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Transforming ENERGY

Pathways for Negative-Emissions Hydrogen: Opportunities and R&D Needs

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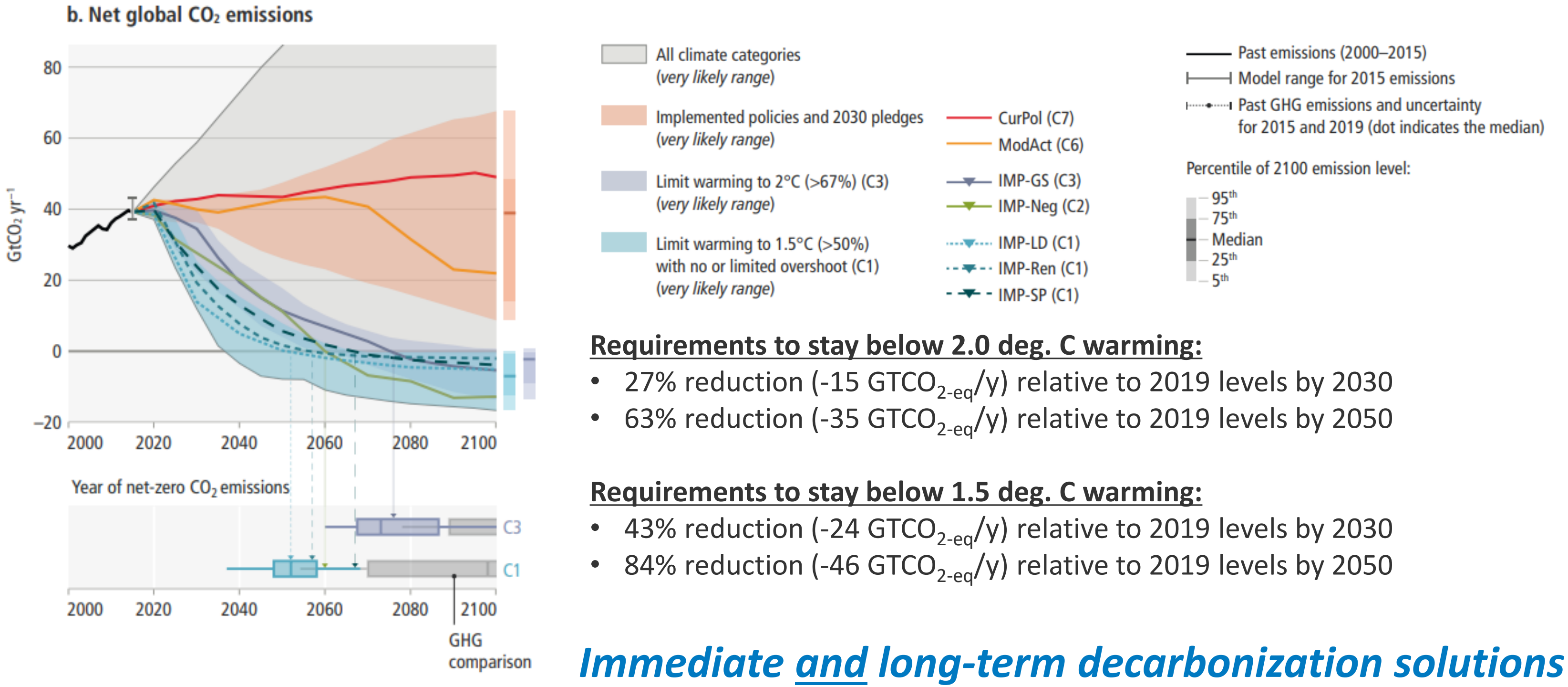
Clear and Present Danger

Modelled mitigation pathways that limit warming to 1.5°C, and 2°C, involve deep, rapid and sustained emissions reductions.



<u>Requirements to stay below 2.0 deg. C warming:</u>

- 27% reduction (-15 $GTCO_{2\text{-}eq}$/y) relative to 2019 levels by 2030
- 63% reduction (-35 $GTCO_{2\text{-}eq}$/y) relative to 2019 levels by 2050

<u>Requirements to stay below 1.5 deg. C warming:</u>

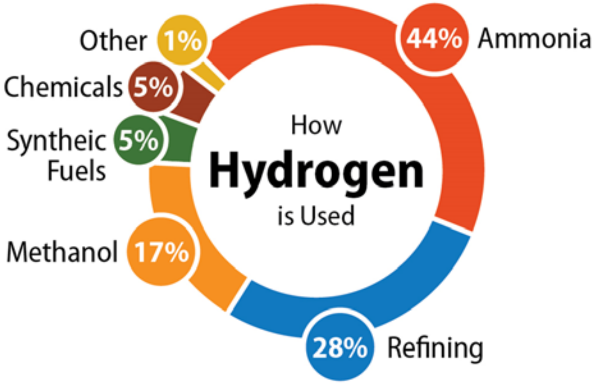
- 43% reduction (-24 $GTCO_{2\text{-}eq}$/y) relative to 2019 levels by 2030
- 84% reduction (-46 $GTCO_{2\text{-}eq}$/y) relative to 2019 levels by 2050

Immediate <u>and</u> long-term decarbonization solutions needed

Source: IPCC ARG WGIII

Trends in Global H_2 Consumption

In 2020, global demand for H_2 reached an estimated 820 billion nm^3 (~74 million metric tonnes)



Current H_2 demand dominated across ammonia synthesis, hydrocarbon refining, and methanol synthesis (~89%)

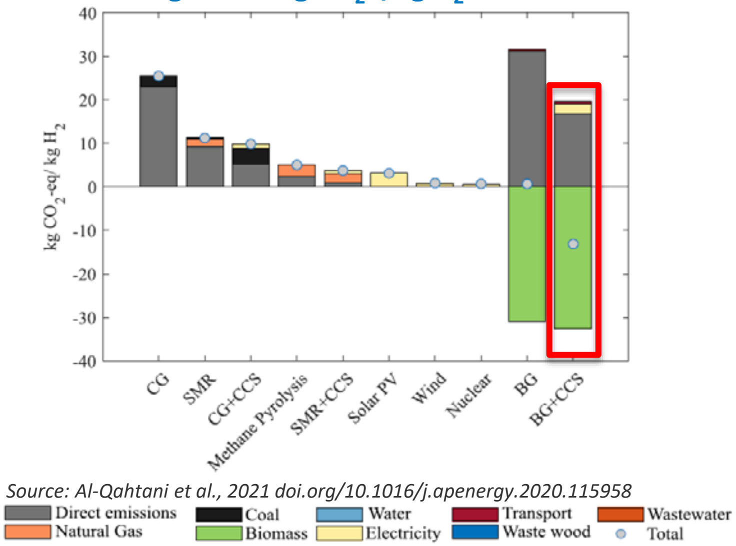
Source: S&P Global

Emissions Reduction Potential of H_2

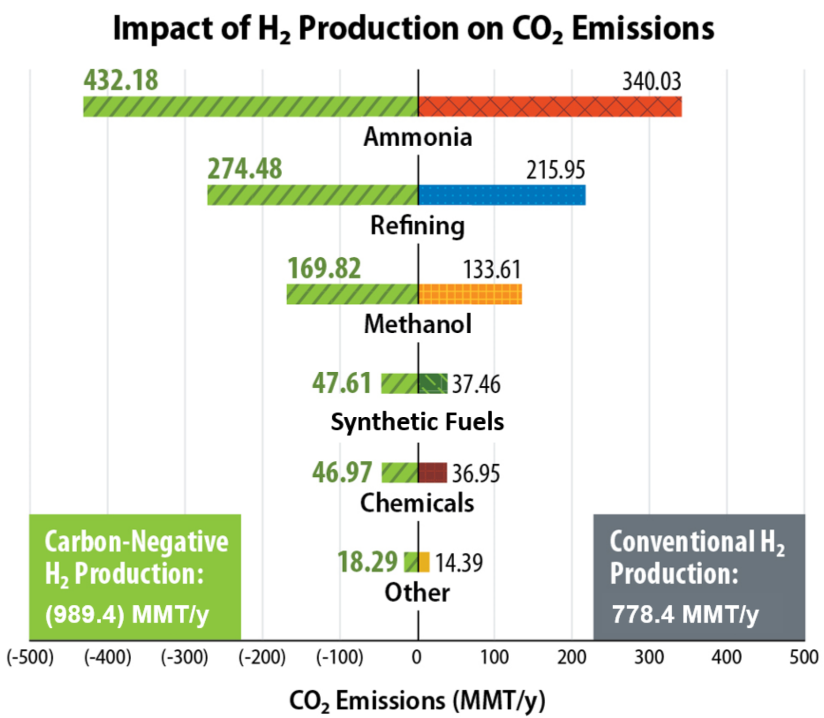
Global H_2 Production Statistics:
- ~82% produced via reforming of methane / hydrocarbons
- ~15% produced via coal gasification
- ~3% from electrolysis/other

H_2 Emission Statistics:
- 9.4 kg CO_2e/kg H_2 (SMR)
- 16.8 kg CO_2e/kg H_2 (Coal)
- ~0 kg CO_2e/kg H_2 (electrolysis)

→ Avg = 10.3 kg CO_2e/kg H_2



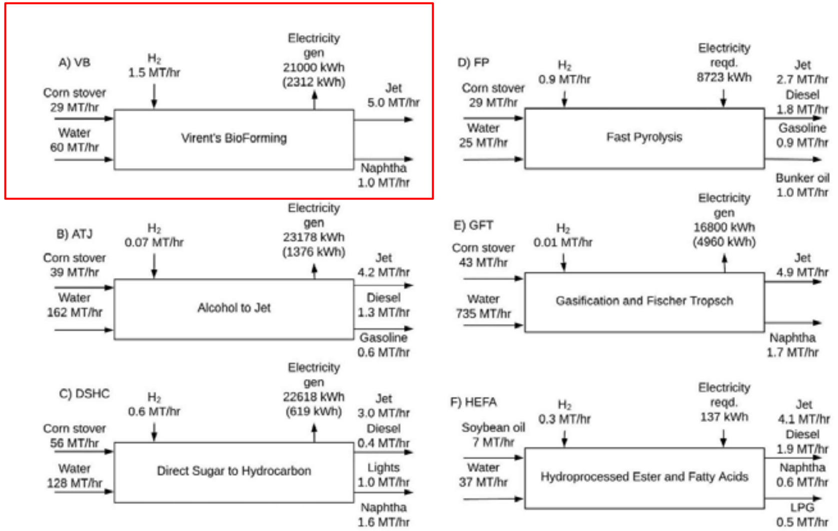
Source: Al-Qahtani et al., 2021 doi.org/10.1016/j.apenergy.2020.115958



Potential to avoid > 0.7 GT CO_2e/y globally + removal of ~ 1.0 GT CO_2e/y across current markets representing >10% of IPCC 2 deg. C 2030 target

Carbon Emitters to Net Carbon Sinks

Product and technology pathways	Baseline carbon intensity	Carbon intensity using green H_2	Carbon intensity using carbon-negative Bio-H_2
BF-BOF steel production ($t\text{-}CO_2/t\text{-}HM$) ($H_2$ replacing pulverized coal for hot air blast)	2.20	1.78	1.13 to 1.65
DRI-EAF gas steel production ($t\text{-}CO_2/t\text{-}HM$) ($H_2$ replacing all DRI gas consumption)	1.35	0.29 (renewable electricity) 0.80 (grid electricity)	−0.61 to 0.39
NG SMR-based ammonia production ($t\text{-}CO_2/t\text{-}NH_3$) (1:1 replacement of original H_2 consumption)	1.97	0.27	−4.04 to −0.6
NG SMR-based methanol production ($t\text{-}CO_2/t\text{-}MeOH$) (1:1 replacement of original H_2 consumption)	2.57 (including feedstock emission) 0.86 (energy emission)	0.77 (no feedstock emission when using external captured CO_2 as feedstock)	−3.89 to −0.17 (no feedstock emission when using external captured CO_2 as feedstock)
NG-based ethylene production ($t\text{-}CO_2/t\text{-}Eth$) (1:1 replacement of original H_2 consumption)	1.42 (including feedstock emission)	0.58	−2.93 to −0.43



NE-H_2 provides opportunity to transform carbon emitters to carbon sinks across multiple sectors

NE-H_2 can be used synergistically with other renewables to dramatically drive down CI

Sugar-to-Jet CI: 2.03 kg CO_2e/kg (GREET)

5.0 MT/hr Jet * 2.03 kg CO_2/kg = 10.15 MT CO_2/hr
1.5 MT H_2/hr * -13 kg CO2/kg = -19.5 MT CO_2/hr

Sugar-to-Jet CI (NE-H_2) = -1.8 CO_2e/kg

Source: Columbia Center for Global Energy Policy: The Potential Role of Biohydrogen in Creating a Net-Zero World, Tanzil et al., doi.org/10.1016/j.biombioe.2020.105942

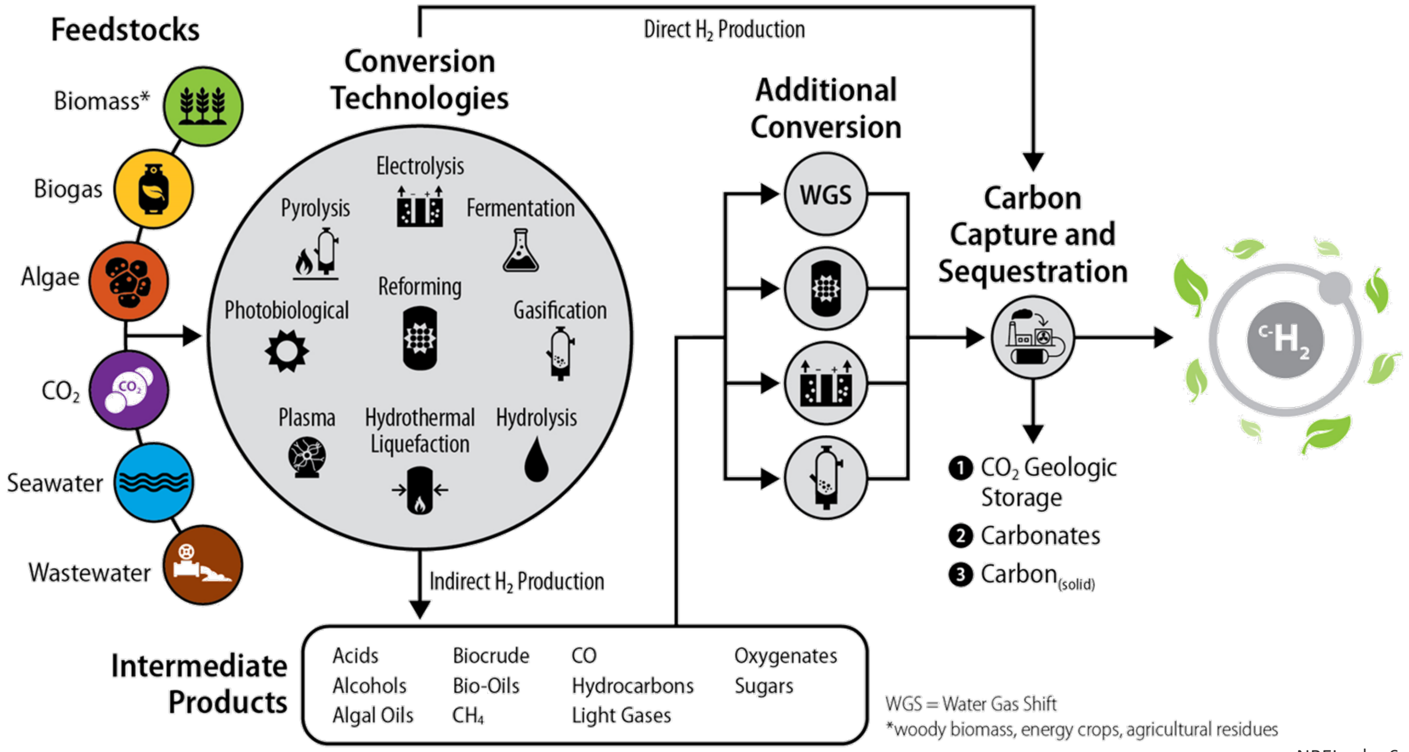
Pathways for NE-H_2

Many feedstock / pathway combinations possible for NE-H_2 production

Is there a one-size-fits-all solution to NE-H_2?

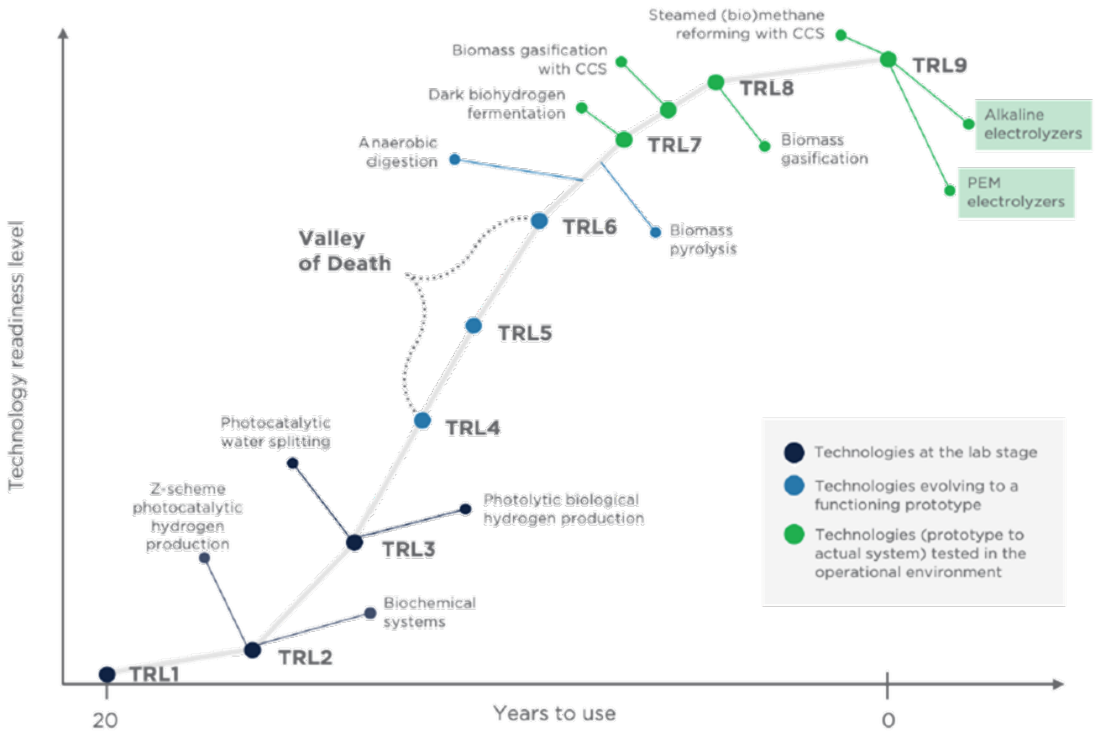
Which areas would benefit from additional R&D and analysis?

Are the long-term solutions different than near-term?



Immediate Options for NE-H_2

Immediate and longer-term decarbonization solutions needed to reach IPCC goals



RNG Reforming + CCS	**[TRL 9]**
Biomass Gasification + CCS	**[TRL 7-8]**
Dark Fermentation	**[TRL 7]**
Biomass Pyrolysis	**[TRL 6-7]**
Anaerobic Digestion	**[TRL 6-7]**

Source: Columbia Center for Global Energy Policy: The Potential Role of Biohydrogen in Creating a Net-Zero World

Challenges for Biomass-Derived NE-H_2 (Columbia)

1. Energy is required for harvesting, gathering, transporting, storage, and conversion of feedstocks. If biomass feedstocks are not carefully selected and the energy consumed during processing is not closely monitored and controlled, the carbon footprint can exceed that of fossil hydrogen

2. Carbon-negativity of bio-H_2 is maximized through use of agricultural and municipal wastes, manures, sewages, etc. which are a constrained resource presenting obstacle to wide-scale deployment. Some feedstocks like RNG may benefit more from direct substitution of NG than H_2 formation

3. Cost and general feasibility tied to co-location of low-cost waste feedstocks and opportunities for geological storage of CO_2. Sites meeting both criteria not equally dispersed globally

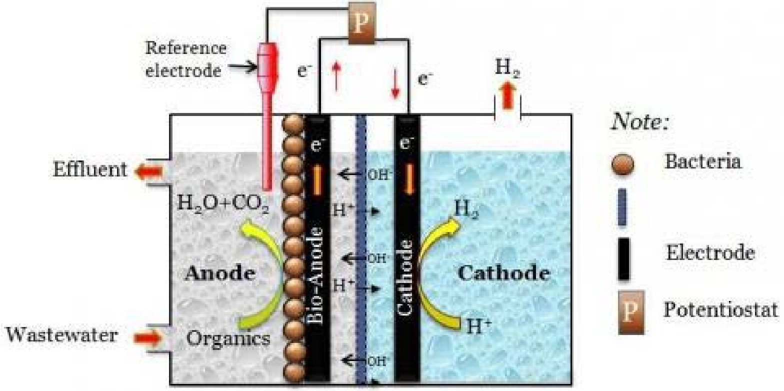
4. Improving technical performance, including catalyst fouling, feedstock heterogeneity issues (inorganics), gas cleaning, low partial pressures, low volumetric yields in metabolic pathways

Will these challenges be showstoppers for widespread deployment?
What would a long-term, de-risked, NE-H_2 portfolio look like?

Source: Columbia Center for Global Energy Policy: The Potential Role of Biohydrogen in Creating a Net-Zero World

Lower TRL Technologies for NE-H_2

Microbial Electrochemical Cell



Anode: $C_2H_4O_2 + 2H_2O \rightarrow 2CO_2 + 8e^- + 8H^+$

Cathode: $8H^+ + 8e^- \rightarrow 4H_2$

- Lower voltage req. than green H_2
- Pure CO_2 stream produced
- ~360 billion m^3/y wastewater available globally

Non-Thermal Plasma Reforming

Plasma Reforming of $CO_2 + H_2O$ Mixtures

$H_2O \rightarrow H_2 + 0.5O_2$

$CO_2 \rightarrow CO + 0.5O_2$

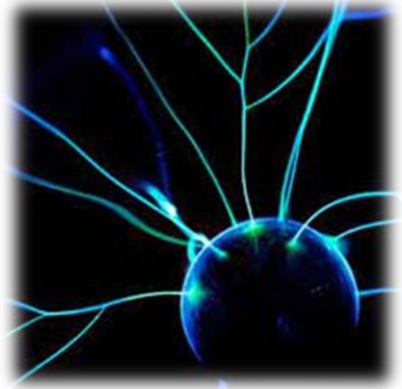
$CO_2 + H_2 \rightarrow C + H_2O$

$2CO \rightarrow CO_2 + C$

$CO + 3H_2 \rightarrow CH_4 + H_2O$

$CH_4 \rightarrow C + 2H_2$

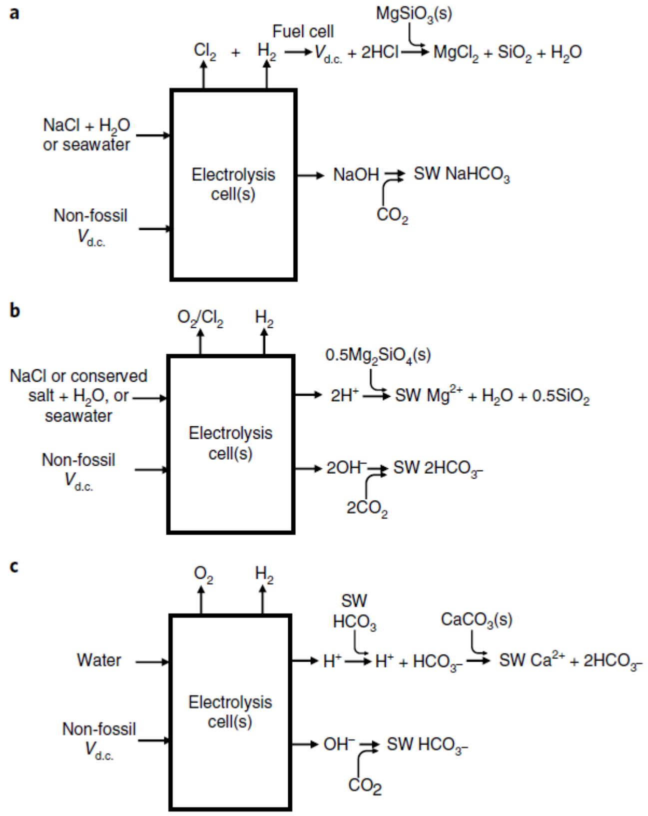
Single-step process capable of sequestering carbon and producing H_2 simultaneously

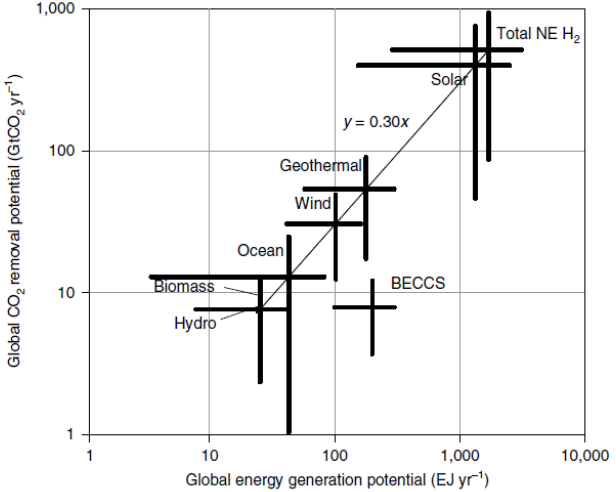


Source: https://uwaterloo.ca/scholar/h95lee/research/mecs, https://www.frontiersin.org/research-topics/41852/non-thermal-atmospheric-pressure-plasma-and-its-biological-applications

Lower TRL Technologies for NE-H_2

Saline Water Electrolysis





> 7x higher CO_2 removal potential per unit energy generated for SWE than BECCS

Utilize renewable electricity to drive H_2O electrolysis and leverage OH- formation/alkalinity to spontaneously capture CO_2 in mineral bicarbonates / carbonates

Source: Rau et al., The global potential for converting renewable electricity to negative-CO2-emissions hydrogen

Low TRL Challenges & R&D Needs

R&D Needs in MEC

- Low synthesis rates
- High internal resistances / ohmic losses
- Low durability; biofouling

- Enhancing microbe/anode electron transport
- Scalable designs

R&D Needs in NTP

- Poor selectivity
- Unoptimized reactor designs
- Degradation of heterogenous catalysts

- Development of tandem catalysts
- Commercially scalable designs

R&D Needs in SWE

- Land use/energy req. for minerals harvesting
- Optimization of electrolysis performance

- Minimize wastes (Cl_2)
- Mitigate environmental upsets

Conclusions and Way Forward

1. A variety of feedstock – pathway combinations exist to produce NE-H_2 spanning a wide TRL range, each with unique tradeoffs and opportunities. *There may not be a one-size-fit-all solution*

2. Carbon negative hydrogen can enable deep decarbonization of some of the worst polluting processes as well as synergize with other sustainable practices

- **High TRL pathways relatively well characterized, need additional cross-cutting analysis to inform value proposition of emerging technologies; what are the optimal use cases? Are the near-term technologies also best suited for long-term use?**

- **How does the ever-evolving policy landscape impact the value proposition for NE-H_2 (e.g., 45Q vs. 45V)?**

Kg of CO2 per kg of H2	Credit Value ($)
4 - 2.5 kg CO2	$0.60 / kg of H2
2.5 - 1.5 kg CO2	$0.75 / kg of H2
1.5 - 0.45 kg CO2	$1.00 / kg of H2
0.45 - 0 kg CO2	$3.00 / kg of H2

Q&A

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