Hydrogen Primer

Color De-Coding, Logistics and Environmental Considerations

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Council of Industrial Boiler Owners
Virtual Key Issue Topic Session

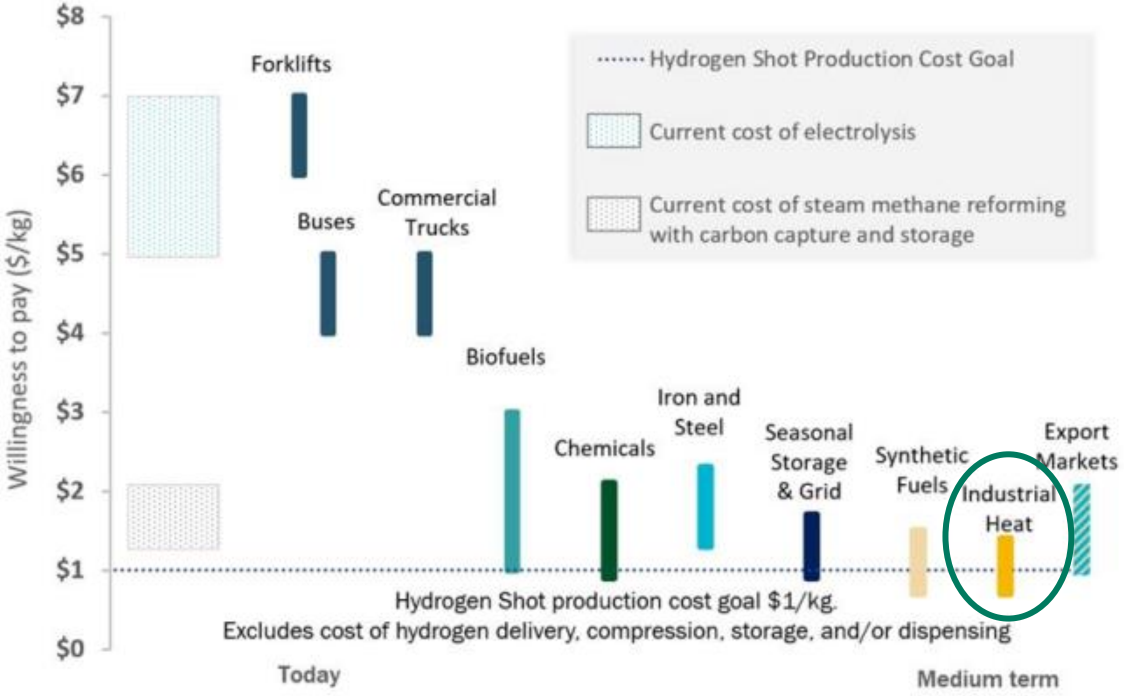
The business of sustainability

ERM

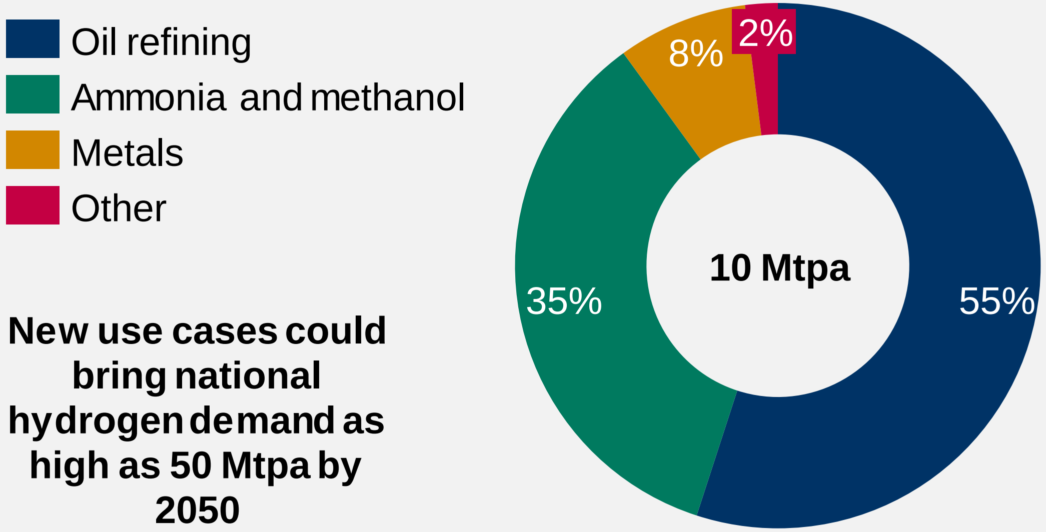
The U.S. produces 10 million metric tonnes of hydrogen per year mainly for use in refining, ammonia and chemical sectors

The U.S. produces hydrogen as chemical feedstock for the petroleum refining, ammonia and chemical industries. This demand is supported by 1,600 miles of hydrogen pipeline and three geological storage caverns.

Future use cases for hydrogen and willingness to pay[1]



Hydrogen consumption in the U.S. by end use



New use cases could bring national hydrogen demand as high as 50 Mtpa by 2050

Hydrogen as a fuel for industrial heat

Hydrogen boilers exist at a commercial level and can be operated much like a traditional boiler. There are few technical barriers; however, the cost of hydrogen as a fuel will have to decrease significantly to promote its use in boilers versus other decarbonisation technologies. Complete combustion of hydrogen results in no carbon dioxide emissions.

 1: U.S. National Clean Hydrogen Strategy and Roadmap, DOE 2023

Implications of hydrogen as a fuel for combustion

Most straightforward (general public) use of hydrogen = direct alternative to natural gas in combustion applications:

- ❑ No CO_2 emissions, but
- ❑ Higher flame temperature → higher NO_x emissions, can be mitigated, may require Selective Catalytic Reduction (SCR) → SCR is associated with NH_3 emissions → increases nutrient nitrogen and acid depositions → stringent emission controls, monitoring and regulations required
- ❑ Regulatory framework to be adjusted to accommodate hydrogen as a primary fuel (g/MJ, mg/Nm^3, higher moisture, no CO_2)

⇒ ‘net zero’ or ‘clean’ only tends to apply to global warming potential, does not consider other emissions/environmental aspects (atmospheric or otherwise)

⇒ ‘net zero’ and ‘air quality’ do not necessarily go hand in hand as will be illustrated in this slidedeck

At present, how is hydrogen produced?

Almost all of today's hydrogen production is highly carbon intensive

Currently, approximately 120 million metric tonnes of hydrogen are produced annually, representing ~3.2% of global final energy consumption.

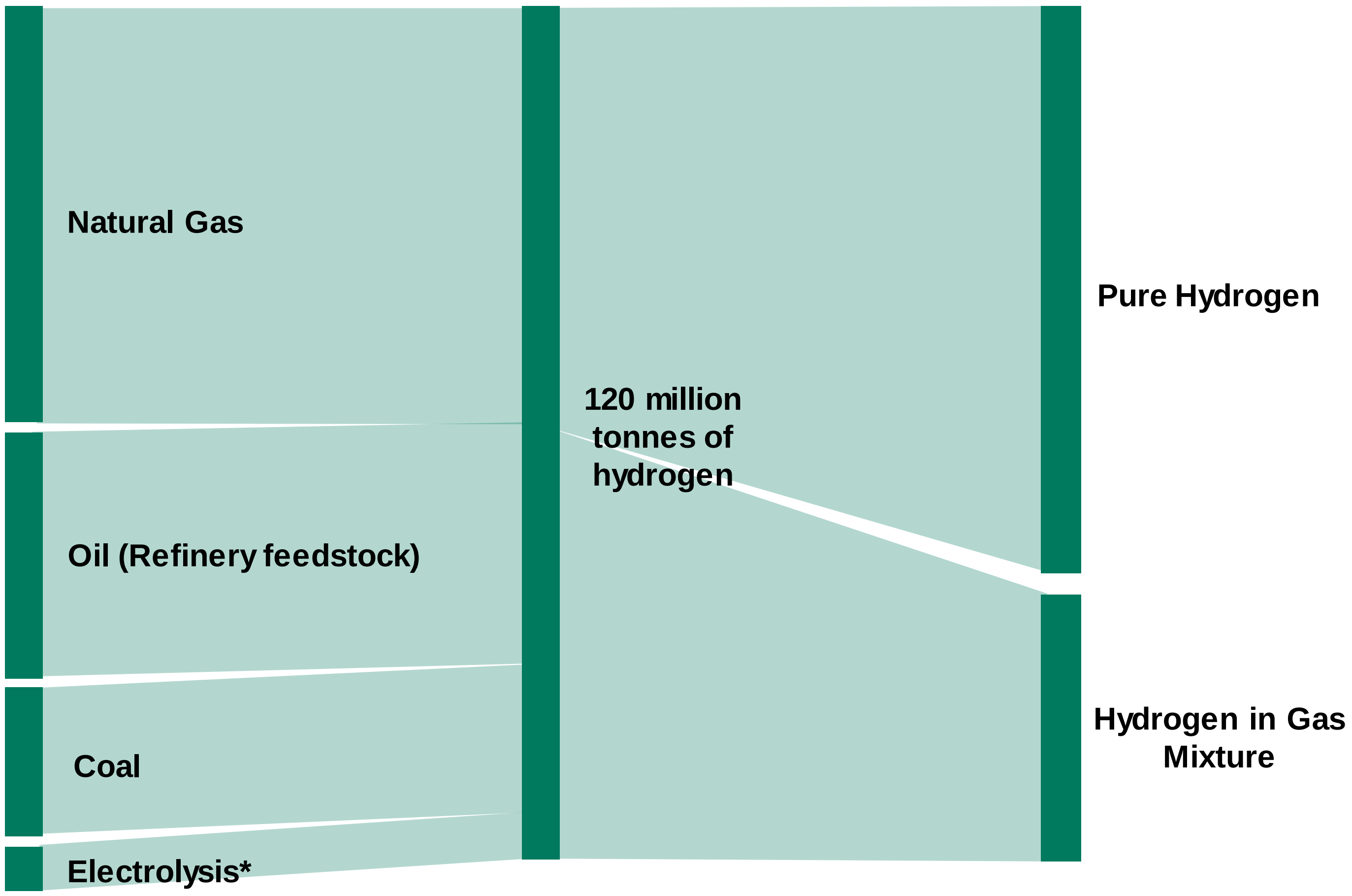
Feedstocks

- ~ 95% of hydrogen is produced from reforming natural gas or gasification of coal
- Crude oil distilled in a petrochemical refinery produces gaseous fractions which are reformed into hydrogen for internal use
- ~ 5% of hydrogen is produced as a by-product from chlorine production through electrolysis

Product composition

- Of the 120 million tonnes of hydrogen produced annually, two thirds is in the form of pure hydrogen while the remaining third is in a mixture with other gases
- Examples of hydrogen in a mixture include coke oven gas from steel production and synthesis gas used to produce methanol

Global hydrogen production split by feedstocks[1]



*Electrolysis, typically with grid averaged electricity but occasionally coupled with hydroelectric dams 1: 'Hydrogen: A renewable energy perspective', IRENA 2019

~95% of Hydrogen is produced directly from fossil fuels in highly emissions intensive processes

Grey Hydrogen – Steam Methane Reforming (SMR)

Methane reacts with steam at high temperature and pressure in the presence of a catalyst to principally produce hydrogen and carbon monoxide before subsequent units continue reactions to maximise the yield of hydrogen and separate out hydrogen from CO_2.

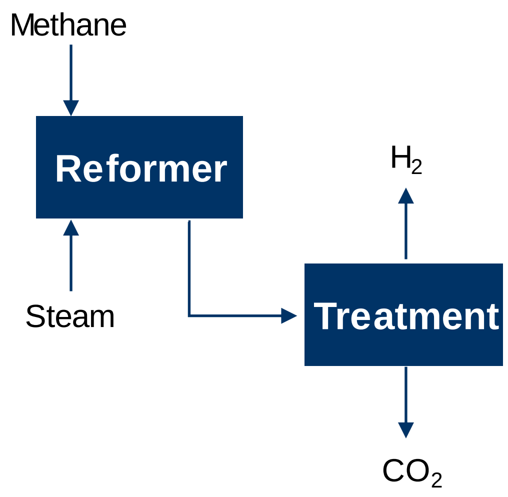
Most hydrogen produced today in the U.S. is made via steam methane reforming.

Direct Emissions[1]

9 $kgCO_{2e}/kgH_2$

Upstream Emissions[1]

2.4 $kgCO_{2e}/kgH_2$



Black/Brown Hydrogen – Coal Gasification

Coal is heated at very high temperatures to form synthesis gas which is further treated to form a stream of CO_2 and hydrogen which are then separated.

While this form of hydrogen production is less common in the U.S., gasification of coal is the major form of production in other countries such as China.

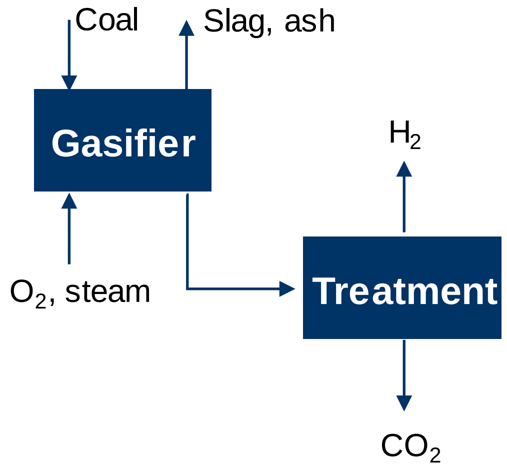
It is also the lowest cost and most emissions intensive form of current hydrogen production.

Direct Emissions[1]

19 $kgCO_{2e}/kgH_2$

Upstream Emissions[1]

4.8 $kgCO_{2e}/kgH_2$



1: 'Towards hydrogen definitions based on their emissions intensity', IEA 2023

How could hydrogen be produced in the future?

Current Production

Black Hydrogen
Process: Gasification
Source: Coal

Grey Hydrogen
Process: Steam Reforming
Source: Natural Gas

Possible future methods

Green Hydrogen
Process: Electrolysis
Source: Low-carbon renewable energy

Yellow Hydrogen
Process: Electrolysis
Source: Solar PV Generation

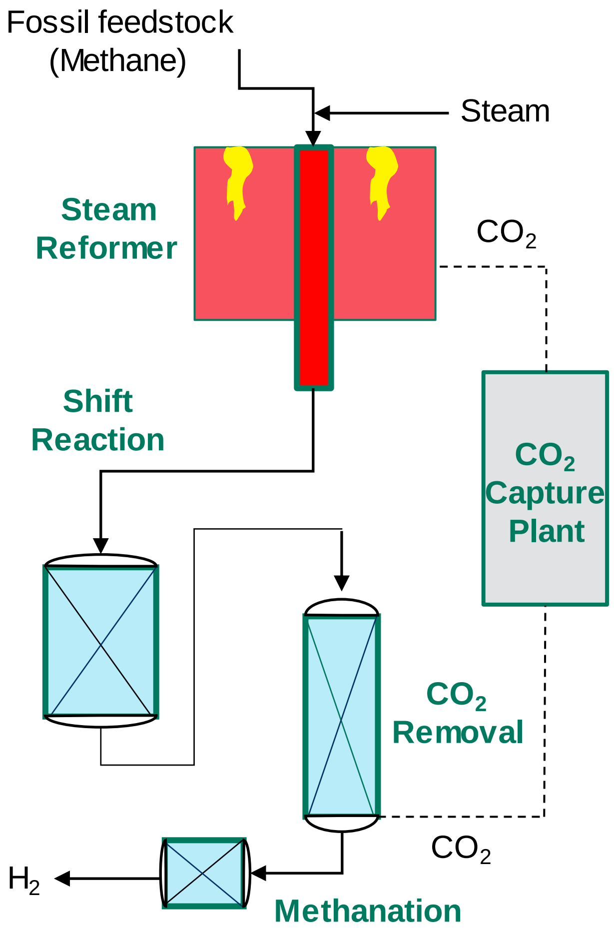
Pink Hydrogen
Process: Electrolysis
Source: Nuclear Energy

Blue Hydrogen
Process: Steam Reforming with Carbon Capture
Source: Natural Gas

Turquoise Hydrogen
Process: Methane Pyrolysis
Source: Natural Gas

Blue Hydrogen: low-carbon hydrogen production with fossil feedstock and carbon capture

Blue hydrogen production (SMR)



Blue hydrogen refers to a collection of hydrogen production methods based around the use of a fossil feedstock (typically methane) and a system to capture CO_2 emissions from the process, which are subsequently stored or utilized.

CO_2 Capture System

The technology for capturing CO_2 from the hydrogen product is likely to be via absorption into a circulating solvent. This capture may be pre or post combustion depending on the chosen plant design.

"The term capture rate refers to the mass of carbon captured as a percentage of the mass of carbon in all feed gas"

Capture rates in excess of 95% (EU-BAT threshold) are thought to be technically feasible; however, there is no defined capture rate threshold associated with the term 'blue hydrogen'.

Blue Hydrogen can refer to other systems beyond the incumbent SMR technology

- **SMR –** CCS can be retrofit to existing SMRs; however, this will be less optimised than a new system. As an endothermic process, a furnace is required which adds an additional CO_2 stream to manage
- **ATR –** Autothermal Reforming requires no furnace since the methane feed is partially oxidised, exothermically providing heat for the reforming process. This simplifies the capture system with only a single stream of process CO_2.
- **GHR –** Gas Heated Reformers can be integrated with SMRs and ATRs to improve system efficiency
- **POX –** Partial OXidation of methane (as in ATR) can be employed by itself without further reforming

Blue Hydrogen: low-carbon hydrogen production with fossil feedstock and carbon capture

Blue hydrogen production (SMR) – Main Air Quality Considerations

The incumbent technology for capturing CO_2 from the hydrogen product is likely to be via absorption into a circulating solvent in the presence of a catalyst

- ❑ Solvent = usually a proprietary mix of amines (amine stripping) → released into atmosphere these convert to nitramines and nitrosamines which are confirmed carcinogens → stringent emission controls and regulations (all of this is new, no ambient monitoring with sufficient detection limit available yet)

- ❑ Catalyst = sensitive to NO_x in exhaust gases → typically removed by SCR → NH_3 emissions → impact to nutrient nitrogen and acid depositions → stringent emission controls, monitoring and regulations required

- ❑ None of the above is insurmountable, especially when considered early on in process design and alternatives selection (techndogy, location)

- ❑ Alternative to amine stripping = condensation but needs high purity streams

Green Hydrogen: water electrolysis powered by low-carbon renewable electricity

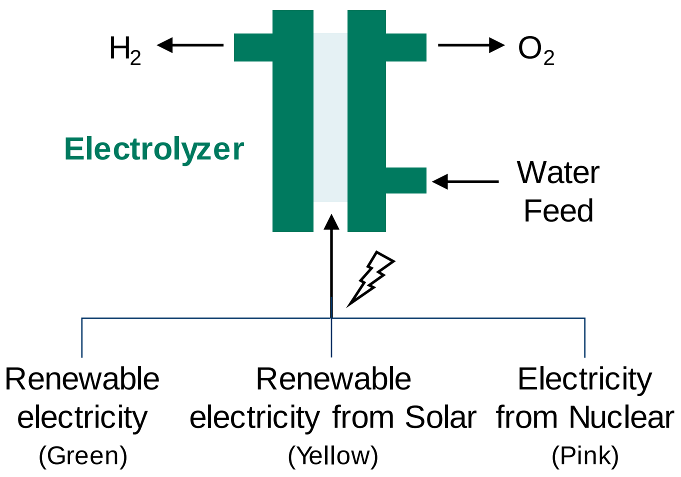
Green hydrogen refers to the production of hydrogen from water using electrolysis powered by renewable electricity. The electrolyzer produces no direct GHG emissions and if the electricity used is from a dedicated low-carbon source then this process can produce hydrogen with a low emissions intensity.

Electrolyzer System

Electrolyzer systems are an area of active research and development. The three main technologies of interest for hydrogen production are:

PEM	Proton Exchange Membrane electrolyzers are **at a commercial scale** and are likely to become the dominant technology for electrolytic hydrogen production in the near future – they are **highly flexible in operation**.
Alkaline	Pressurized alkaline electrolyzers are the **most established** electrolyzer technology and **currently the lowest cost**; however, they have **low conversion efficiencies** and are **less flexible**.
SOEC	Solid Oxide Electrolyzer Cells are fuel cells running in regenerative mode to electrolyze water. They r**equire high temperature heat** (1300 – 1560 °F) but achieve **higher efficiencies** than other technologies. This technology is high TRL but not yet commercial.

Electrolytic Hydrogen Production



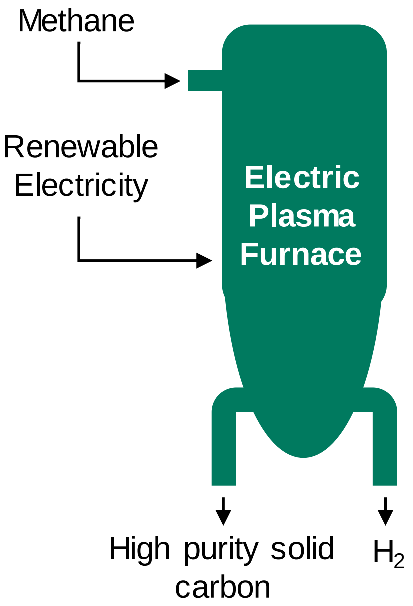
***'Yellow'** hydrogen is the name given to electrolysis powered by electricity from solar generation which has a higher emissions intensity than wind or hydro. **'Pink'** refers to electrolysis powered by electricity from nuclear power stations*

Energy intensity

Electrolysis is a highly energy intensive process and consequently the unit cost of hydrogen is highly dependent on the cost of electricity (70 - 80% of the total cost). Reductions in electricity prices are crucial for green hydrogen to become cost competitive.

Turquoise Hydrogen: pyrolysis of methane in the absence of oxygen

Low carbon methane pyrolysis



Turquoise hydrogen refers to the production of hydrogen via pyrolysis of methane. This involves raising methane to high temperatures in the presence of a catalyst at which point it is decomposed to solid carbon and hydrogen. The lack of process CO_2 emissions provides an immediate emissions reduction and this can be further reduced by using renewable electricity to provide the heating for the pyrolysis reaction.

Thermal Plasma Pyrolysis

The energy demand of the pyrolysis can be supplied by electricity which forms a plasma reaching temperatures in the range of 1800-3600 °F and splits methane into its elements. By using dedicated low-carbon electricity to provide the plasma, emissions from a high temperature gas furnace are avoided. This technology is still in development and there is currently only one commercial scale demonstration plant operational, the Olive Creek 1 plant owned by Monolith Materials in Nebraska.

Solid carbon product

The high-quality solid carbon byproduct is valuable for industries that require carbon black such as tire and mechanical rubber production. This displaces the requirement for conventional carbon black production which is highly emissions intensive. Some firms plan to use the carbon for graphite production.

Limitations on scale

For this production method to be economical, it is important that the solid carbon by-product has a market value. Current global markets for carbon black and graphite are 14 and 4.4 Mtpa respectively which equates to around 6 Mtpa (22 GW) of associated hydrogen production. With a growing graphite market this could increase to 40 + GW.

Green and Turquoise Hydrogen: Main Air Quality Considerations

No direct emissions to atmosphere, however there is still the life cycle aspect:

- Materials for electrolyzers are often associated with mining/production of rare metals → mining and refining emissions
- Green hydrogen using wind power → turbine blades are composite material and have limited lifespan especially when applied offshore
- Yellow hydrogen = solar panels are made from rare metals → mining and refining emissions
- Pink hydrogen = nuclear fuel → mining and refining emissions
- Turquoise hydrogen = methane → natural gas extraction and refining emissions

There is no holy grail, but all the above already happens, it is about finding the most efficient extraction, use and re-use of materials/energy

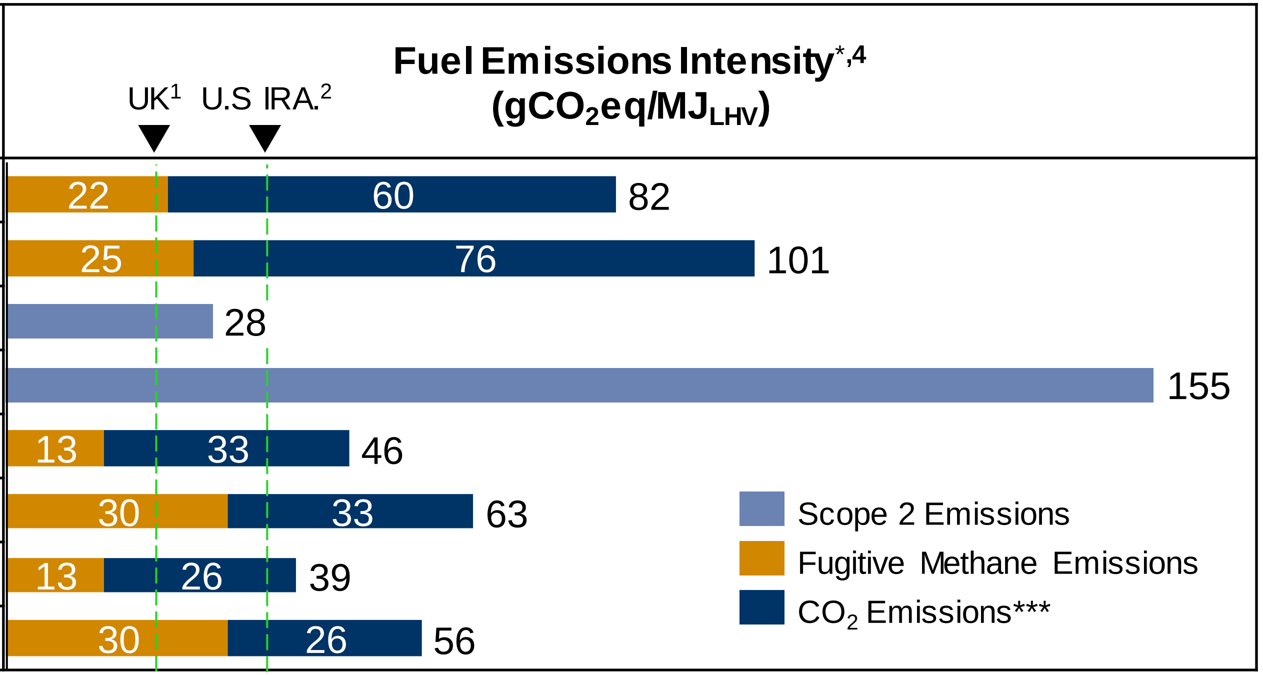
How clean are the major production methods?

"The atmosphere cares not about colors, only emissions intensity"

There are many emerging definitions for 'clean hydrogen'. Below are three provisional definitions that may evolve with time:

UK Low Carbon Hydrogen Standard[1]	IRA 45V 'qualified clean hydrogen'[2]	IIJA 'clean hydrogen production'[3]
≤ 20 gCO_2eq/MJ_{LHV}	**≤ 33 gCO_2eq/MJ_{LHV}**	**≤ 17 gCO_2eq/MJ_{LHV}**
Lifecycle GHG emissions	Lifecycle GHG emissions	GHG emissions at production site

Fuel	Methane Leakage %	CO_2 Capture Rate
Natural Gas	3.5%	-
Grey Hydrogen (SMR)	3.5%	-
Electrolytic** (@70 gCO_2/kWh)	-	-
Electrolytic** (@390 gCO_2/kWh)	-	-
SMR + Carbon capture	1.5%	85%
SMR + Carbon capture	3.5%	85%
SMR + Carbon capture	1.5%	95%
SMR + Carbon capture	3.5%	95%



*Fugitive methane emissions are accounted for with a GWP100 value of 28 gCO_{2e}/g **Electrolyzer efficiency of 70% LHV ***Includes upstream CO_2 emissions from gas extraction, purification and transport
1: UK Low Carbon Hydrogen Standard, 2: 42 U.S.C. § 16166(b)(1)(B) 3: 42 U.S.C. § 16166(b)(2). 4: Numbers are indicative internal estimates adapted from IEA and Howarth & Jacobson 2021

What conditions must be met for hydrogen to contribute to net emissions reduction?

What does 'blue' hydrogen need to be 'clean'?

The emissions intensity of blue hydrogen is highly sensitive to the magnitude of fugitive methane emissions and the CO_2 capture rate

Maximize capture rate

To minimize direct CO_2 emissions, designs with high carbon capture rates are required. Systems with higher purity exhausts can more easily achieve higher capture rates.

Minimize fugitive emissions

Methane has a significant global warming impact and fugitive emissions from methane leakage should be minimized if hydrogen is to achieve net emissions reductions.

Minimize natural gas usage

Use efficient designs to improve feedstock yield and use alternative fuels to provide thermal input for the capture system and reforming unit, to reduce the natural gas and associated fugitive and upstream emissions.

What does green hydrogen need to be 'clean'?

If new fossil generation is added or ramped up in a local bidding zone as a result of new electrolyzer load then the hydrogen produced is not clean. To prevent this, three conditions are proposed; however, these requirements increase cost of production, prompting resistance

Additional Generation

'Additionality' guarantees that hydrogen is produced from dedicated renewable capacity that would not have been built if not for the production of hydrogen. This prevents fossil plants having to ramp up to meet the demands of new electrolyzer loads.

Temporal Correlation

This requires that hydrogen is produced within the same time interval as renewable generation to ensure the electrolysers are not running during periods of low renewable production, inadvertently creating extra demand from fossil plants

Geographical Correlation

This requires the renewable electricity source and electrolyzer to be within the 'same region' defined by a criteria on bidding zones. This prevents bottlenecks between renewable supply and demand, avoiding new fossil capacity being added to a local bidding zone.

Moving beyond colors toward emissions-based terminology

‘Colors’ are used to categorize hydrogen based on how it is produced, yet no formal definitions are agreed for these terms and as demonstrated, relying on colors can obscure a wide range of emissions intensities for the product

Many stakeholders are calling for an internationally agreed emissions accounting framework to bring greater visibility for investors and provide a more rigorous basis for contracts

The International Energy Agency is one such stakeholder who have developed a report[1] reviewing ways to use emissions intensity in the development of regulations and certification schemes

(How) Will aspects beyond GWP be accounted for in the global ‘net zero’ discussions?

1: ‘Towards hydrogen definitions based on their emissions intensity’, IEA 2023

Thank you

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