FAMU-FSU
Engineering

Georgia Institute
of Technology

Fossil Energy in the H_2 Economy – A Carbon-Water-Energy Adaptive Evaluation Platform

Project number: DE-FE0032084

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Contents

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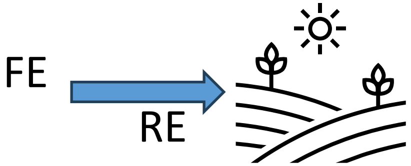
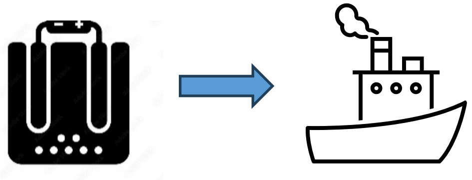
Project objectives

Major Goals and Objectives:

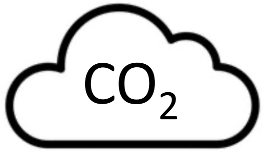


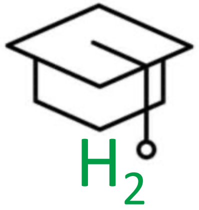
- Support the efficient, environmentally sound integration of fossil fuels into the H_2 economy as a complement - and not a competitor - to more renewable energy resources penetration;
- Review and assess fossil-focused hydrogen production and utilization within the hydrogen economy;



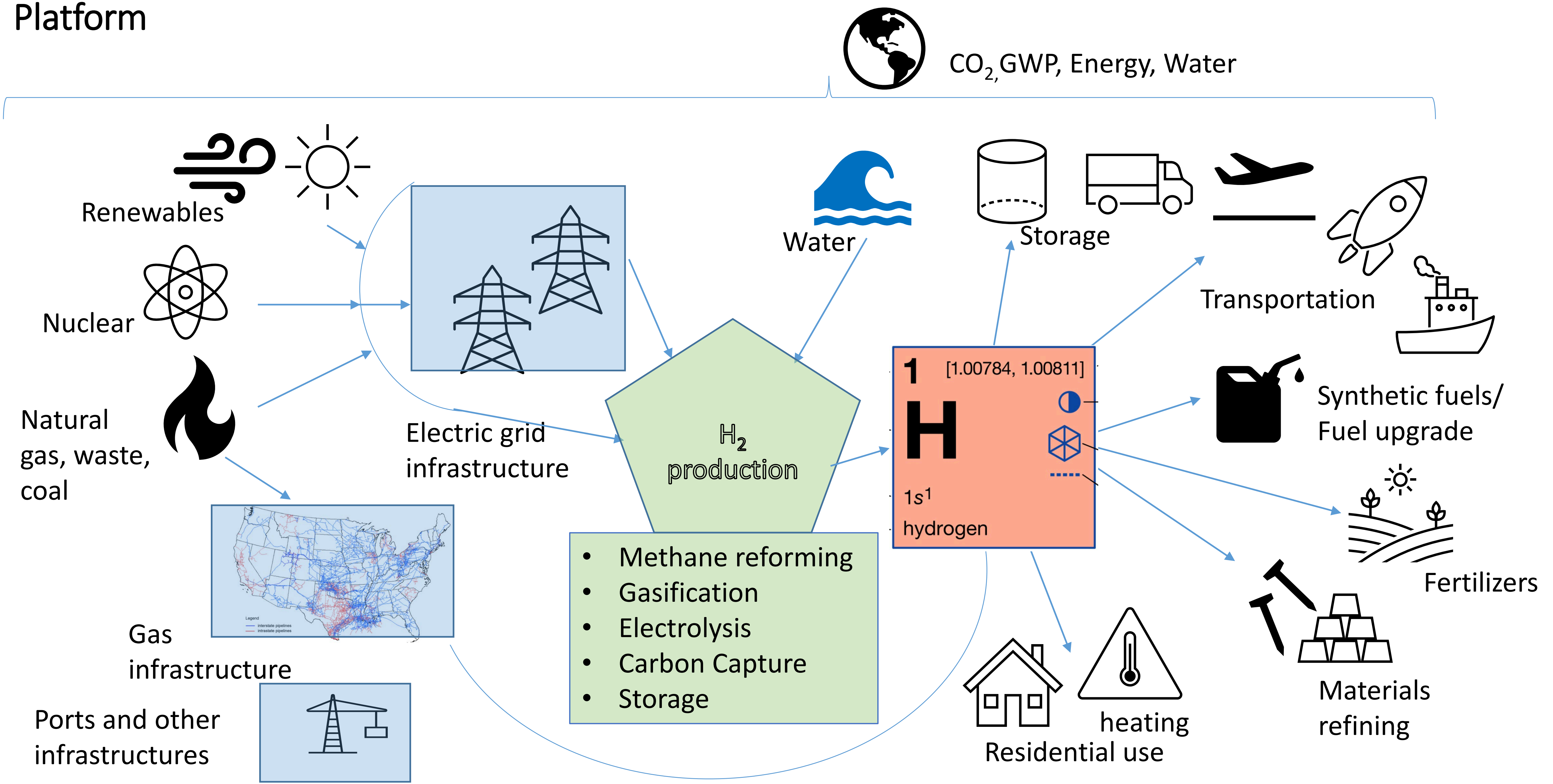
Specific Objectives:

- Quantify the water intensity (water-energy nexus);
- Quantify the carbon footprint of the different fossil fuel hydrogen technologies (generation, transport, storage, and use) and identify existing and novel approaches to mitigate carbon footprint;
- Educate and prepare the next generation minority engineers on relevant aspects of the H_2 economy.





Fossil Energy in the Hydrogen Economy -A Carbon-Water-Energy Nexus Adaptive Evaluation Platform



CO_2, GWP, Energy, Water

Renewables

Nuclear

Natural gas, waste, coal

Electric grid infrastructure

Gas infrastructure

Ports and other infrastructures

Water

H_2 production

- Methane reforming
- Gasification
- Electrolysis
- Carbon Capture
- Storage

1 [1.00784, 1.00811]

H

$1s^1$

hydrogen

Storage

Transportation

Synthetic fuels/ Fuel upgrade

Fertilizers

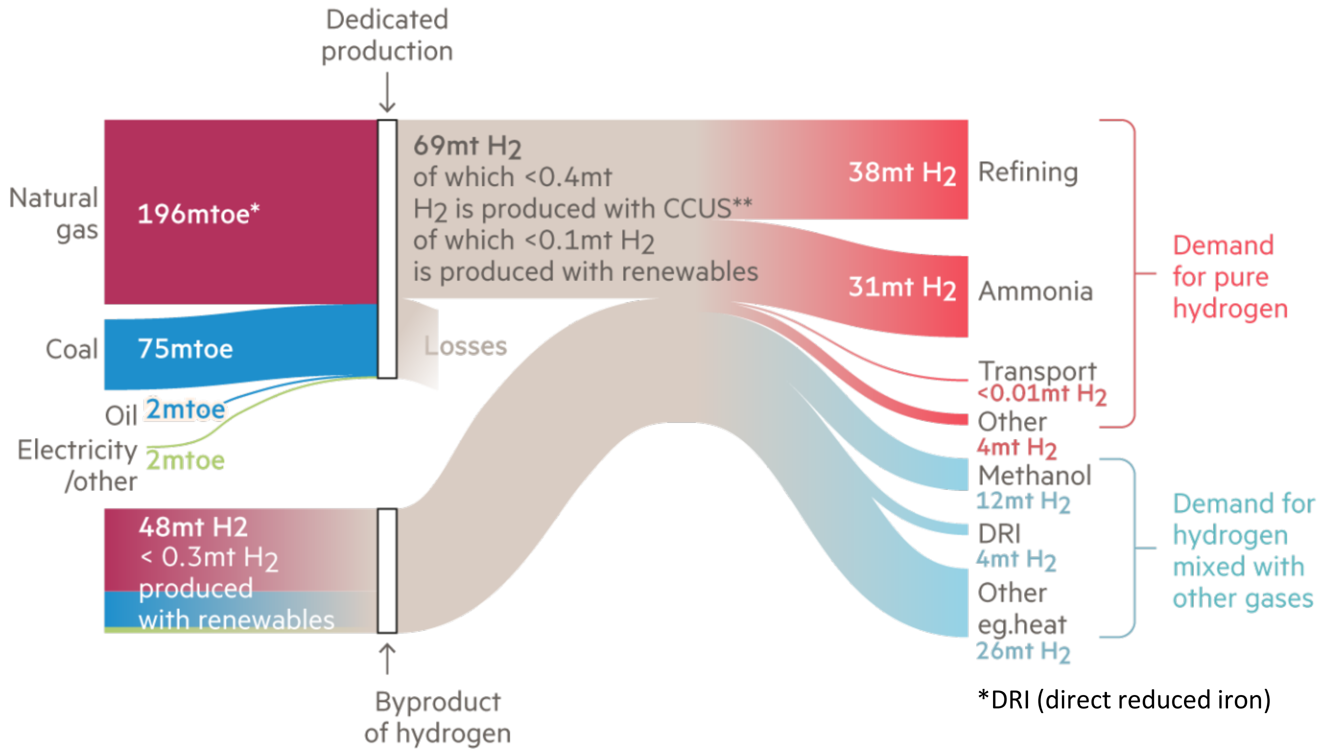
Materials refining

heating

Residential use

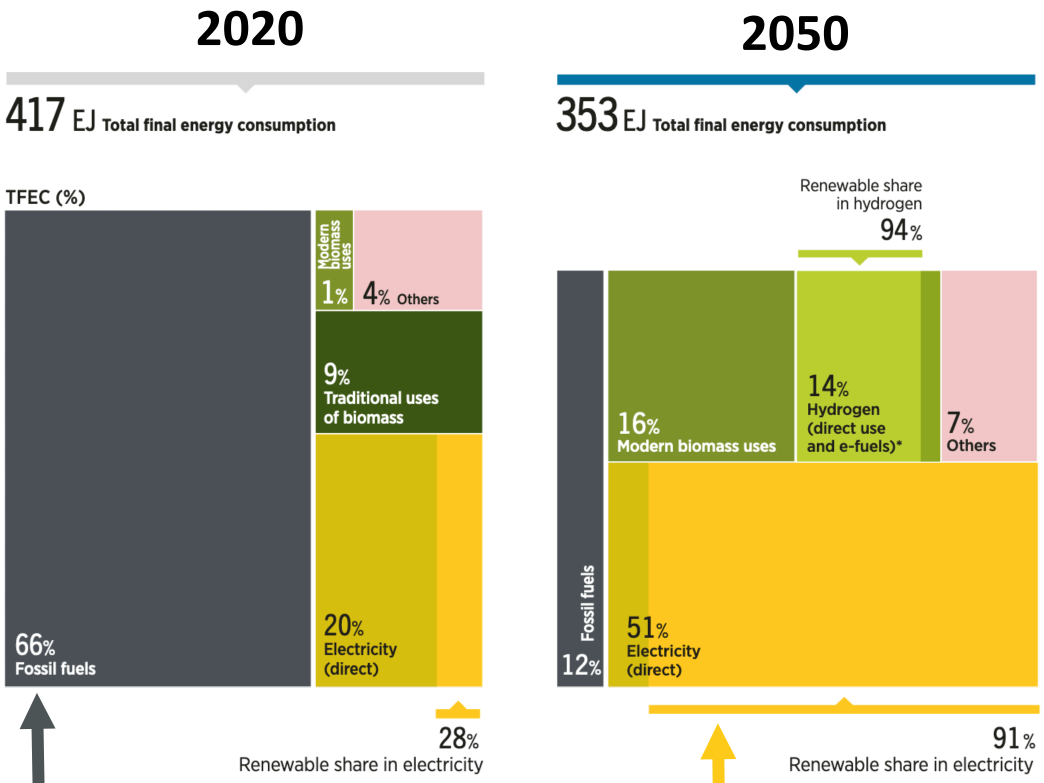
Hydrogen today and into the future

Hydrogen value chains



*DRI (direct reduced iron)

* mtoe=million tonnes of oil equivalent
** CCUS=carbon capture, utilisation and storage
Source: International Energy Agency
© FT

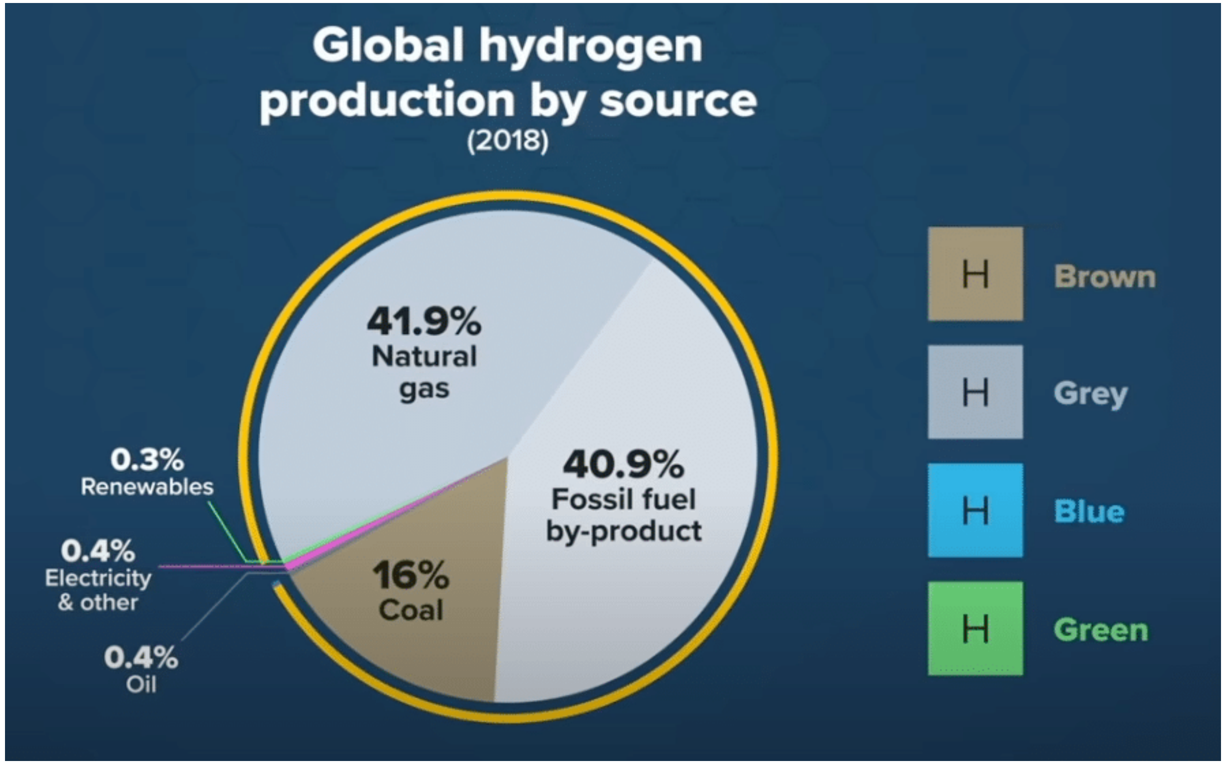


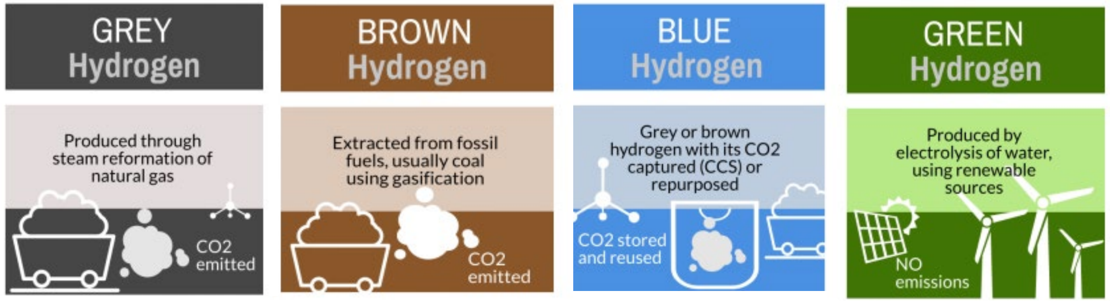
IRENA, 2023

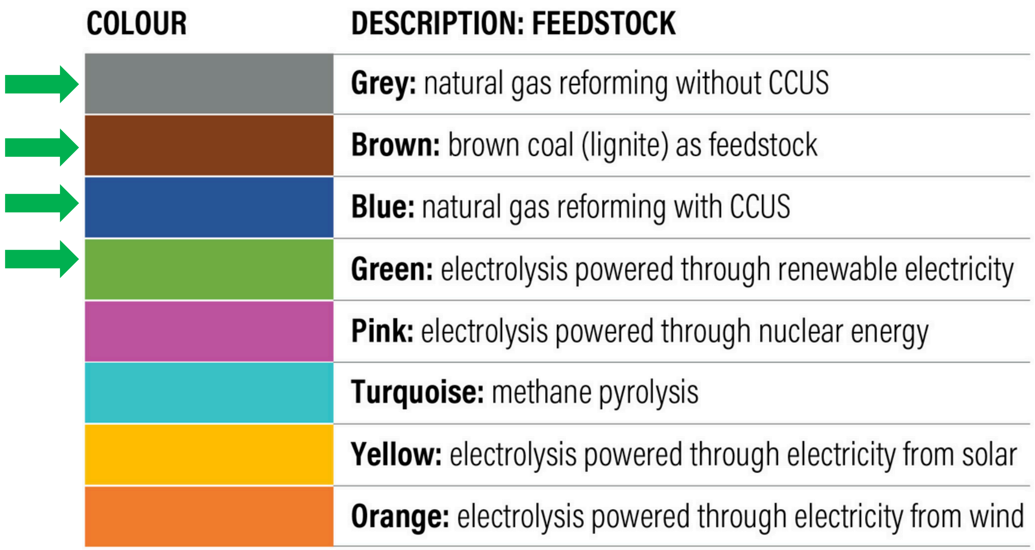
High fossil fuel reliance

Increase in renewables

Hydrogen today







COLOUR	DESCRIPTION: FEEDSTOCK
⬛	**Grey:** natural gas reforming without CCUS
🟫	**Brown:** brown coal (lignite) as feedstock
🟦	**Blue:** natural gas reforming with CCUS
🟩	**Green:** electrolysis powered through renewable electricity
🟪	**Pink:** electrolysis powered through nuclear energy
🟦	**Turquoise:** methane pyrolysis
🟨	**Yellow:** electrolysis powered through electricity from solar
🟧	**Orange:** electrolysis powered through electricity from wind

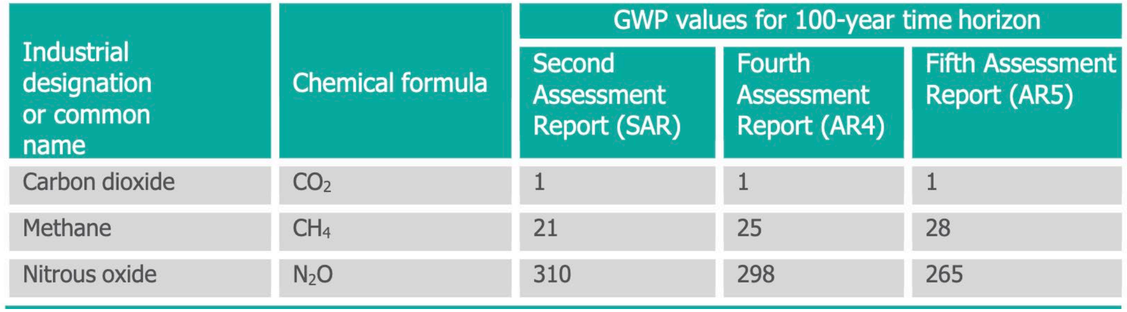
Use as fuel…

Uses

- → Direct combustion
  - Turbines
- → Fuel cells

- In modern aircraft its deployment requires significant changes to the airplane/propulsion system to accommodate fuel storage and address associated thermal management challenges.

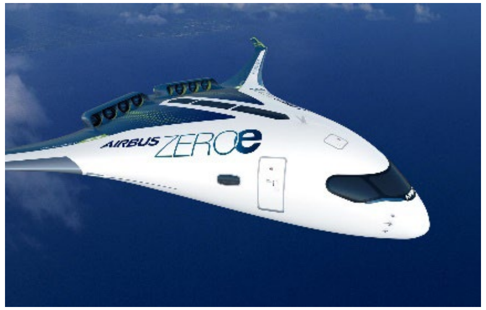
Global warming potential (GWP) values relative to CO_2



Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second Assessment Report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	21	25	28
Nitrous oxide	N_2O	310	298	265

Montgolfier brothers, 1783

Airbus, 2023



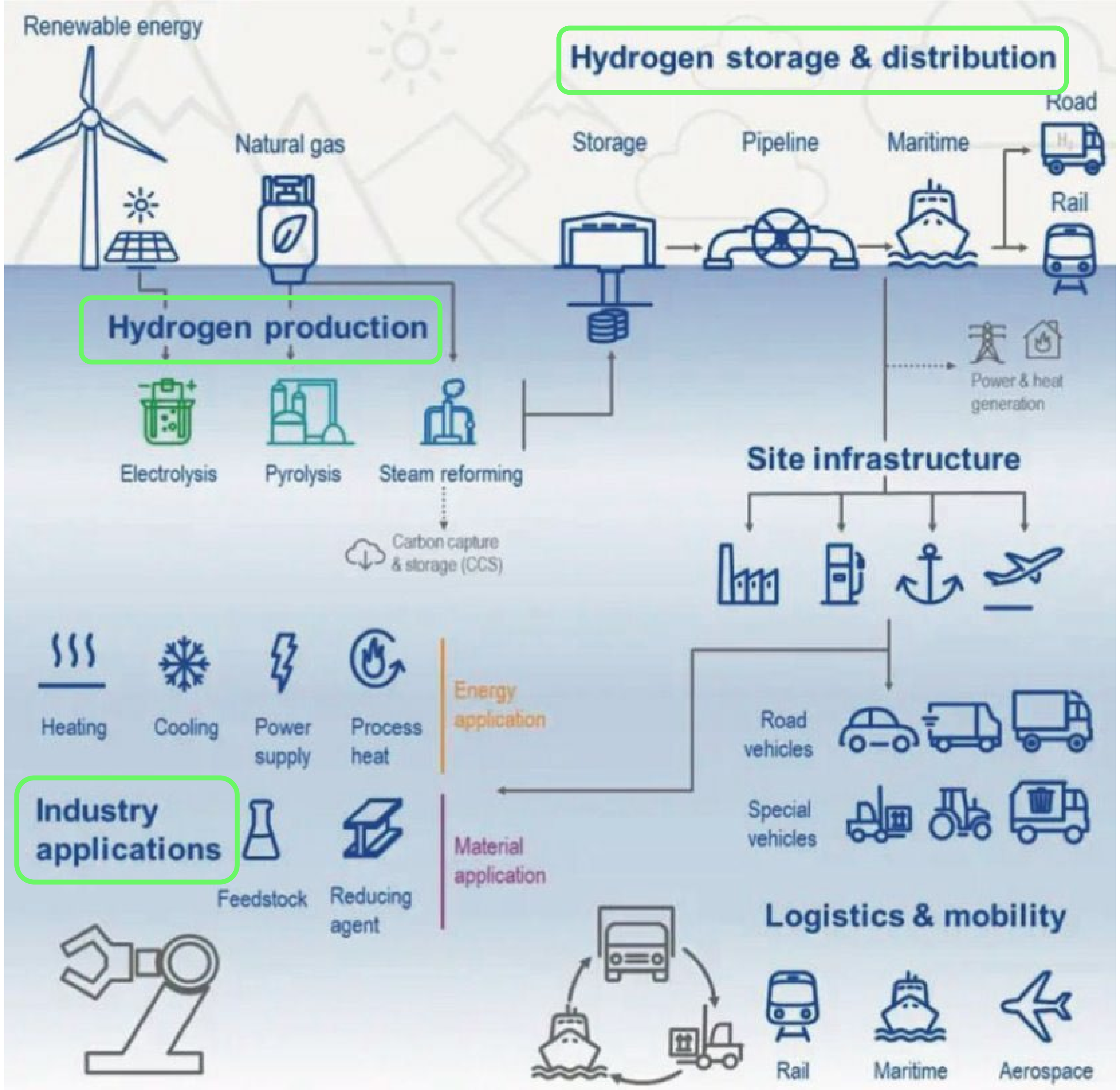
Hydrogen value chain fields, interconnection and roles

1) Production

2) Storage

3) Distribution (storage)

4) End-user consumption



Source: Garcia-Navarro et al. (2023)

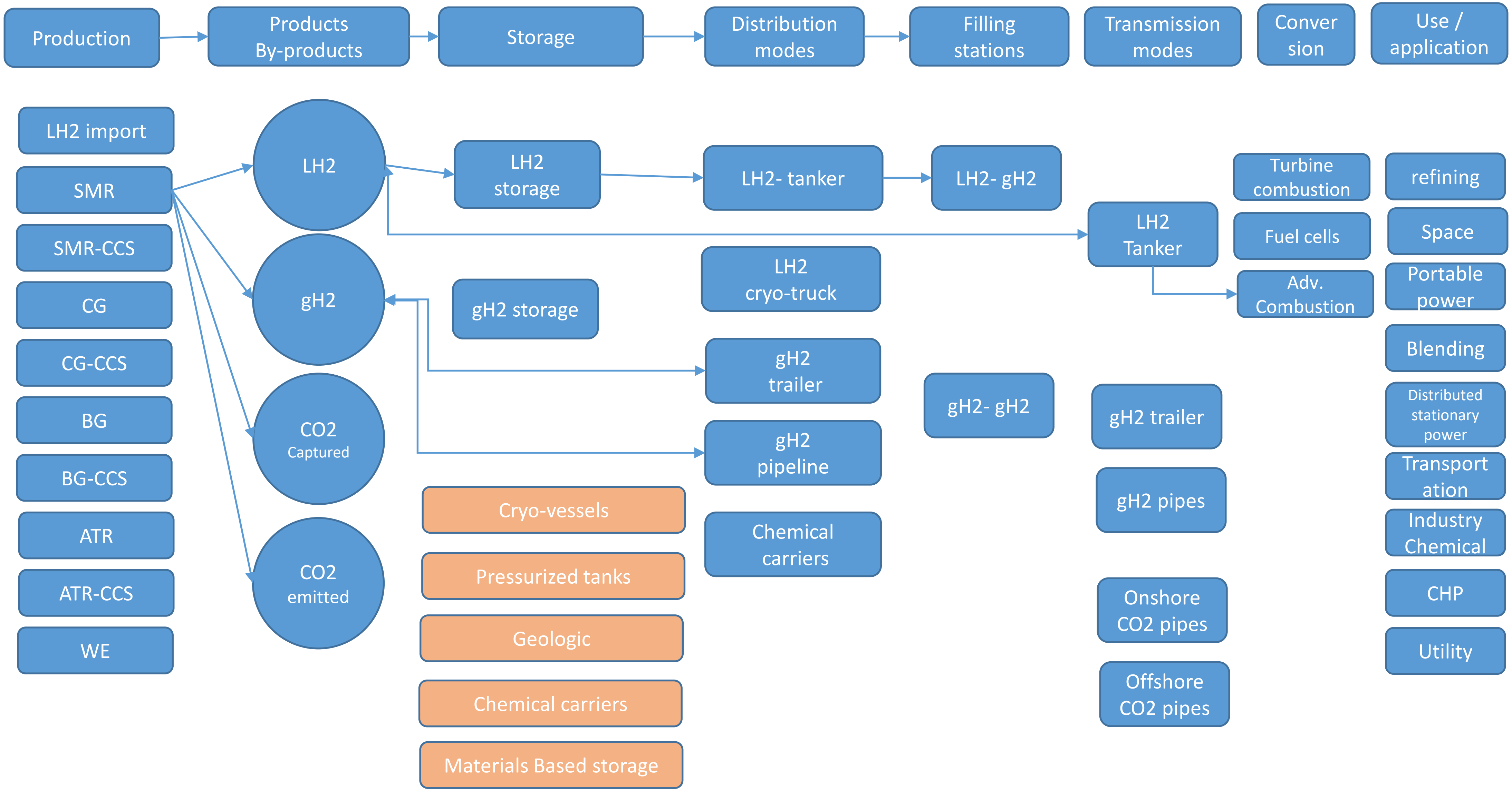
RESOURCES:

- Fuel
- Energy
- Water

Hydrogen supply chain superstructure

Additional metrics:

- LCA - cost
- LCOH



Production → Products By-products → Storage → Distribution modes → Filling stations → Transmission modes → Conversion → Use / application

Production:
- LH2 import
- SMR
- SMR-CCS
- CG
- CG-CCS
- BG
- BG-CCS
- ATR
- ATR-CCS
- WE

Products By-products:
- LH2
- gH2
- CO2 Captured
- CO2 emitted

Storage:
- LH2 storage
- gH2 storage
- Cryo-vessels
- Pressurized tanks
- Geologic
- Chemical carriers
- Materials Based storage

Distribution modes:
- LH2- tanker
- LH2 cryo-truck
- gH2 trailer
- gH2 pipeline
- Chemical carriers

Filling stations:
- LH2- gH2
- gH2- gH2

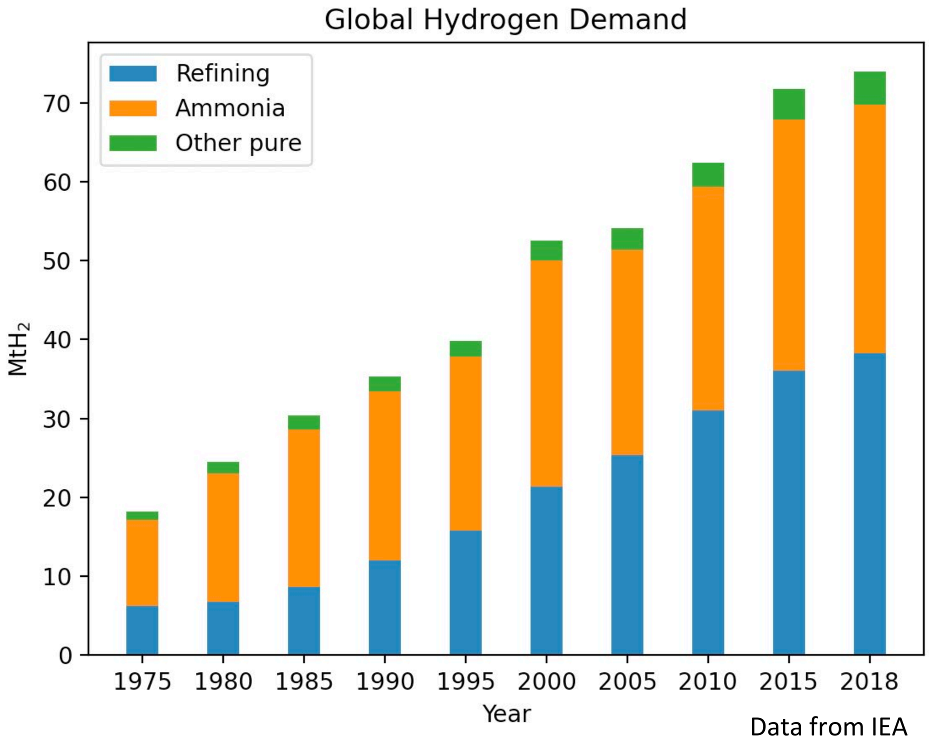
Transmission modes:
- LH2 Tanker
- gH2 trailer
- gH2 pipes
- Onshore CO2 pipes
- Offshore CO2 pipes

Conversion:
- Turbine combustion
- Fuel cells
- Adv. Combustion

Use / application:
- refining
- Space
- Portable power
- Blending
- Distributed stationary power
- Transportation
- Industry Chemical
- CHP
- Utility

Big Picture Questions

- *What role should fossil fuels play in the development of the hydrogen economy?*
- *Can Fossil Energy (FE) complement the introduction of renewable forms of hydrogen production?*



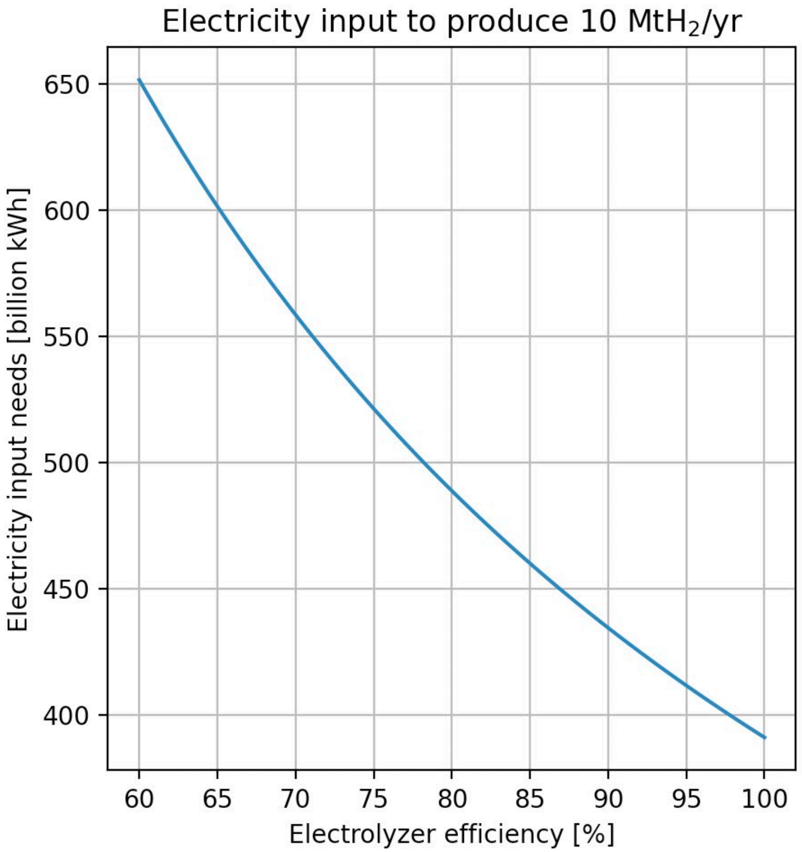
Mt = 10^9 kg = billion kg

- US ~ 10 MtH_2.
- Worldwide, approximately 96% of H_2 is generated from fossil fuels, particularly from steam methane reforming (SMR) of natural gas but also from coal gasification.

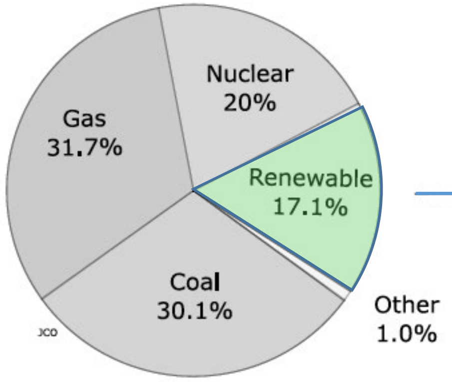
- Could we, today, generate all H_2 via electrolysis from renewables?

Context

- 10 MtH_2 =10 x 10^9 kg H_2 (10 billion kg); (Others use MMT).
- Ideal electrolysis electricity requirement (HHV) 141.9 MJ/kg = 39.4 kWh/kg



- US electricity generation in 2020 ~ 4009 billion kWh (utility scale) + 41.7 billion small scale. [EIA]

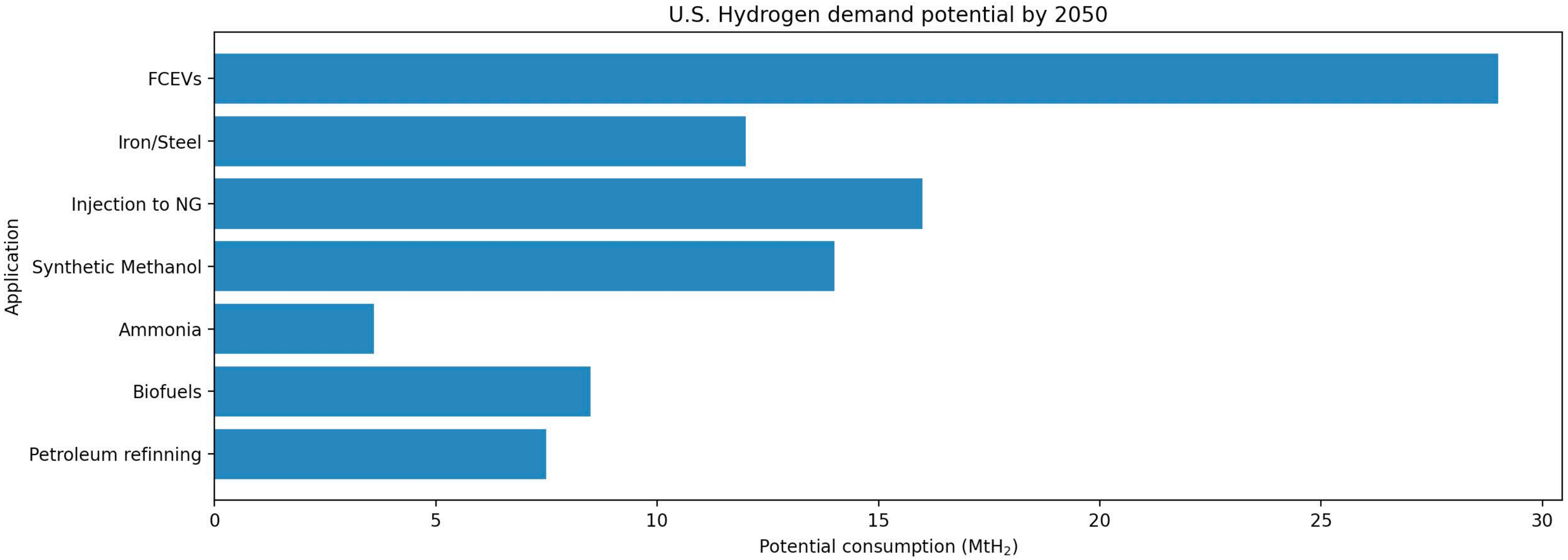


Da Rosa, Ordonez, 2021

~693 billion kWh (from renewables) (17.1%).

How much H_2 will we need?

U.S. Current use: 10 MtH_2



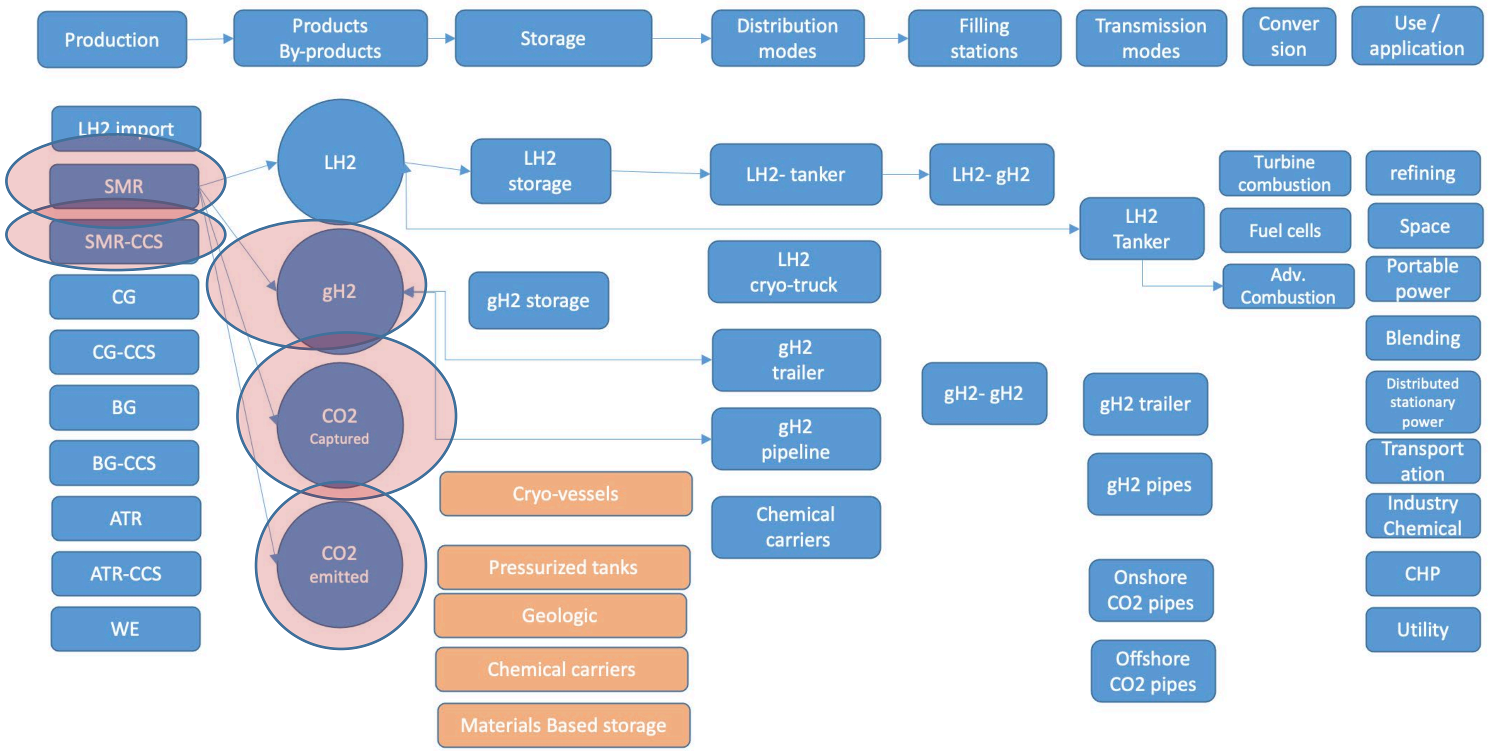
Plot from data from ANL, 2020 (Warning, categories may not be additive)

Future: ~85 MtH_2

Progress and current status of the project

1. CO_{2e} emissions
2. Water use considerations – Explicit and Implicit
3. Levelized Cost of Hydrogen and dynamic maps representation
4. Dashboard implementation status
5. Final considerations and future plans

1. CO2 footprint



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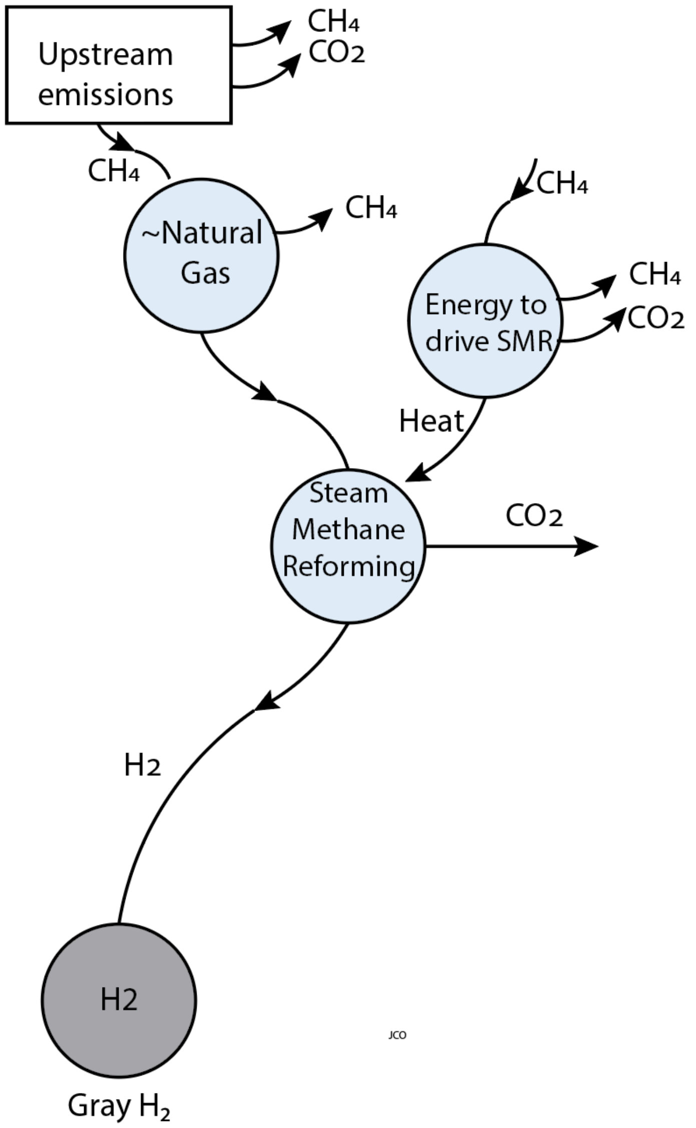
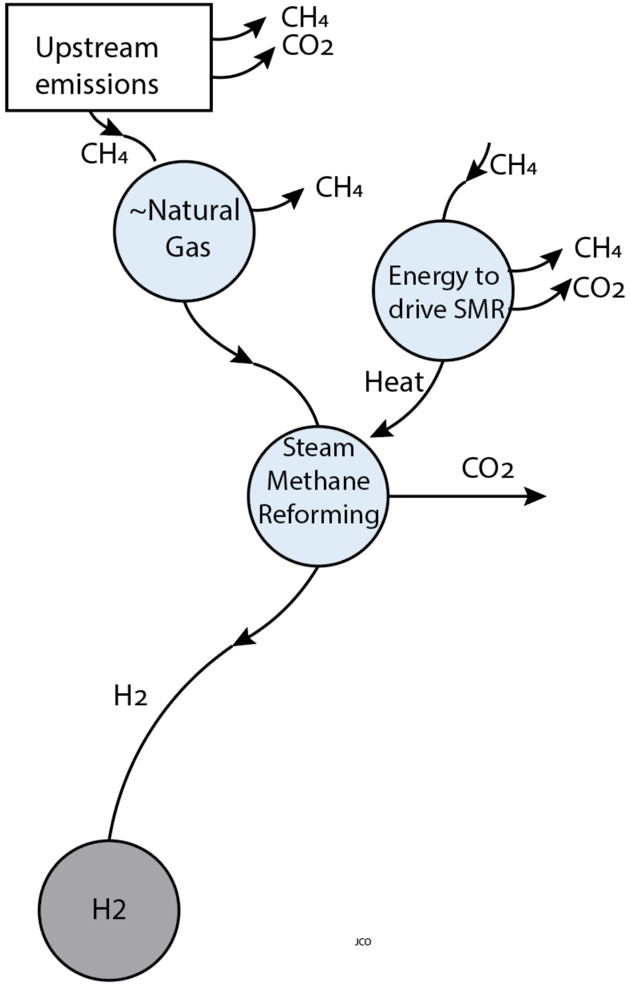


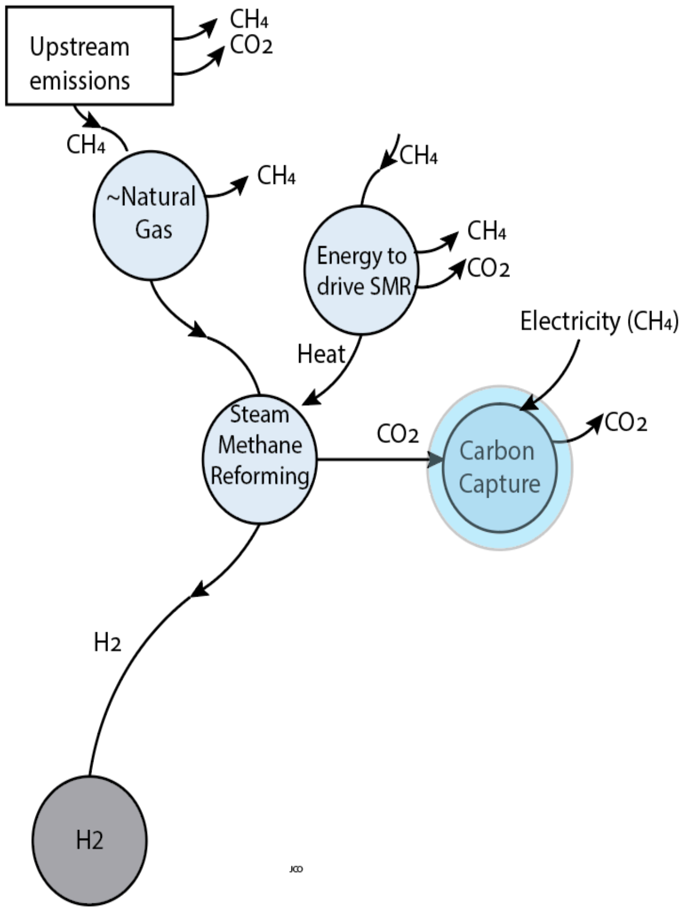
Upstream emissions
CH_4
CO_2
CH_4
~Natural Gas
CH_4
CH_4
Energy to drive SMR
CH_4
CO_2
Heat
Steam Methane Reforming
CO_2
H_2
H2
Gray H_2

JCO

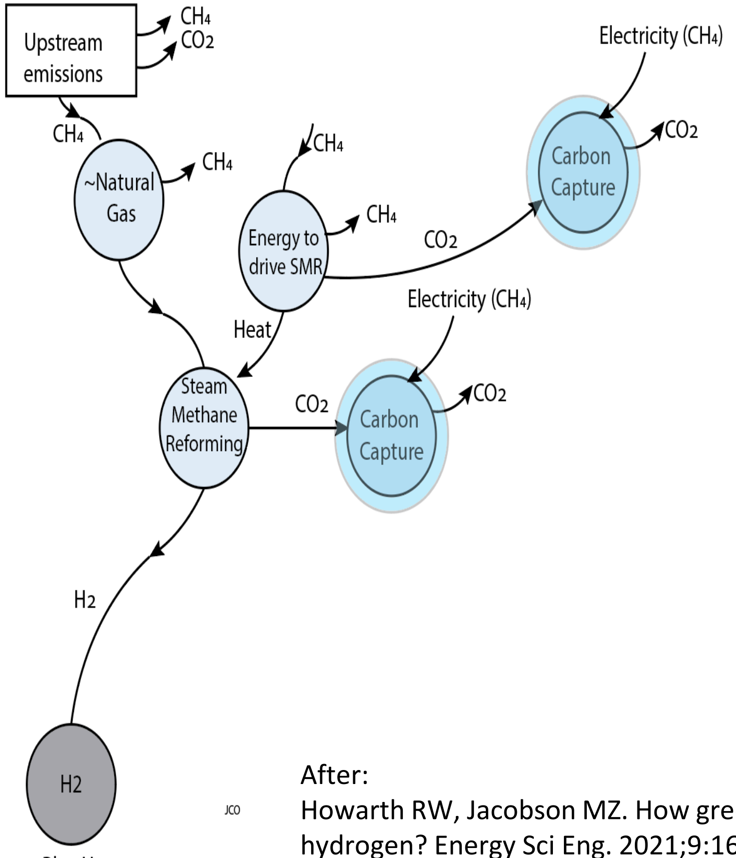
Three different levels of carbon capture



Gray H_2



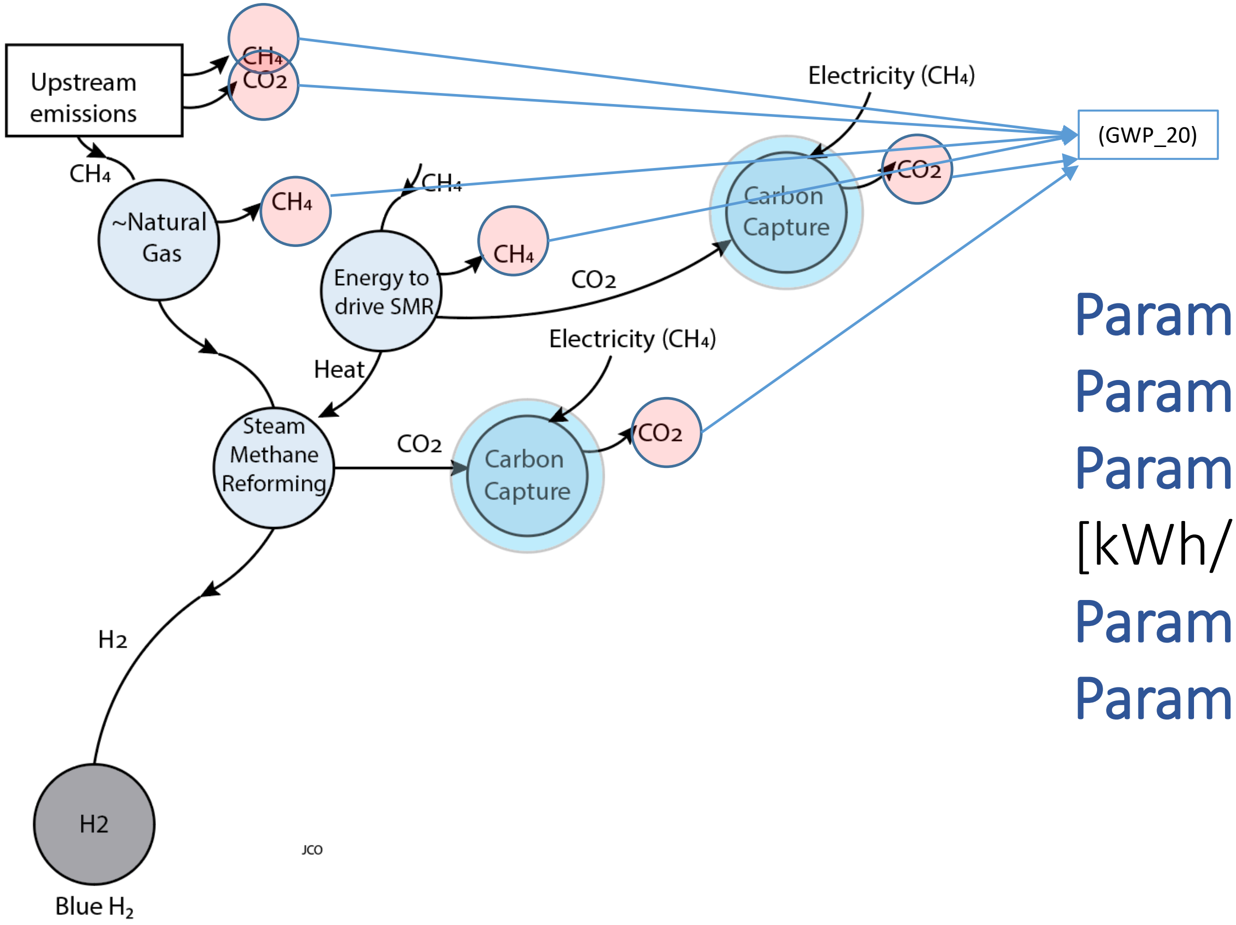
Blue H_2



Blue H_2

After:
Howarth RW, Jacobson MZ. How green is blue hydrogen? Energy Sci Eng. 2021;9:1676– 1687. https://doi.org/10.1002/ese3.956
26 July 2021

Blue H2- carbon capture in heat production to drive SMR



Parameter 1: CH4 leakage (fugitive CH4).

Parameter 2: Indirect upstream emissions.

Parameter 3: Energy consumption in SMR [kWh/m^3]

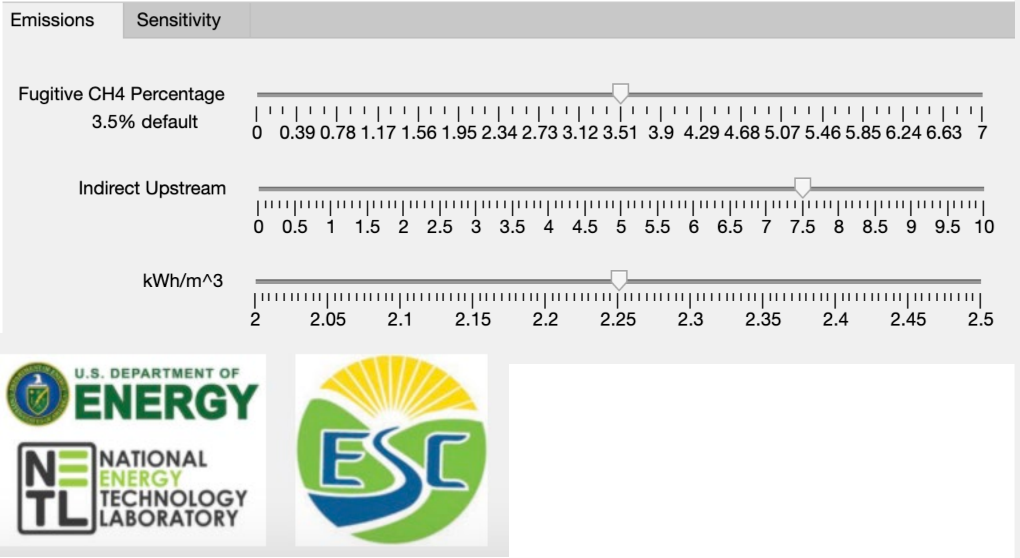
Parameter 4: CO2 capture efficiency in SMR.

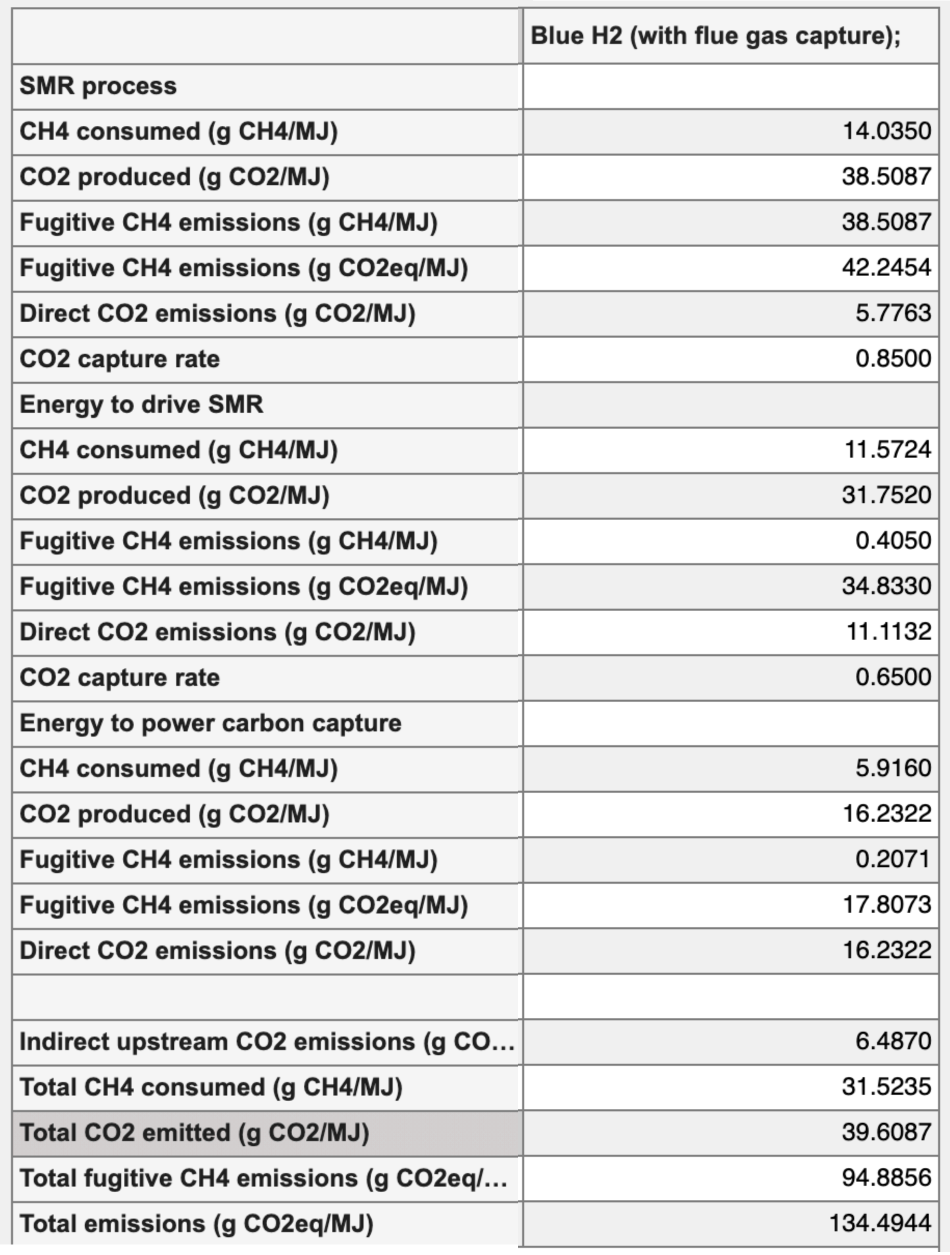
Parameter 5: **CO2 capture in flue**

After:
Howarth RW, Jacobson MZ. How green is blue hydrogen? Energy Sci Eng. 2021;9:1676– 1687. https://doi.org/10.1002/ese3.956
26 July 2021

MATLAB (and Python)

An application that allows the user to set (using sliders) the primary emission parameters for SMR under three cases of CC has been developed in MATLAB

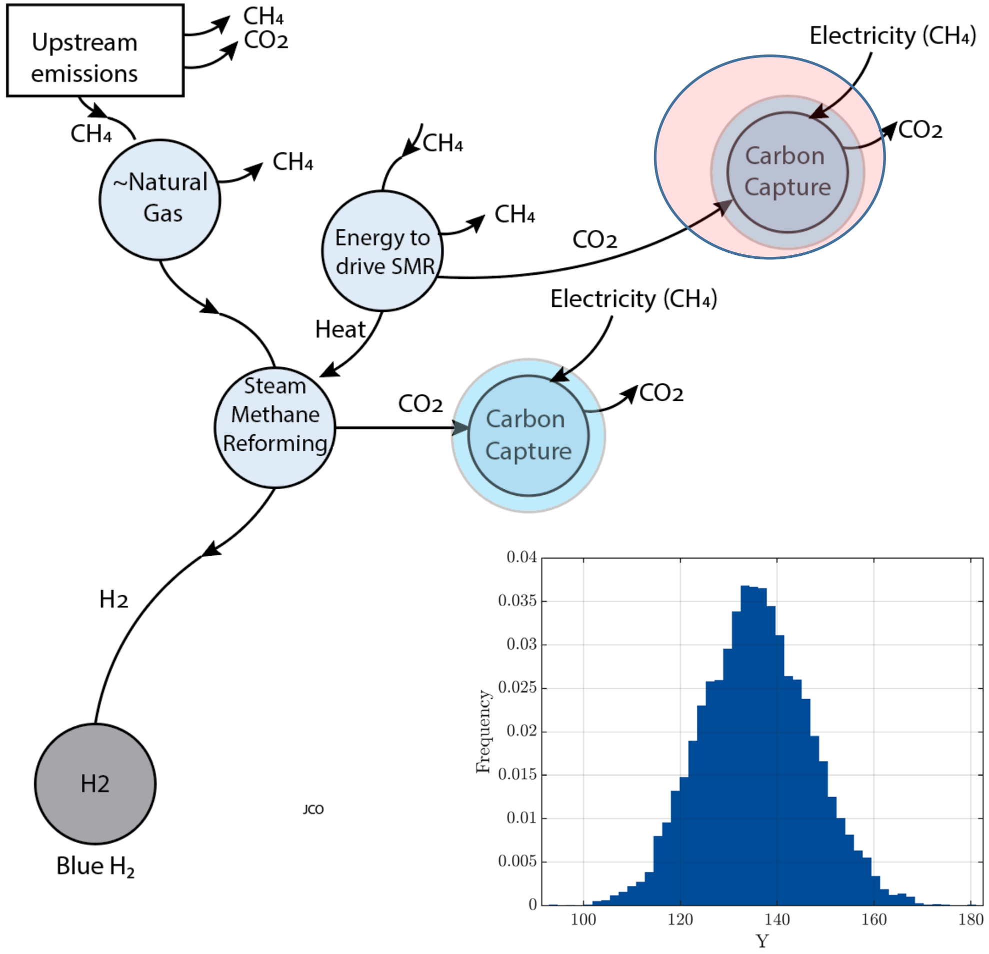




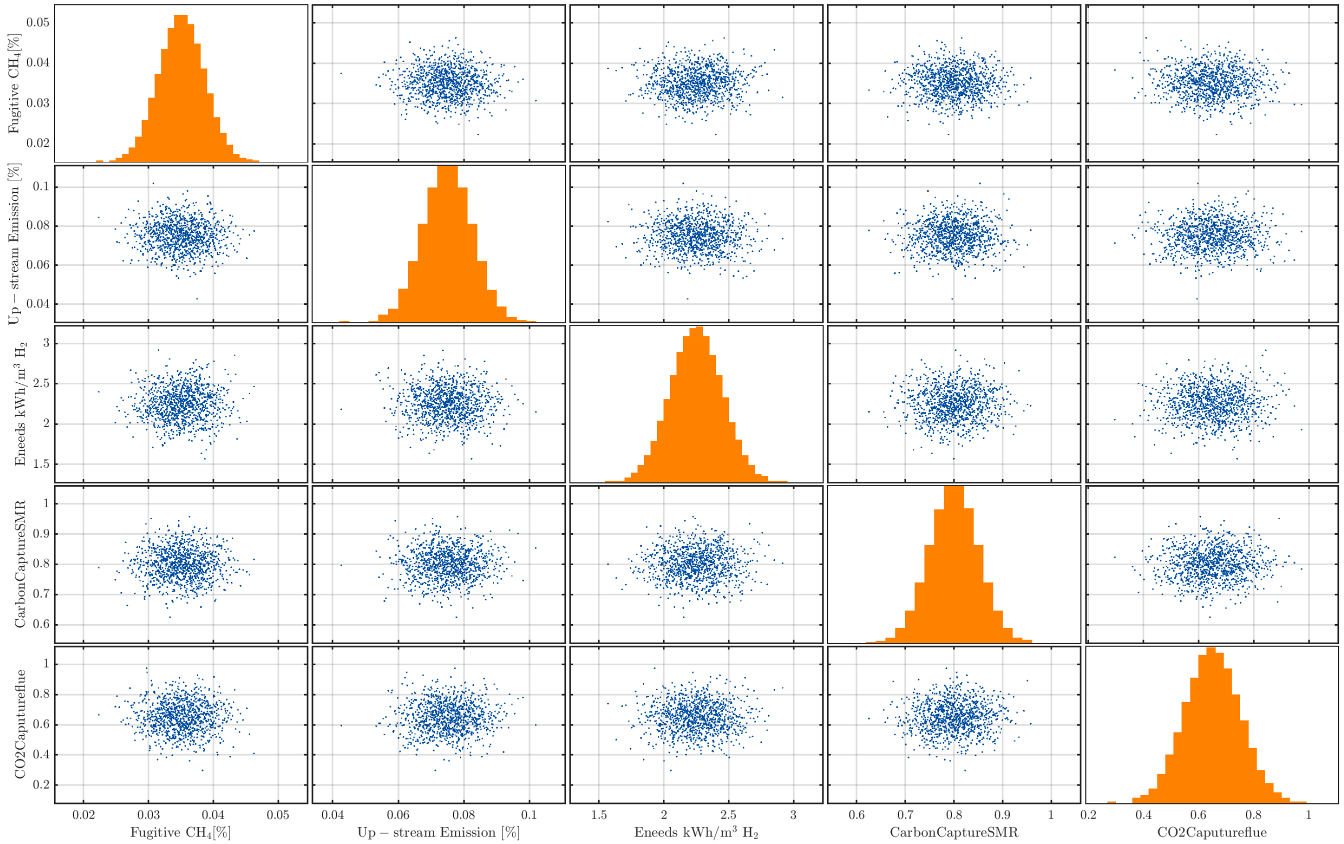
	Blue H2 (with flue gas capture);
SMR process	
CH4 consumed (g CH4/MJ)	14.0350
CO2 produced (g CO2/MJ)	38.5087
Fugitive CH4 emissions (g CH4/MJ)	38.5087
Fugitive CH4 emissions (g CO2eq/MJ)	42.2454
Direct CO2 emissions (g CO2/MJ)	5.7763
CO2 capture rate	0.8500
Energy to drive SMR	
CH4 consumed (g CH4/MJ)	11.5724
CO2 produced (g CO2/MJ)	31.7520
Fugitive CH4 emissions (g CH4/MJ)	0.4050
Fugitive CH4 emissions (g CO2eq/MJ)	34.8330
Direct CO2 emissions (g CO2/MJ)	11.1132
CO2 capture rate	0.6500
Energy to power carbon capture	
CH4 consumed (g CH4/MJ)	5.9160
CO2 produced (g CO2/MJ)	16.2322
Fugitive CH4 emissions (g CH4/MJ)	0.2071
Fugitive CH4 emissions (g CO2eq/MJ)	17.8073
Direct CO2 emissions (g CO2/MJ)	16.2322
Indirect upstream CO2 emissions (g CO…	6.4870
Total CH4 consumed (g CH4/MJ)	31.5235
Total CO2 emitted (g CO2/MJ)	39.6087
Total fugitive CH4 emissions (g CO2eq/…	94.8856
Total emissions (g CO2eq/MJ)	134.4944

Next:
Enable exploration of uncertainty in these parameters

Distribution of CO_2eq estimates for the given input

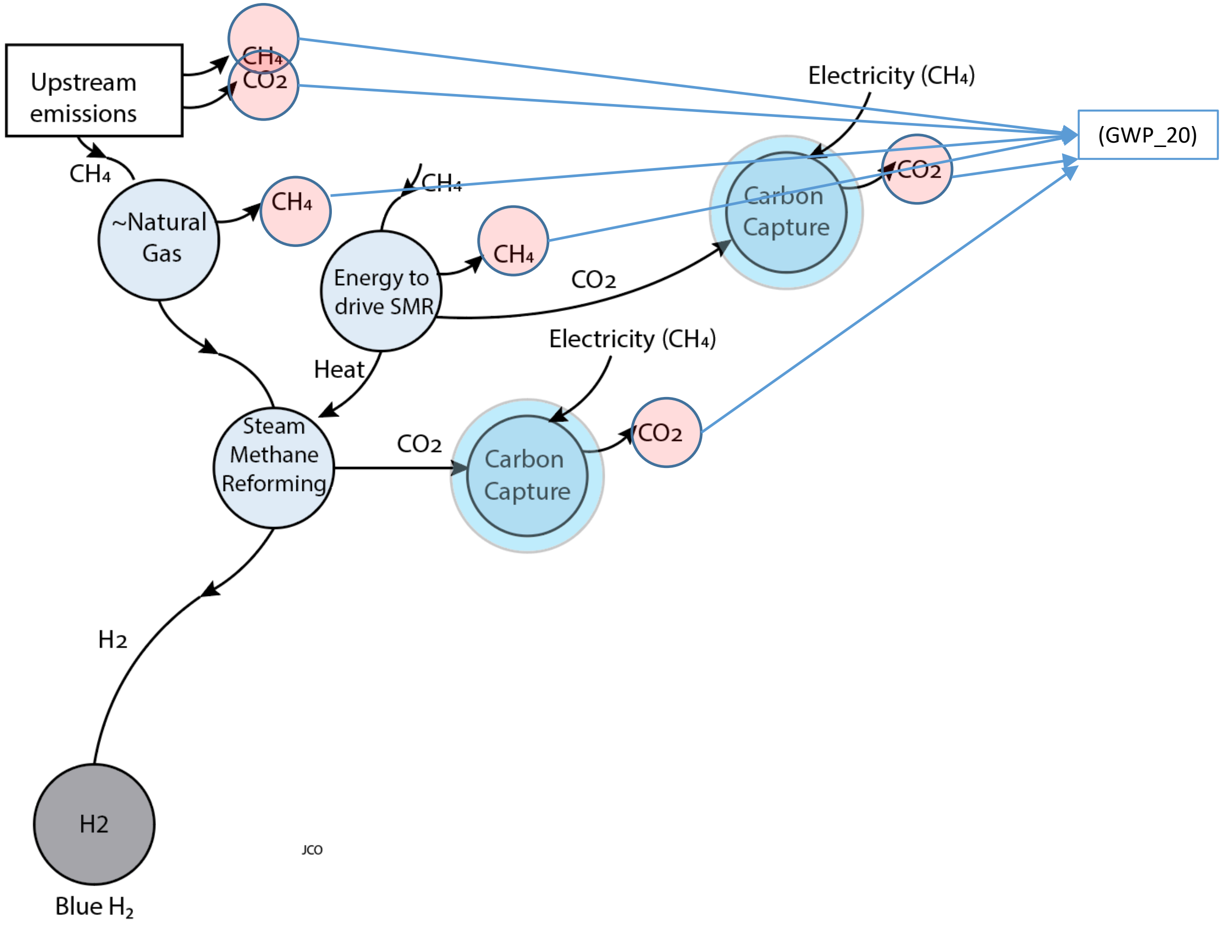


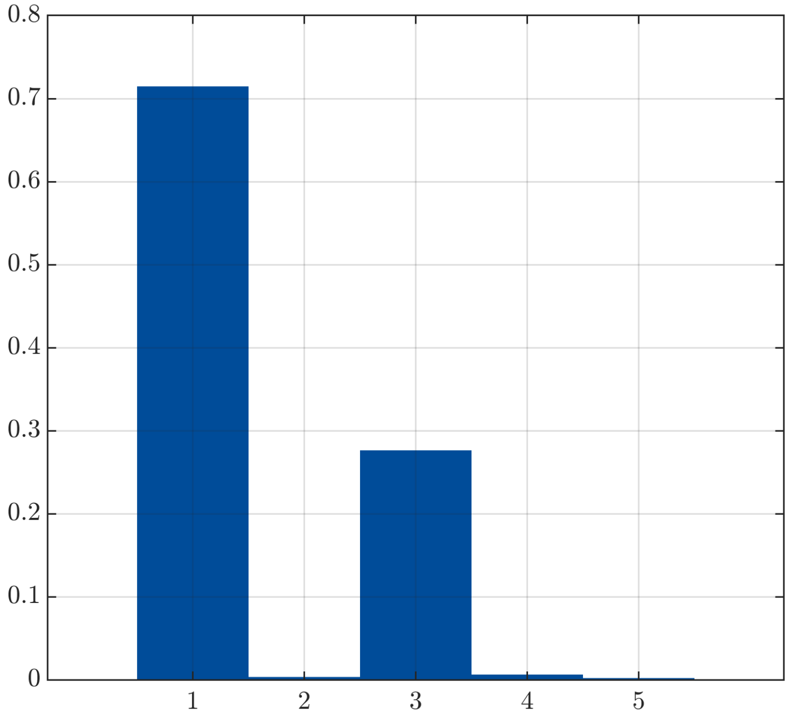
Total emissions (g CO2eq/MJ)



Sampling using gaussians around base case estimate; 10^5 samples (Sobol). Implemented in MATLAB via UQLab.

Blue H2- carbon capture in heat production to drive SMR





Parameter 1: CH4 leakage (fugitive CH4).

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Parameter 3: Energy consumption in SMR [kWh/m^3]

Parameter 4: CO2 capture efficiency in SMR.

Parameter 5: CO2 capture in flue

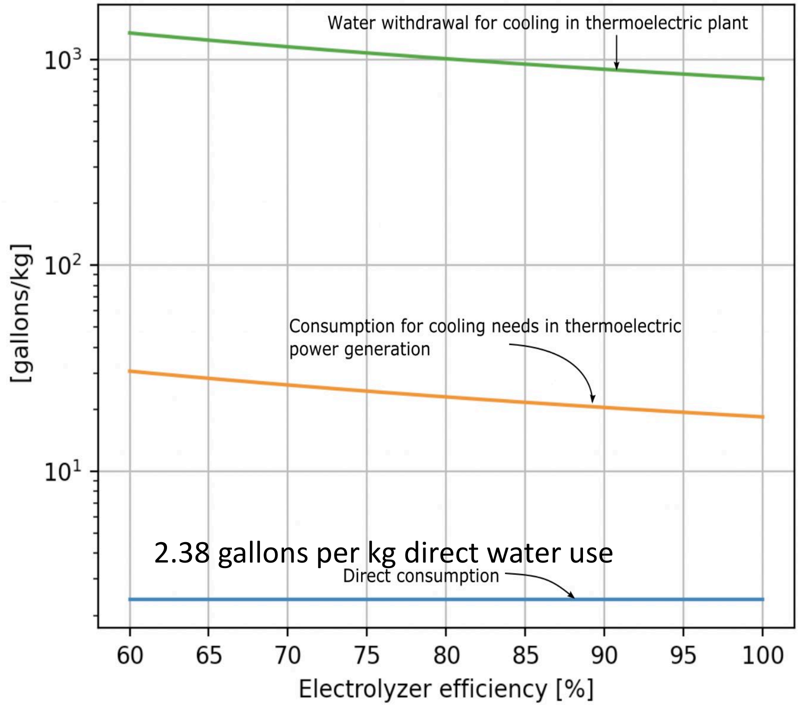
Explicit and implicit water considerations for H_2

This effort seeks to quantify water usage in H2 production.

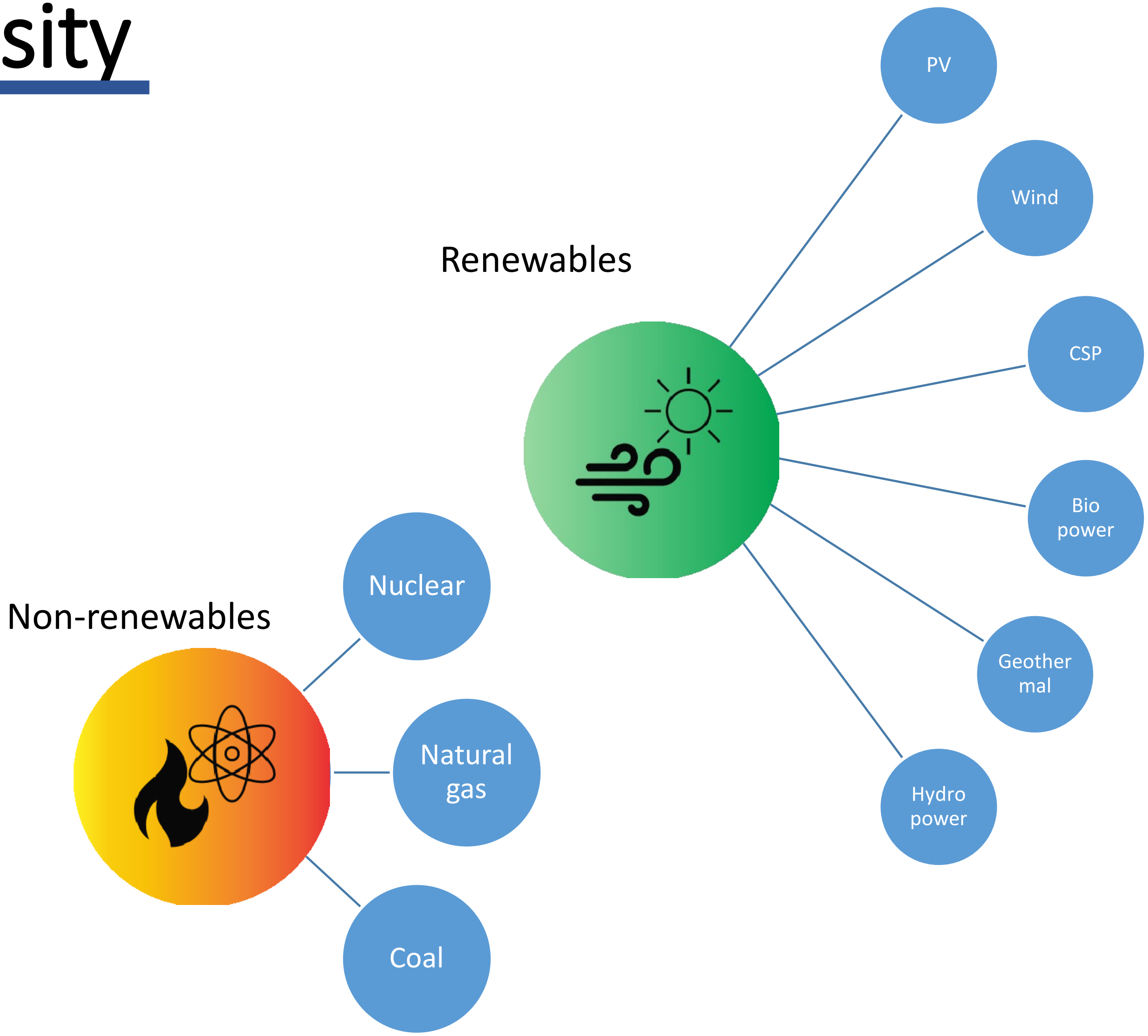
- Explicit (those dictated by the stoichiometry).
- Implicit opportunities for water savings primarily associated with meeting the energy needs.

  Water – Energy Nexus

Explicit Water Intensity

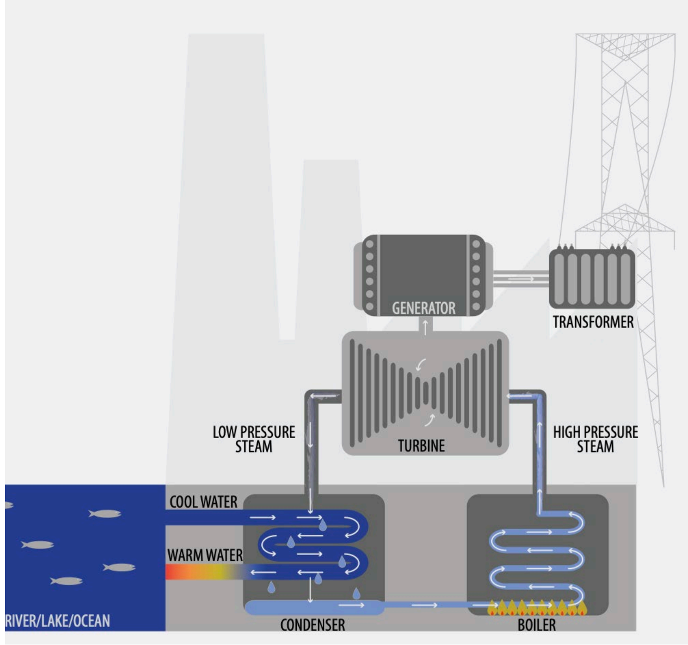

2.38 gallons per kg direct water use

We have explored the disaggregation of this average [water withdrawal is around 20.6 gallons per kWh [1, 2, 3] and the average water consumption for cooling is about 0.47 gallons kWh^{-1} [1].] leveraging mostly NREL studies of water consumption for different modes of electricity generation [4].

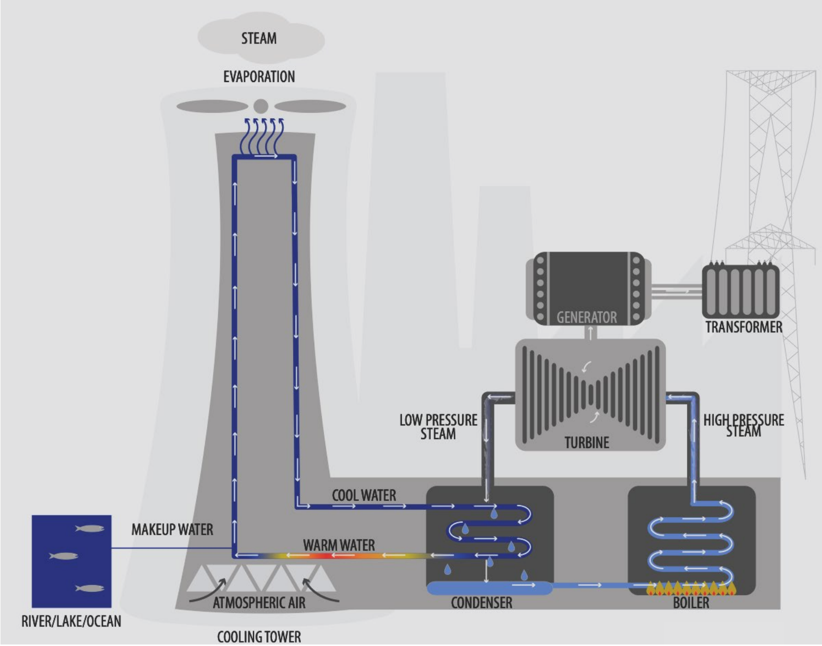


Cooling Technologies

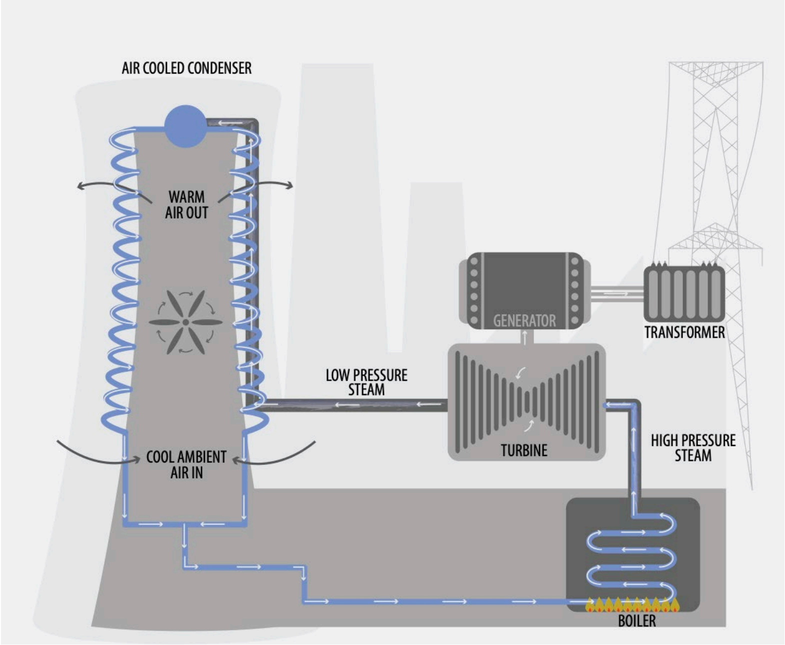
https://www.nrdc.org/sites/default/files/power-plant-cooling-IB.pdf



Once-Through



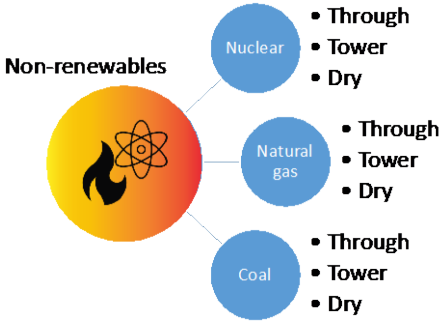
Tower



Dry

- The water footprint is divided between water consumption and water withdrawal.
- Water usage is, in most cases, tied to the cooling technology employed in the energy conversion system.

Many alternatives



Non-renewables

Nuclear
- Through
- Tower
- Dry

Natural gas
- Through
- Tower
- Dry

Coal
- Through
- Tower
- Dry

Cooling Technologies

Renewables

Fuel Type	Cooling	Technology
PV	N/A	Utility Scale PV
Wind	N/A	Wind Turbine
CSP	Tower	Trough
		Power Tower
		Fresnel
	Dry	Trough
		Power Tower
	Hybrid	Trough
		Power Tower
	N/A	Stirling
Biopower	Tower	Steam
		Biogas
	Once-through	Steam
	Pond	Steam
	Dry	Biogas
Geothermal[1]	Tower	Dry Steam
		Flash (freshwater)
		Flash (geothermal fluid)
		Binary
		EGS
	Dry	Flash
		Binary
		EGS
	Hybrid	Binary
		EGS
Hydropower	N/A	Aggregated in-stream and reservoir

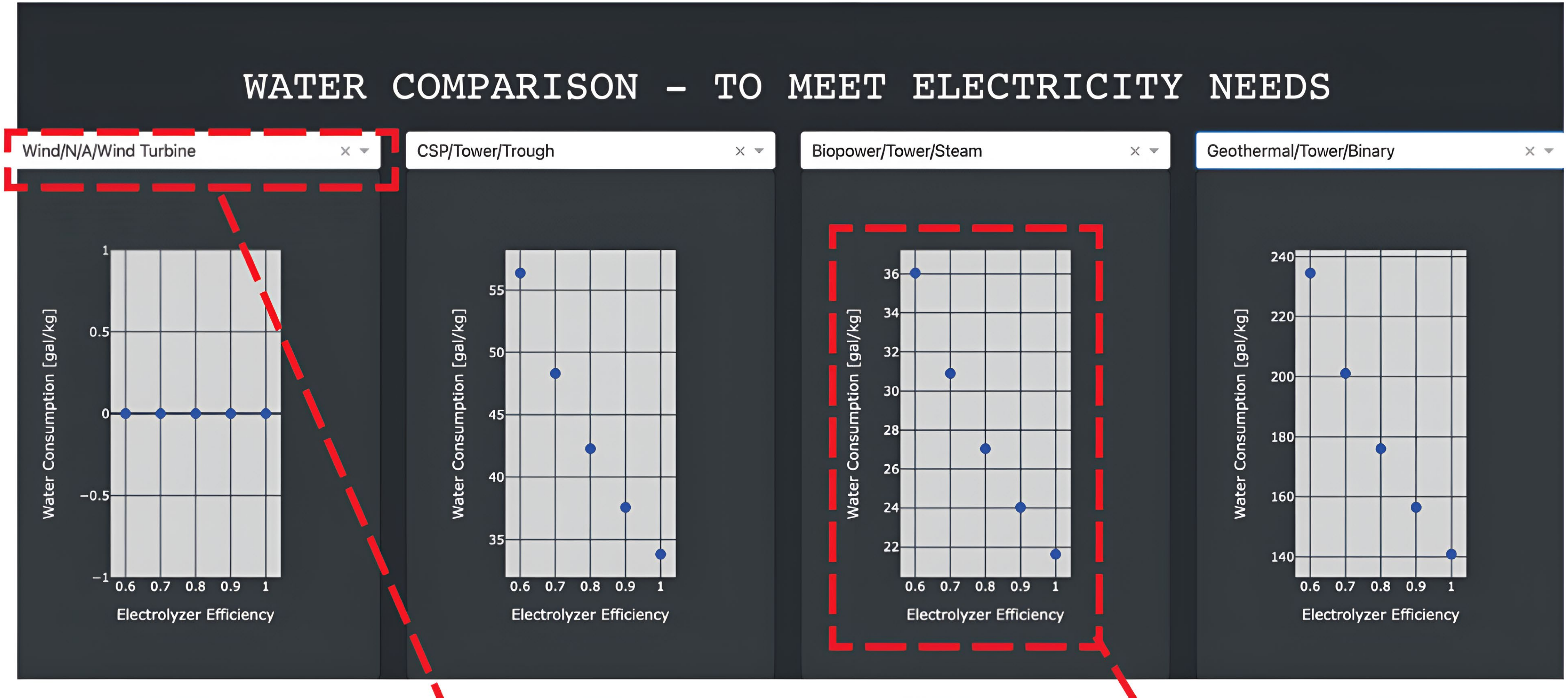
[1] Most geothermal facilities can use geothermal fluids or freshwater for cooling.

Non-renewables

Fuel Type	Cooling	Technology
Nuclear	Tower	Generic
	Once-through	Generic
	Pond	Generic
Natural Gas	Tower	Combined Cycle
		Steam
		Combined Cycle with CCS
	Once-through	Combined Cycle
		Steam
	Pond	Combined Cycle
	Dry	Combined Cycle
	Inlet	Steam
Coal	Tower	Generic
		Subcritical
		Supercritical
		IGCC
		Subcritical with CCS
		Supercritical with CCS
		IGCC with CCS
	Once-through	Generic
		Subcritical
		Supercritical
	Pond	Generic
		Subcritical
		Supercritical

Source:
NREL/TP-6A20-50900 March 2011
A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies
Jordan Macknick, Robin Newmark, Garvin Heath, and KC Hallett

Water Consumption Comparisons



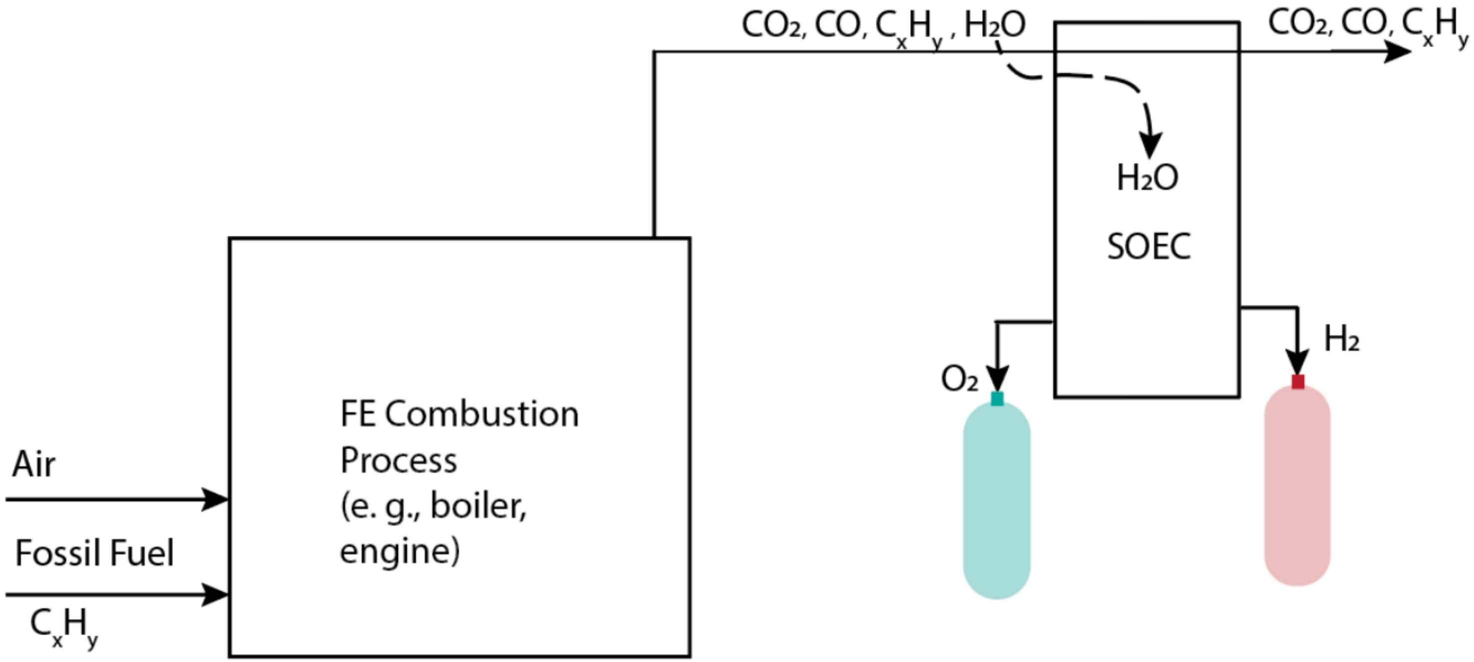
Drop down menu to specify user selected technology

Specific water consumptions for different needs according to electrolyzer efficiencies.

Dashboard Utility screenshot – A water requirements comparison tool.

Implicit Water Savings

- We have started exploring approaches to combine combustion processes and SOEC systems.
- We are interested in efficient ways to obtain flue gas composition (and water molar fraction in particular).



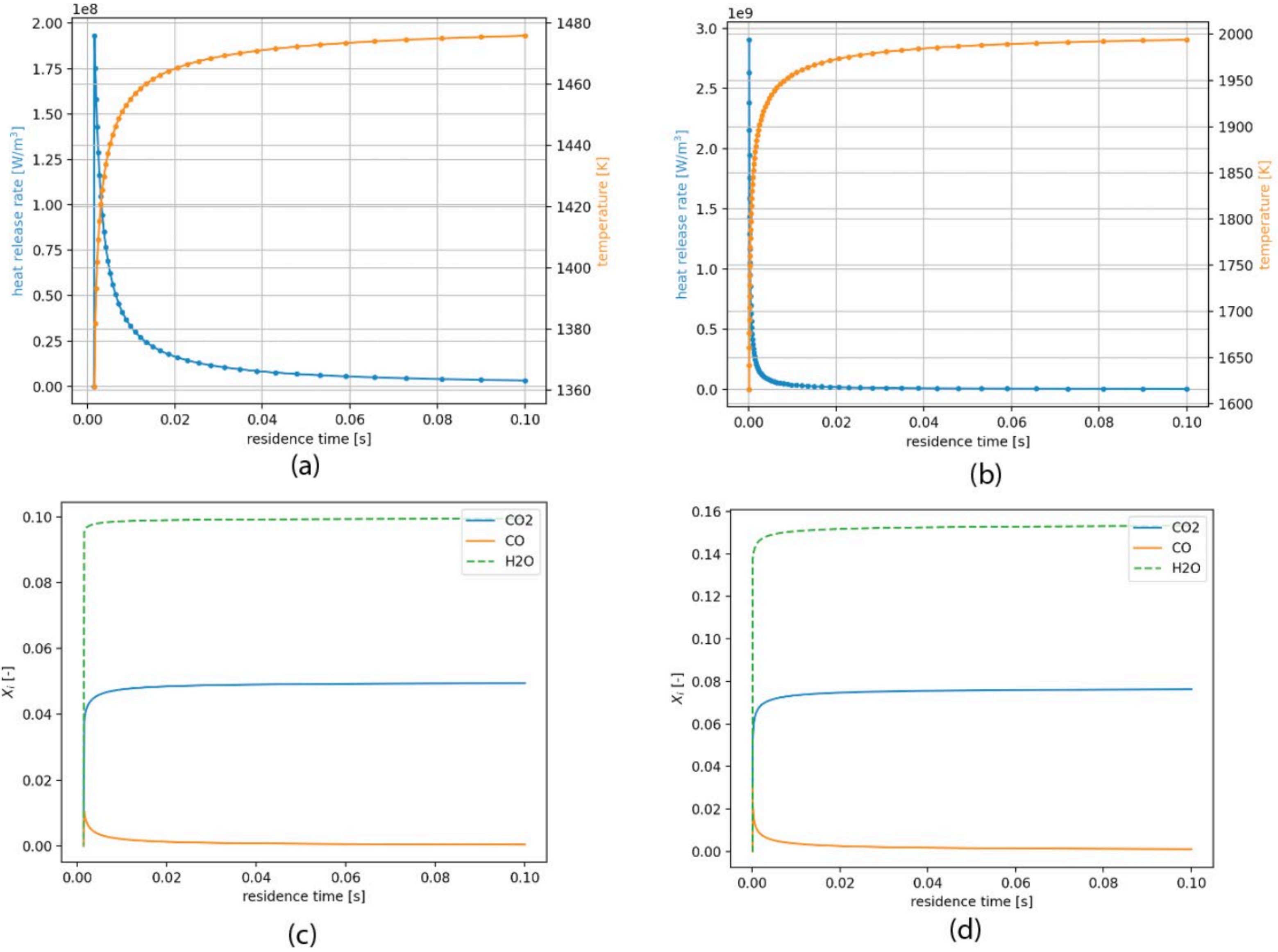
Schematic representation of potential use of flue gas water content in SOEC electrolysis.

Implicit Water Savings

Cantera

- Example: a steady-state combustor modeled as a well-stirred reactor (evaluation of the effect of residence time on heat release and temperature).

- CANTERA toolkit will be useful in future explorations of the combustion-SOEC.



(a)

(b)

(c)

(d)

CANTERA results for a combustor burning natural gas with air. (a) Base case: equivalence ratio =0.5. Output from combustor example: Heat release and Temperature. (b) Modified case: equivalence ratio =0.5; (c) Added computation of Molar Fractions. Equivalence ratio =0.5; (d) Added computation of Molar Fractions. Equivalence ratio =0.8.

Source: Goodwin et al. (2023).

Levelized Cost of Hydrogen

Fundamental calculation used in the preliminary assessment of a H2 project.

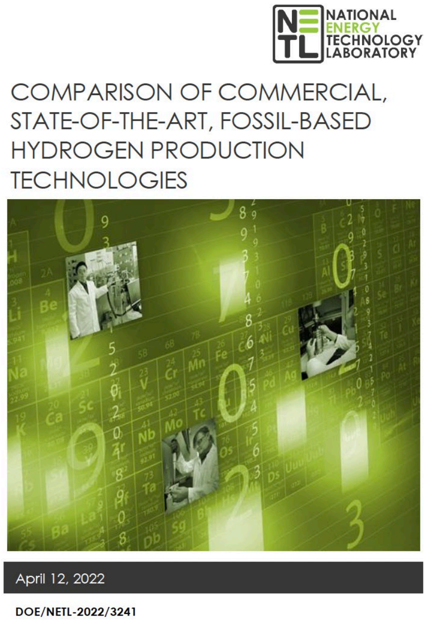
Cost of Hydrogen and Electricity.

Considers the average net current cost of H2 generation over the lifetime of the plant.

Hydrogen plants:
- *NG SMR with CCS*
- NG SMR without CCS
- NG ATR with CCS

- Coal Gasification with CCS
- Coal Gasification without CCS
- Coal/Biomass Co-Gasification with CCS

Sub-costs:
- Levelized Costs of Capital
- Levelized Fixed Operating Costs
- Levelized Variable Operating Costs
- Levelized Fuel Costs
- Levelized CO2 Transportation and Storage Costs


NATIONAL ENERGY TECHNOLOGY LABORATORY

COMPARISON OF COMMERCIAL, STATE-OF-THE-ART, FOSSIL-BASED HYDROGEN PRODUCTION TECHNOLOGIES

April 12, 2022

DOE/NETL-2022/3241

Eric Lewis, Shannon, Matthew Jamieson, Megan S. Henriksen, H. Scott Matthews ,John White, Liam Walsh, Jadon Grove, Travis Shultz, Timothy J. Skone, Robert Stevens (2022)

Dynamic maps

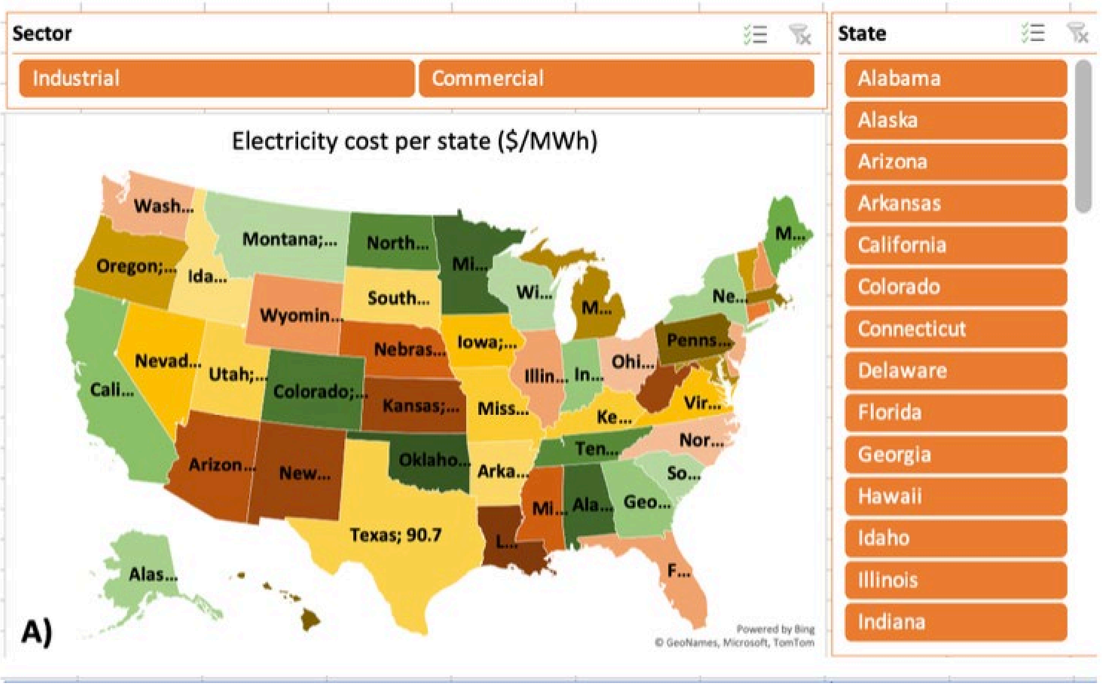
Development of dynamic maps to visualize and evaluate

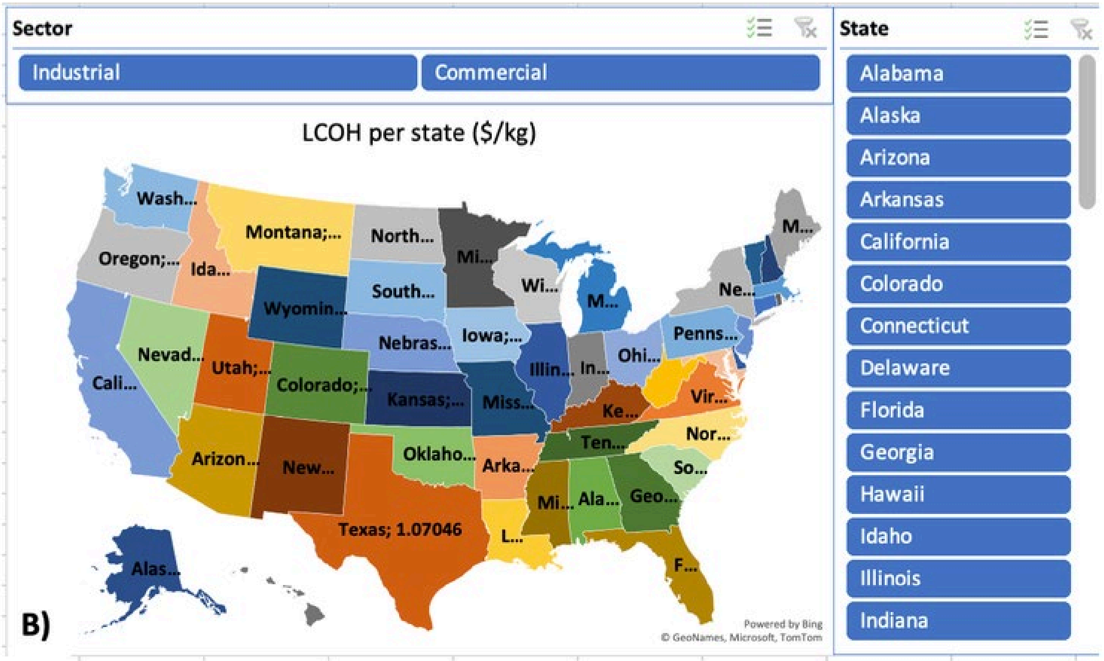
- The maps are used to display quantifiable data supported in a dynamic and interactive solution.

Electricity cost ($/MWh)

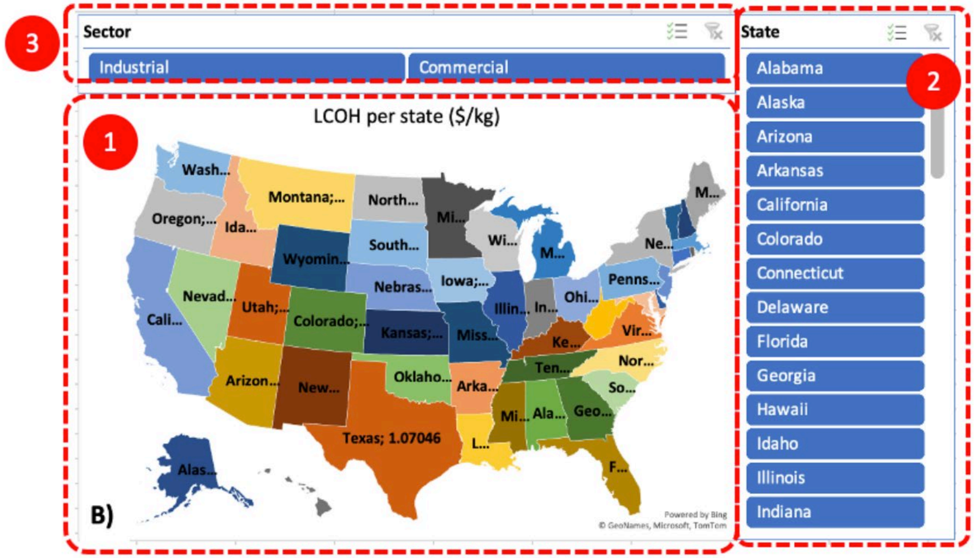
Levelized cost of hydrogen (LCOH) ($/kg)

in different regions of the U.S.



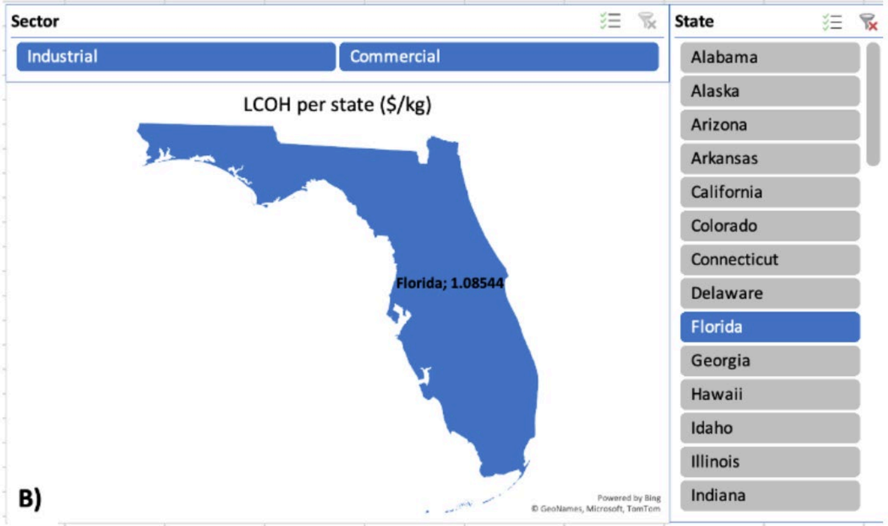


Dynamic maps



The user can Interact with the maps by:

1) LCOH Nationwide
2) Allows for state selection for closer look
3) Sectors: Industrial and Commercial



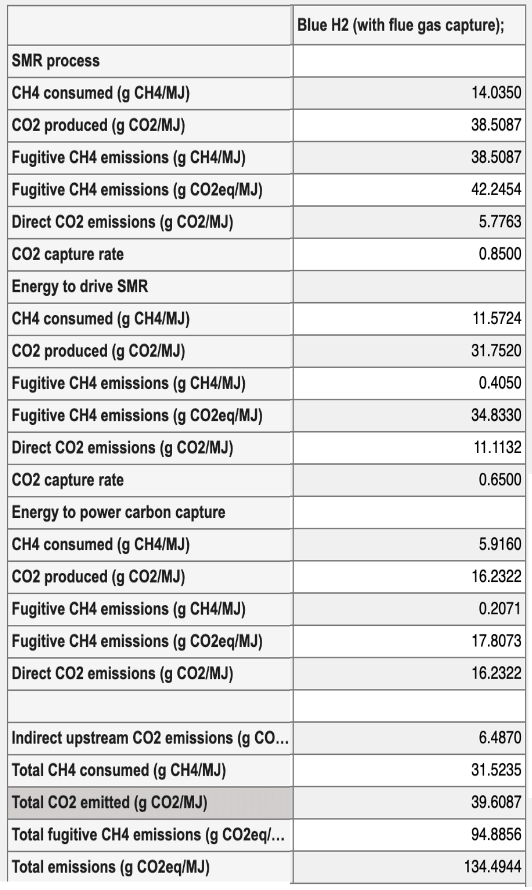
- LCOH for other technological routes will be considered for integration into the dashboard.

- More comprehensive overview of H2 economy.

Dashboard Implementation

Impact of H2 Integration (e.g., buildings)

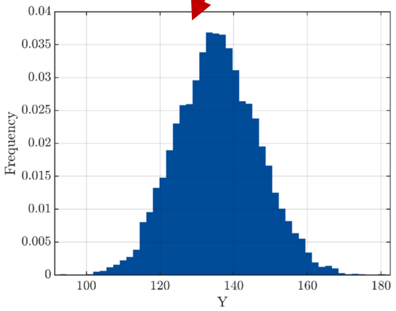
CO2 eq. Emissions



	Blue H2 (with flue gas capture);
SMR process	
CH4 consumed (g CH4/MJ)	14.0350
CO2 produced (g CO2/MJ)	38.5087
Fugitive CH4 emissions (g CH4/MJ)	38.5087
Fugitive CH4 emissions (g CO2eq/MJ)	42.2454
Direct CO2 emissions (g CO2/MJ)	5.7763
CO2 capture rate	0.8500
Energy to drive SMR	
CH4 consumed (g CH4/MJ)	11.5724
CO2 produced (g CO2/MJ)	31.7520
Fugitive CH4 emissions (g CH4/MJ)	0.4050
Fugitive CH4 emissions (g CO2eq/MJ)	34.8330
Direct CO2 emissions (g CO2/MJ)	11.1132
CO2 capture rate	0.6500
Energy to power carbon capture	
CH4 consumed (g CH4/MJ)	5.9160
CO2 produced (g CO2/MJ)	16.2322
Fugitive CH4 emissions (g CH4/MJ)	0.2071
Fugitive CH4 emissions (g CO2eq/MJ)	17.8073
Direct CO2 emissions (g CO2/MJ)	16.2322
Indirect upstream CO2 emissions (g CO...	6.4870
Total CH4 consumed (g CH4/MJ)	31.5235
Total CO2 emitted (g CO2/MJ)	39.6087
Total fugitive CH4 emissions (g CO2eq/...	94.8856
Total emissions (g CO2eq/MJ)	134.4944

Emissions

Uncertainty



HYDROGEN ECONOMY

Effects of Hydrogen generation on the US electric resources.

Production Type

× Shell Gasif. w/o CCS
× SMR w/ CCS
× SMR w/o CCS

State: Kansas
Climate Zone: 4A

Fuel Cost

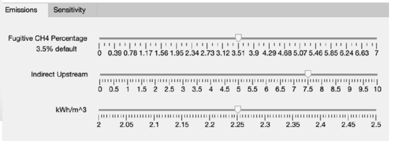
Capaciy Fctor

BUILDING TYPE: SINGLE FAMMILY RESIDENTIAL

Annual Energy Cost

Emission	gray H2	blue H2 w/o flue gas capture	blue H2 with flue gas capture
SMR process		null	null
CH4 consumed	14.035	14.035	14.035
Co2 produced	38.50875	38.50875	38.50875
Fugitive CH4 emissions	0.491225000000000	38.50875	38.50875
Fugitive CH4 emissions	42.24535000000001	42.24535000000001	42.24535000000001
Direct CO2 emissions	38.50875	5.7763125	5.7763125
CO2 capture rate	0	0.85	0.85
Energy to drive SMR			
CH4 consumed	11.57241717791410	11.57241717791410	11.57241717791410
CO2 produced	31.75199999999999	31.75199999999999	31.75199999999999

Sliders for key parameters



Fugitive CH4 Percentage
3.5% default

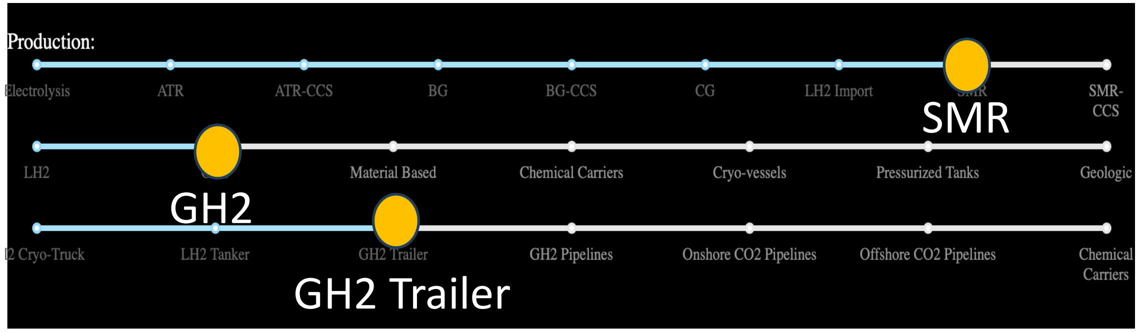
Indirect Upstream

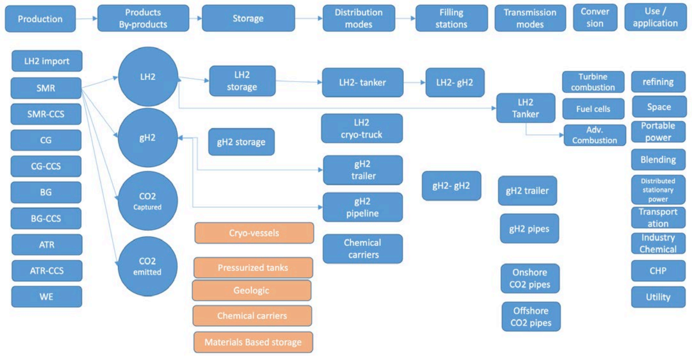
kWh/m^3

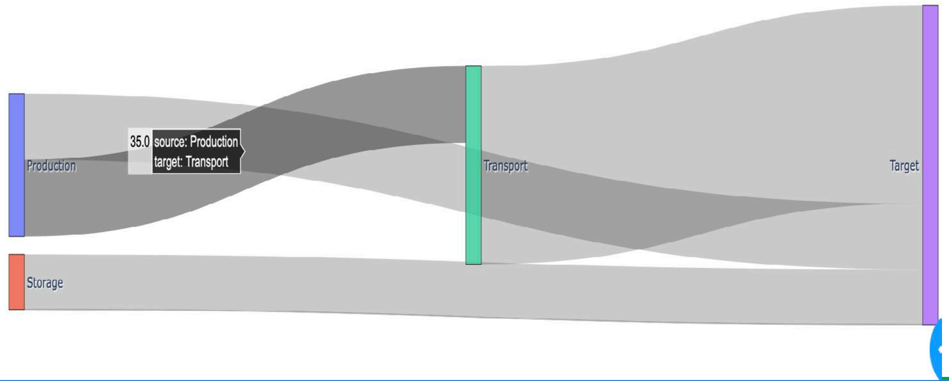
Geographically dependent building load variance and electricity cost

LCOH

Comparison among H2 routes

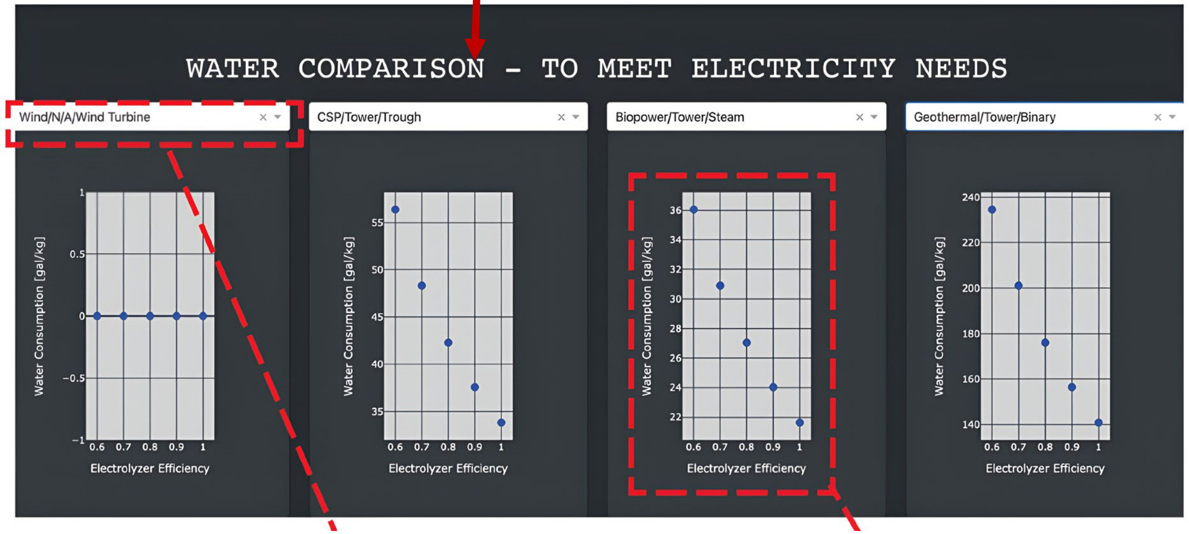






Water Consumption Comparisons

Water comparisons among electricity sources for hydrogen electrolysis


WATER COMPARISON – TO MEET ELECTRICITY NEEDS

Drop down menu to specify user selected technology

Specific water consumptions for different needs according to electrolyzer efficiencies.

Final Considerations

Future plans

In this project:

a. Finalize the H2Dash with information from the last reports:

1) LCOH and electricity costs for different end-use sectors (dynamic maps);

2) Use of water to produce electricity to generate H2 via electrolysis.

b. Submission of collaborative publications:

1) Journal publication: manuscript being prepared reviewing the integration of fossil fuels and different technologies in the H_2 economy;

2) Conference: participation and publication of a paper summarizing the main results of the project.

Final Considerations

After this project:

We plan to explore as a next project:

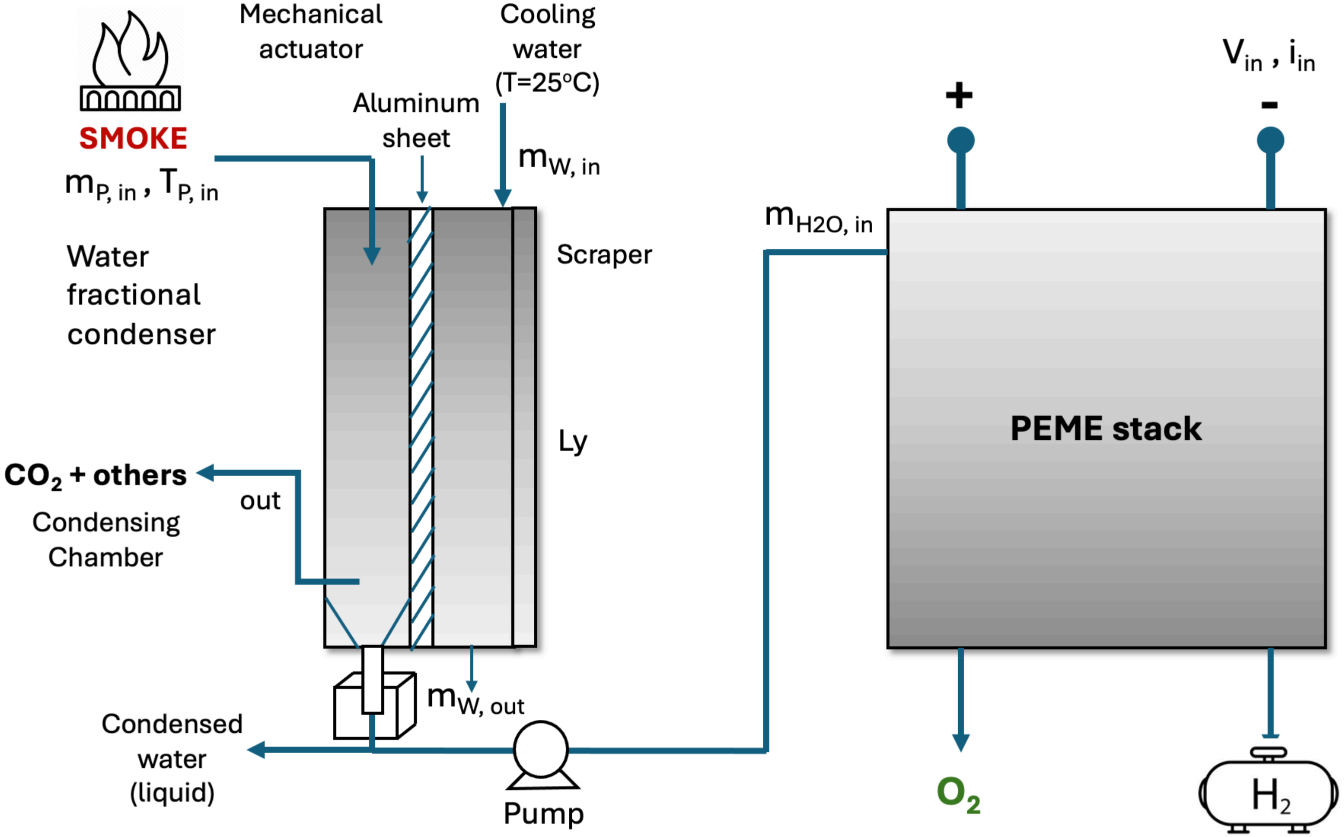
Fossil fuel emissions derived water for H_2 production

Using a Proton Exchange Membrane Electrolyzer Stack (FFEDW / PEME stack)

*Could be used as reverse/regenerative fuel cell (either as a Fuel Cell or Water Electrolysis

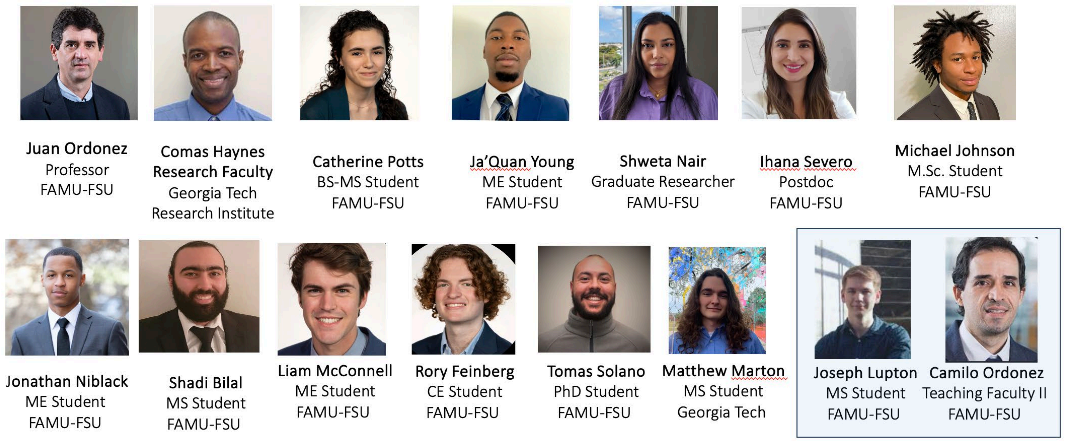
m_P – products of combustion:

$CO_2 + H_2O$ + others (NO_X, SO_X, CO, dioxins, furans, particulates…)



Other achievements

- Workforce training



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- Training and development of students in the use of new tools and water-CO2-Energy relevant processes,

python Cantera MATLAB® LCA Life Cycle Analysis

- PI engaged with colleagues at UFPR (Brazil) on H_2 generation strategies for transportation;
- Co-PI involved in H2Hub activities.

Appendix

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Acknowledgments

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pinions presented are solely ours and do not represent in any way an official position of DOE.

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Thank you!

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