel combustion in high temperature furnaces

But rather than using electricity to produce that hydrogen via Electrolysis it would be

~ 1.5X more energy efficient to use that electricity directly in electric heaters

Similar direct use of electricity in heat pumps would produce a further 3X energy efficiency

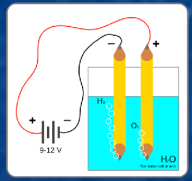
improvement for room air heating, while also allowing for room air cooling

H_2 Fueled Electric Power Plants: Make energy sense only if used for

matching the natural cycles of wind and solar electricity production

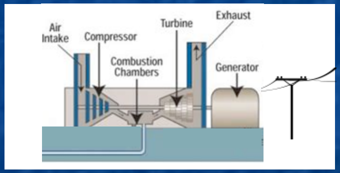
to the substantially different human cycles of electricity consumption

Electricity →



→ ***H_2*** →

→ ***H_2*** →



→ ***Electricity***

Highway Transportation: H_2 FCEVs will remain **2X to 3X times less energy efficient** than BEVs

But if research programs succeed, **future** FCEVs might indeed offer significantly longer range

Part III: Applications of H_2 (cont'd)

Rail Transportation:

Europe's already extensive mainline over-rail electric lines seems to make it more likely that travel onto now non-electrified branch lines will be provided via added "battery tenders"

Whereas, despite the immensely longer and entirely non-electrified U.S. main and branch lines, the fact that engines now use diesels to generate electricity powering electric wheel motors, makes replacing those diesel engines with batteries, or adding "battery tenders" plausible enough that proponents are beginning to argue for such a change

Ocean Transportation: Battery electric conversion seems to be prohibitively expensive

But while Fuel Cell driven ships are being discussed and test ships are even being built, the fuel of choice is now Ammonia, chosen because it can be stored onboard with only modest cooling or pressurization (**-33.3 ºC or 9.9 Atm.**) versus the extreme cooling required to liquify H_2 (**-240 to -253 ºC**)

Air Transportation: **ONLY** Fossil-fuels or their synthetic near equivalents are energetic enough AND light enough for income-producing (passenger / cargo hauling) long distance flights

My Personal Takeaways?

Climate-driven Visions of a Hydrogen Economy are severely challenged

by their underlying need for a radical expansion of Green electricity capacity,

a challenge shared with other visions such as those relying heavily on Batteries

But this nevertheless severely undercuts claims that a Hydrogen Economy

stands out as a potentially **far simpler & far faster** way of cutting GHG emissions

While **Industry-driven Visions** seem to implode when one digs into their claims

that huge amounts of GHG-free Hydrogen could be produced from fossil fuels

based on now grossly underutilized and grossly ineffective carbon capture schemes

The only place where use of Hydrogen seems to offer an unambiguously superior result

is for future research-improved **Fuel Cell Electric Vehicles** **(and possibly trains)**

where despite, lower Energy Efficiency, much longer Ranges might be possible

These limited opportunities for Hydrogen seem like they would be better addressed

by much more limited and much more focused additions to our infrastructure,

such as a new national highway network of Hydrogen-fuel offering truck-stops

(with a possibly parallel network of Hydrogen-fuel offering train-stops)

Credits / Acknowledgements

Some materials used in this class were developed under a National Science Foundation "Research Initiation Grant in Engineering Education" (RIGEE).

Other materials, including the WeCanFigureThisOut.org "Virtual Lab" science education website, were developed under even earlier NSF "Course, Curriculum and Laboratory Improvement" (CCLI) and "Nanoscience Undergraduate Education" (NUE) awards.

This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.