Alternative Fuels

ISSUE BRIEF

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HYDROGEN TECHNOLOGY

KEY MESSAGES

Hydrogen Energy and its Uses

Hydrogen holds promise as a crucial tool in decarbonizing “hard-to-abate sectors,” such as the steel industry and long-haul transport, which cannot be electrified. Molecular hydrogen (H_2), when produced sustainably, can be used through hydrogen fuel cells, hydrogen internal combustion engines, as e-fuels (e.g., methanol, sustainable aviation fuels, etc.), and as a feedstock (e.g., ammonia etc.) for specific industrial processes to achieve decarbonization.

Technological Readiness

Due to the technical challenges and cost of renewable hydrogen (RH2) production, 99% of hydrogen production still comes from fossil sources (by steam reforming of natural gas and other fossil fuels by partial oxidation and coal gasification, as well as methane pyrolysis); until RH2 can be produced on a large scale and in a competitive way, low-carbon hydrogen (LCH2) can serve as an interim solution to facilitate the energy transition. RH2 is primarily produced with water electrolysers powered by renewable energy sources, which is an energy- and water-intensive process limited by manufacturing capacity development, access to expensive critical raw materials, low efficiency, and material degradation, causing high production costs and low off-taker commitments.

RH2 Production Expansion

Scaling up RH2 production and heightening its contribution to limiting global warming necessitates a 6,000-fold increase in electrolyser capacity by 2050, according to the IEA. As renewable energy generation capacity rises in many markets and makes up a substantial share of all power generation, energy can also be used to power water electrolysers. Additionally, RH2 can also be produced from biomass/biomethane ($BioCH_4$), and its gasification represents an effective and promising conversion technology to different energy carriers and chemicals. In the short term, however, LCH2 remains essential for a smooth transition.

Barriers

RH2 production and deployment also face barriers in terms of cost, infrastructure, commercial risks, and government support. As it stands, RH2 is more expensive to produce than fossil hydrogen (3 to 20 times, depending on the electricity price for electrolytic hydrogen). Transport and distribution challenges necessitate investment to convert H_2 into other more “stable” carriers, as well as infrastructure such as storage support or dedicated pipelines. Additionally, government programs are vital for hydrogen to break even, and international differences in region- or country-specific regulatory frameworks raise trade barriers that hinder the development of RH2 production and adoption by off-takers.

Safety and Environmental Issues

Hydrogen’s flammability and potential for leaks underscore the need for strict adherence to safety standards.

DEC 08, 2023

Large scale hydrogen production could put pressure on the supply of critical raw materials as well as on the already limited water resources, while leaks could indirectly contribute to global warming. Additionally, proper handling, storage, and adherence to safety standards are crucial to ensure the safe production and use of H_2.

Criteria for Industrial Scale Development of Hydrogen Industry

Industrial scale development of the clean hydrogen industry has proven difficult, while fossil hydrogen continues to dominate. Only about 4% of announced global hydrogen projects have reached the Final Investment Decision or the construction phase. Uniform global and legal regulatory frameworks, specifically in the form of non-tariff barriers and financial support, are critical for a large and rapid adoption of RH2 in the frame of the net zero emissions target by 2050.

Scope of Brief

The deployment and upscaling of hydrogen technologies is recognized as an essential step for the energy transition to a Net Zero-Energy System. Novel technologies and business models based on low-carbon and renewable solutions need to be evaluated to guide the development and deployment of hydrogen technologies across different regions.

This brief is meant to respond to the following issues:

- The current readiness of renewable hydrogen technology for deployment;
- Potential environmental risks of hydrogen production and use;
- Trade-offs between different types of hydrogen to avoid stranded assets.

INTRODUCTION

The hydrogen atom in the chemical Periodic Table of Elements is H; and the molecule dihydrogen, H_2, represents a great potential for reducing greenhouse gas (GHG) emissions. Many countries worldwide are now investing significantly in this booming market. H is the most abundant atom in the universe, representing nearly three-quarters of the mass found in the universe. It is found in water, hydrocarbons (coal, oil, natural gas etc.), and in all organic matter. Molecular hydrogen (H_2) also exists naturally on Earth. It is known as “white hydrogen”. H_2 is not toxic, is 14 times lighter than air, dissipates quickly when released or leaked in open air, and has a wide range of flammable concentrations in air – including a lower ignition energy than natural gas. It contains more energy per unit mass than natural gas, gasoline, oil, and coal; however, it has the lowest energy content by volume, very low volumetric density, which is an issue for storage and transportation.[1] To increase the volumetric density, it must either be liquefied (liquid hydrogen – LH_2) at an extremely low temperature (-253°C), compressed (compressed hydrogen – CH_2) at a very high pressure (e.g., 700 bar for passenger fuel cell electric vehicles - FCEV)[2] stored in metal hydrides (up to 5wt%) or transformed in other forms of chemicals (e.g., liquid organic hydrogen carriers - LOHC, ammonia, methanol, or others).

H_2 is now clearly recognized as one of the best potential energy carriers toward our decarbonization pathway.[3] Because H_2 is a versatile

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1. Bruno Pollet and Jacob Lamb, “Hydrogen, Biomass and Bioenergy - Integration Pathways for Renewable Energy Applications.”

2. These two operations are very energy intensive.

3. Petra Schwager, Luis Umanzor, Amparo González et. al., “Green Hydrogen Industrial Clusters Guidelines,” 8-44.

molecule, it can be used directly via hydrogen fuel cells (to produce electricity and water), hydrogen internal combustion engines (direct combustion with oxygen) and as a feedstock to produce chemical derivatives such as ammonia, methanol, and sustainable aviation fuels (SAF) to specific industrial and transport applications.[4]

Today, approximately 99% of global H_2 is produced from fossil fuels: 47% is produced from global natural gas (NG), 27-29% is produced from global coal (from NG reforming and coal gasification), and 22% is produced from oil (as a by-product).[5] 75-95 Million tonnes (mt) of hydrogen is produced globally (that includes only circa 0.035 Mt of electrolytic hydrogen), and is responsible for around 830 Mt–1Gt (Gigatonnes) CO_2-eq (carbon dioxide-equivalent) emitted per year.[6]

H_2 has been labelled with various colours depending on the CO_2 emission intensity upon production: including grey (H_2 produced from NG), brown/black (H_2 produced from coal), blue (H_2 produced from NG using CCS – Carbon Capture Sequestration), green (H_2 produced from renewable energy technologies using a water electrolyser as well as produced from biomass/biomethane by thermolysis and steam reforming), yellow (H_2 produced via the electrical network), pink (H_2 produced via nuclear power), and turquoise (H_2 produced via NG pyrolysis). However, it is now well-accepted in the field that colour coding is no longer meaningful. CO_2 emission intensity on production is the most important factor. H_2 that was previously called grey is now called "fossil", green hydrogen is now called "renewable" and blue, yellow, and pink hydrogen are grouped together under the name of "low carbon". Figure 1 compares the emission intensity of different H_2 production routes.[7]

The European Union (EU) is now referring to "low-carbon hydrogen – LCH2" and "renewable hydrogen – RH2" by setting a threshold of life cycle GHG emission of 3 $kgCO_2/kgH_2$ (Commission Delegate Act 20212139).[8] Equally, the US Department of Energy (DoE) has defined "clean hydrogen" as H_2 produced with a carbon intensity equal to or less than 2 kg CO_2-eq. produced at the site of production per kilogram of hydrogen produced (kg H_2).[9] H_2 is now seen as an option in decarbonizing "hard-to-abate", "hard-to-decarbonize," or "hard-to-electrify" sectors, also known as the, "no regret sectors" which include steel production, chemical production, and refineries. Additionally, H_2 is also an option to decarbonize the heavy transport sector: it could lower emissions of passenger trains, class 8 trucks, and - indirectly, in the form of synthetic fuels and ammonia - even marine transportation and aviation.[10]

Deloitte estimates that by 2050, the "no regret sectors" and the transport sector could respectively account for 42% and 36% of total clean hydrogen demand. Additionally, to achieve climate neutrality, the clean hydrogen market capacity could grow up to 170 Mt H_2-eq in 2030 and up to 600 Mt H_2-eq in

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[4] Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

[5] Petra Schwager, Luis Umanzor, Amparo González et. al., "Green Hydrogen Industrial Clusters Guidelines," 8-48; Truby, Johannes, Pradeep Philip, and Bernhard Lorentz, "Green hydrogen: Energizing the path to net zero," 3-74; Hydrogen Council and McKinsey & Company, "Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America," 1-27; International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity," 7-87; "International Energy Agency (IEA), "The State of Clean Technology Manufacturing," 4-33; International Energy Agency (IEA), "Global Hydrogen Review 2023," 11-171; International Energy Agency (IEA), "Net Zero by 2050," 29-187; United Nations Economic Commission for Europe (UNECE), "UNECE Technology Brief Hydrogen," 1-38.

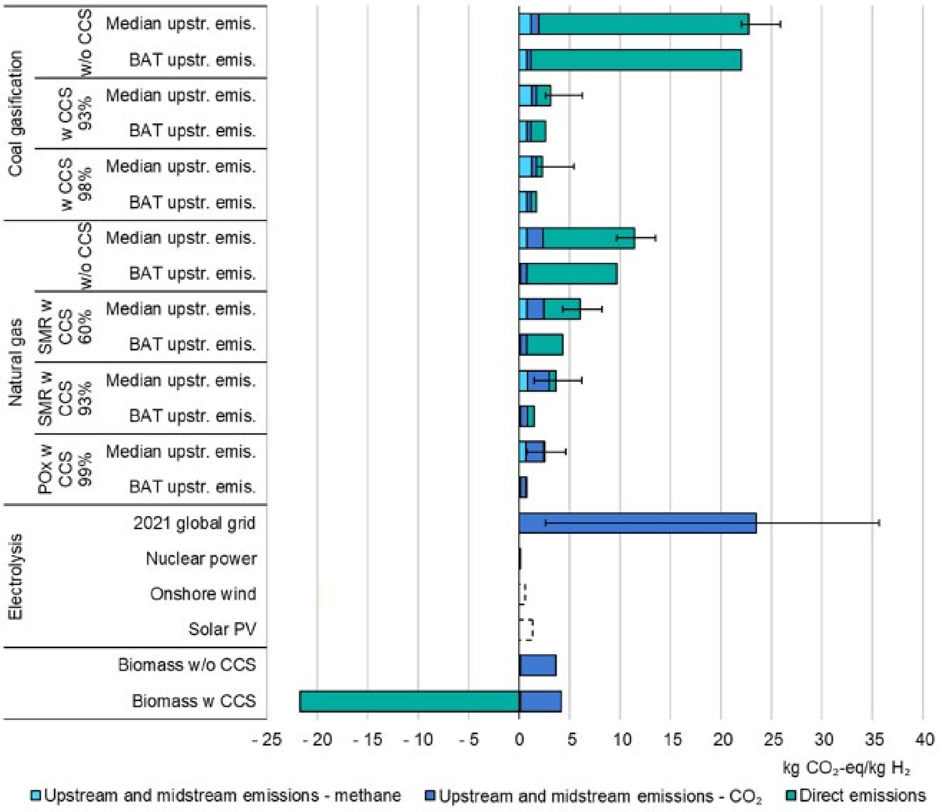
[6] Petra Schwager, Luis Umanzor, Amparo González et. al., "Green Hydrogen Industrial Clusters Guidelines," 8-48; Truby, Johannes, Pradeep Philip, and Bernhard Lorentz, "Green hydrogen: Energizing the path to net zero," 3-74; Hydrogen Council and McKinsey & Company, "Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America," 1-27.

[7] International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity," 7-87.

[8] European Energy Commission, "Hydrogen."

[9] US Department of Energy – Energy Efficiency and Renewable Energy, "Alternative Fuels Data Center."

[10] Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.



IEA. CC BY 4.0.

Figure 1 – Comparison of the emissions intensity of different hydrogen production routes. Source: International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity." (International Energy Agency, April 2023) 7-87.

2050, with an estimated US $1.4 trillion market. It is worth noting that it is unlikely that hydrogen use for heating buildings will be significant in this market due to poor round-trip efficiency.[11] Since 2020, H_2 momentum continues to grow with more than 1,000 hydrogen projects requiring $320 billion announced globally through 2030.[12]

Although hydrogen is required in certain industrial and transport sectors, the latest report from the IEA, *Global Hydrogen Review 2023,* indicates an insufficiently rapid scale up of LCH2 and RH2 projects around the world. For example, only 4% of the announced global LCH2 and RH2 production projects have reached the Final Investment Decision (FID) or construction phase. Technology Readiness Level (TRL) of H_2 production processes

H_2 production is currently almost exclusively from fossil sources (e.g., NG – 48%, oil – 30%, and coal – 18%).[13] The average emissions intensity of global H_2 production in 2021 was in the range of 12-13 kg

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11. Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

12. Hydrogen Council and McKinsey & Company, "Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America," 1-27.

13. Petra Schwager, Luis Umanzor, Amparo González et. al., "Green Hydrogen Industrial Clusters Guidelines," 8-48; Truby, Johannes, Pradeep Philip, and Bernhard Lorentz, "Green hydrogen: Energizing the path to net zero," 3-74; Hydrogen Council and McKinsey & Company, "Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America," 1-27; International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity," 7-87; "International Energy Agency (IEA), "The State of Clean Technology

CO_2-eq/kg H_2. According to the IEA Net Zero by 2050 Scenario report, these emissions intensities could reach 6-7 kg CO_2-eq/kg H_2 by 2030 and fall below 1 kg CO_2-eq/kg H_2 by 2050.[14] The EU, UK, USA, and Canada have already set their LCH2 standards to accelerate production and deployment of clean hydrogen. This standard is expected to come into effect by 2024, and should pave the way to a nationwide subsidy and other support policies for clean hydrogen. The current hydrogen production technologies with Technology Readiness Levels (TRL)[i] efficiencies and CO_2 emissions are shown in Figure 2.

At present, many countries are focusing on producing RH2 via water electrolysis powered by Renewable Energy Sources RES.[15] To scale RH2, and to make its contribution to limiting global warming to 1.5°C, the electrolyser capacity needs to grow 6,000-fold by 2050 from today's levels of 600 MW.[16] 400-550 Mt of RH2 needs to be produced by electrolysis, requiring 3,000-4,000 GW of electrolysers and 4,500-6,500 GW of renewables capacity dedicated to RH2 production.[17] Today, electrolyser manufacturing capacity sits at nearly 8 GW/yr, and, based on industry announcements, could exceed 60 GW/yr by 2030.[18] Currently, the announced capacity is matured, 120 GW, and among them, only 8- 9 GW capacity has passed Final Investment Decision (FID). China has the highest capacity of passed FID electrolysis, 40%, due to heavy government support. In contrast, Europe and North America have 15 % each.[19] A breakthrough to high electrolyser capacity is likely to happen during the coming decades.[20] It is predicted that close to $130 billion will be spent on electrolysers between now and 2030.[21]

RH2 could also be produced from biomass/biomethane (bioCH_4), and its gasification represents an effective and promising conversion technology to different energy carriers and chemicals.[22] Biomass/conversion system with negative CO_2 emissions.

Furthermore, BioCH_4 reforming using RES is indistinguishable from NG, and can replace fossil gas without changing the existing gas infrastructure, producing RH2 through steam reforming. In addition, the by-product of the biogas/bioCH_4 production process results in rich nutrient biofertilizers such as digestate, which can help restore depleted soils. BioCH_4 has also a significant role in the energy transition and the circular economy.

Manufacturing," 4-33; International Energy Agency (IEA), "Global Hydrogen Review 2023," 11-171; International Energy Agency (IEA), "Net Zero by 2050," 29-187; United Nations Economic Commission for Europe (UNECE), "UNECE Technology Brief Hydrogen," 1-38; United Nations Economic Commission for Europe (UNECE), "UNECE Technology Brief Hydrogen," 1-38.

14. International Energy Agency (IEA), "Net Zero by 2050," 29-187.

15. Marian Chatenet, Bruno Pollet, Dario Dekel, et. al., "Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments," 4583-4762; Adrian Odenweller, Ueckerdt Falko, Gregory Nemet, et. al., "Probabilistic feasibility space of scaling up green hydrogen supply," 854-865; International Energy Agency (IEA), "Electrolysers," Emanuele Taibi, Herib Blanco, Raul Miranda, et. al., "Green hydrogen cost reduction, scaling up electrolysers to meet the 1.5 C climate goal, 8-102; Jacopo Ide Maigret, Edoardo Macchi, and Herib Blanco, "Global hydrogen trade to mee the 1.5 C climate goal: Part III – Green hydrogen cost and potential," 5-41; Emanuele Bianco, Sufyan Diag, and Herib Blanco, "Green hydrogen for industry: A guide to policy making, International Rebewable Energy Agency," 6-59; Refhyne, "Refhyne – Clean reginery hydrogen for Europe."

16. International Energy Agency (IEA), "Net Zero by 2050," 29-187

17. International Energy Agency (IEA), "Global Hydrogen Review 2022," 11-71.

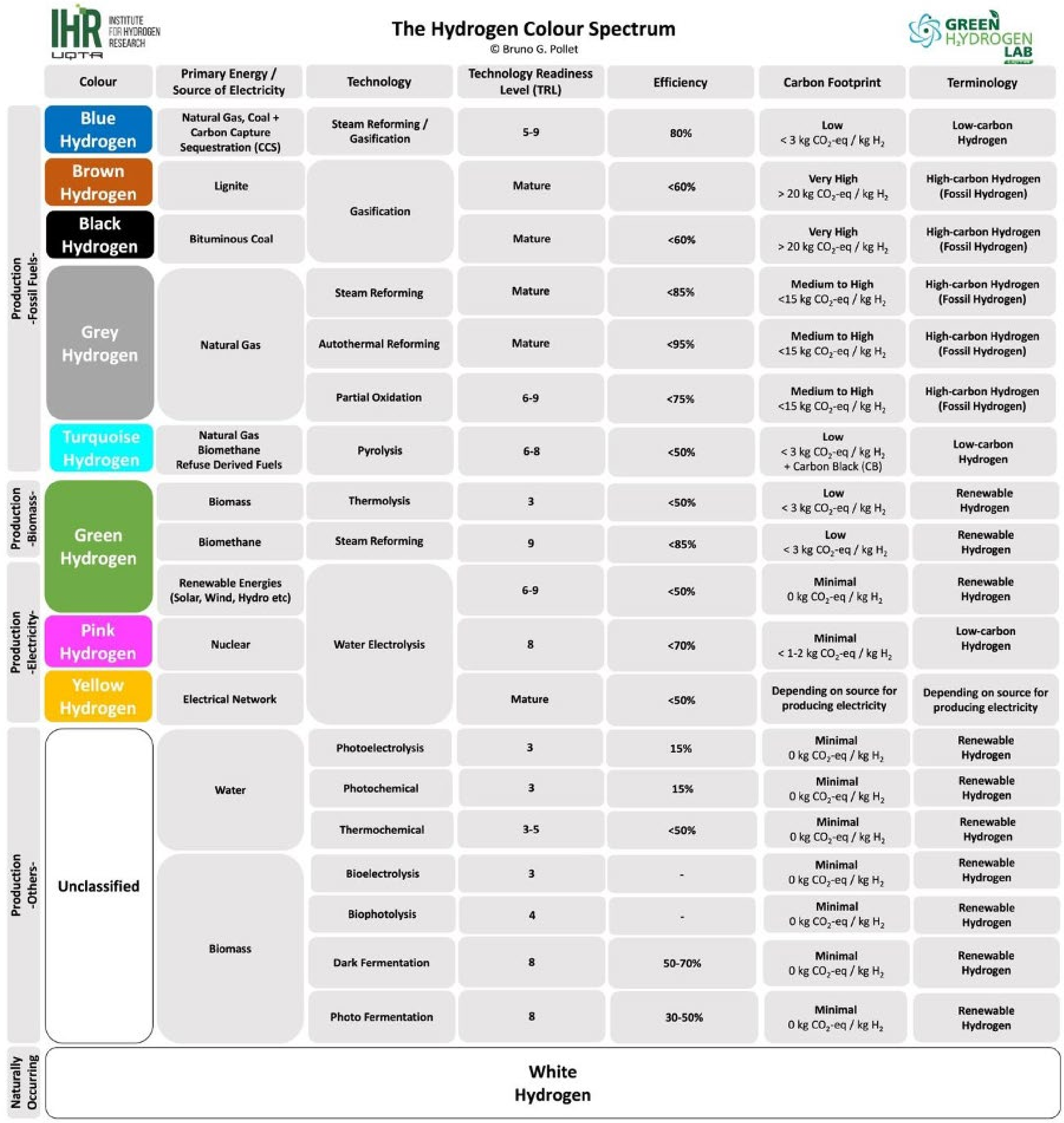
18. Hydrogen Council and McKinsey & Company, "Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America," 1-27.

19. Hydrogen Council and McKinsey & Company, "Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America," 1-27.

20. Emanuele Taibi, Herib Blanco, Raul Miranda, et. al., "Green hydrogen cost reduction, scaling up electrolysers to meet the 1.5oC climate goal," 8-102.

21. Refhyne, "Clean refinery hydrogen for Europe."

22. Matthias Binder, Michael Kraussler, Matthias Kuba, et. al., "Hydrogen from biomass gasification," 4-78.



The Hydrogen Colour Spectrum

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	Colour	Primary Energy / Source of Electricity	Technology	Technology Readiness Level (TRL)	Efficiency	Carbon Footprint	Terminology
Production -Fossil Fuels-	Blue Hydrogen	Natural Gas, Coal + Carbon Capture Sequestration (CCS)	Steam Reforming / Gasification	5-9	80%	Low < 3 kg CO_2-eq / kg H_2	Low-carbon Hydrogen
	Brown Hydrogen	Lignite	Gasification	Mature	<60%	Very High > 20 kg CO_2-eq / kg H_2	High-carbon Hydrogen (Fossil Hydrogen)
	Black Hydrogen	Bituminous Coal		Mature	<60%	Very High > 20 kg CO_2-eq / kg H_2	High-carbon Hydrogen (Fossil Hydrogen)
	Grey Hydrogen	Natural Gas	Steam Reforming	Mature	<85%	Medium to High <15 kg CO_2-eq / kg H_2	High-carbon Hydrogen (Fossil Hydrogen)
			Autothermal Reforming	Mature	<95%	Medium to High <15 kg CO_2-eq / kg H_2	High-carbon Hydrogen (Fossil Hydrogen)
			Partial Oxidation	6-9	<75%	Medium to High <15 kg CO_2-eq / kg H_2	High-carbon Hydrogen (Fossil Hydrogen)
	Turquoise Hydrogen	Natural Gas Biomethane Refuse Derived Fuels	Pyrolysis	6-8	<50%	Low < 3 kg CO_2-eq / kg H_2 + Carbon Black (CB)	Low-carbon Hydrogen
Production -Biomass-	Green Hydrogen	Biomass	Thermolysis	3	<50%	Low < 3 kg CO_2-eq / kg H_2	Renewable Hydrogen
		Biomethane	Steam Reforming	9	<85%	Low < 3 kg CO_2-eq / kg H_2	Renewable Hydrogen
Production -Electricity-		Renewable Energies (Solar, Wind, Hydro etc)	Water Electrolysis	6-9	<50%	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
	Pink Hydrogen	Nuclear		8	<70%	Minimal < 1-2 kg CO_2-eq / kg H_2	Low-carbon Hydrogen
	Yellow Hydrogen	Electrical Network		Mature	<50%	Depending on source for producing electricity	Depending on source for producing electricity
Production -Others-	Unclassified	Water	Photoelectrolysis	3	15%	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
			Photochemical	3	15%	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
			Thermochemical	3-5	<50%	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
		Biomass	Bioelectrolysis	3	-	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
			Biophotolysis	4	-	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
			Dark Fermentation	8	50-70%	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
			Photo Fermentation	8	30-50%	Minimal 0 kg CO_2-eq / kg H_2	Renewable Hydrogen
Naturally Occurring	White Hydrogen						

Figure 2 – The colours of hydrogen production. Source: Figure created by the author.

MAIN BARRIERS

The main barriers to RH2 and LCH2 deployments are related to:

- Production, transportation, and distribution costs as well as infrastructure development;
- Policy and regulatory framework development and harmonisation between regions;
- Lack of market structure and off-takers (demand uncertainty);
- Lack of financial support in the early stage of deployment;
- Access to natural resources;
- Environmental and safety issues.

The Levelized Cost of Hydrogen (LCOH[2]) provides policymakers and industrialists with the techno-economic basis on which to make their decisions on H_2 projects and lead the early deployment of the H_2 market. In the following section, some of these barriers, mainly those connected with technology issues, are addressed.

TECHNOLOGICAL BARRIERS TO RH2 PRODUCTION

Currently, RH2 is principally produced by water electrolysis connected to the grid or to RES. Electrolysis uses direct current (DC) electricity and water, ultrapure in some cases, to produce hydrogen and oxygen. This process is typically between upward of 70-85% efficient depending on the electrolyser type and application.[23] Alkaline Water Electrolyser (AWE) is the oldest technology, having been used for over a century. Its commercial, system efficiency is 50-78 kWh/kg. Other water electrolysers based on polymeric membrane such as Proton Exchange Membrane Water Electrolyser (PEMWE, TRL9, system efficiency: 50- 83 kWh/kg) and Anion Exchange Membrane Water Electrolyser (AEMWE, TRL6, system efficiency: 57-69 kWh/kg) are fairly new.[24]

In the case of high temperature electrolysers such as Solid Oxide Electrolyser Cell (SOEC, TRL7, system efficiency: 40-50 kWh/kg) and Proton Conducting Ceramic Electrolyser Cell (PCCEL, TRL2-4, system efficiency: 40-50 kWh/kg), both are either commercialised or still under research and development.[25] In the case of newcomer electrolyser technologies such as Hysta, of Australia, and H2Pro, from Israel, (TRL6, system efficiency: 39.9-50 kWh/kg), the technologies have yet to be proven at large scale.

The main technical challenges to lower the LCOH[ii] of RH2 produced by RES are:

- **Conversion efficiency of electrolysis**: Most of the regions are typically characterized by low-capacity factors, 25%-51%, from combined wind and solar, and by generation profiles that do not match grid electrical load demands. On the other hand, converting H_2 into mechanical and electrical energy is constrained by maximum efficiencies of up to 60%. The round-trip of H2 efficiency is in the range of 15%–30%, making RE from H2 production require up to 2-3 times more electricity production compared to direct electricity transmission. However, this ratio is much lower and may not be accurate in some locations where the wind capacity factor reaches up to 70% such as Australia, Chile, and Morocco.

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23. Refhyne, “Refhyne – Clean Refinery Hydrogen for Europe.”

24. Marian Chatenet, Bruno G. Pollet, Dario Dekel, et. al., “Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments,”4583-4762.

25. Marian Chatenet, Bruno Pollet, Dario Dekel, et. al., “Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments,”4583-4762; Emanuele Taibi, Herib Blanco, Raul Miranda, et. al., “Green hydrogen cost reduction, scaling up electrolysers to meet the 1.5oC climate goal,” 8-102.

- **Electrolyser lifetime:** There is a maximum of 10 years for some of these technologies, although most of the electrolyser companies will not guarantee 10 years. This is due to dynamic material degradation caused by the intermittent operation, such as the load change of a renewable power supply. Moreover, when varying the supply of RES, the electrolyser is subjected to ramp-up and down of operations, which requires to modulation of process parameters (e.g., pressure, temperature, flow rate etc), in turn causing mechanical equipment fatigue (e.g., hydrogen compressors). This leads to higher OPEX.

- **Critical Raw Materials (CRM):** CRM used in electrolysers are expensive and scarce. For example, the cost of iridium (Ir), a Platinum Group Metal (PGM), which is used in PEMWE, has increased by 800-1,000 % since 2000.[26] Platinum is also used in PEMWE.

MANUFACTURING CAPACITY AND SUPPLY CHAIN

Currently, there is a limited manufacturing capacity for water electrolysers, solar photovoltaic (PV) panels and wind turbines. However, manufacturing capacity growth is expected to increase to more than 200 GW per year in 2030.[27]

In the water electrolyser supply chain, there is a strong dependence on CRM that is characterised by both high environmental impact and social risk. This is present in regions that could be seen geopolitically unwelcoming and, or, unstable. Additionally, the rapid growth in electrolyser deployment is expected to lead to a huge increase in demand for CRM, thus, efforts to reduce and recycle these CRM demands will be necessary.[28] When it comes to the polymeric membrane, especially for the PEMWE technology, the European Chemicals Agency (ECHA) has proposed an outright ban to their use, including per- and polyfluoroalkyl substances.[29]

Furthermore, the increase of RES generation required to produce RH2 will lead to an increase in the request for other minerals. For example, electric cables, transformers, rectifiers, and inverters need aluminium and copper, known as the “metal of electrification”; and wind turbines require manganese, platinum, and rare earth elements used for the creation of permanent magnets in electric motors.[30]

INFRASTRUCTURE BARRIERS

H_2 transport is technically challenging as it is a very light, volatile, and highly flammable gas with a wide low explosivity level range. However, it is worth noting, that, being a very light gas, it disperses very quickly. H_2 embrittlement is also an issue. Ideally, it should be produced as close as possible to the consumption sites. However, there is potential to modify existing gas transmission and distribution networks to transport and distribute H_2. Apart from pipelines, two solutions currently exist for the safe and affordable transportation of H_2: compression and, or, liquefaction to increase its volumetric density, and conversion into a more practical carrier with a reconversion step prior to final use for long

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[26] Bruno Pollet, “The clean energy transition is underway with hydrogen and critical minerals.”

[27] Deloitte, “Green hydrogen: Energizing the path to net zero,”3-74; Hydrogen Council and McKinsey & Company, “Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America,” 1-27.

[28] Bruno G. Pollet, “The clean energy transition is underway with hydrogen and critical minerals”; Thijs Van de Graaf, Claire Kiss, Deepti Siddhanti, et. al., “Geopolitics of the energy transition:critical materials”; Emanuele Taibi, Herib Blanco, Raul Miranda, et. al., “Green hydrogen cost reduction, scaling up electrolysers to meet the 1.5oC climate goal,” 8-102.

[29] European Chemicals Agency, “ECHA publishes PFAS restriction proposal.”

[30] Bruno Pollet, “The clean energy transition is underway with hydrogen and critical minerals”; Thijs Van de Graaf, Claire Kiss, Deepti Siddhanti, et. al., “Geopolitics of the energy transition:critical materials.”

distances.[31] For medium distances, up to 3,000 km, compression and pipeline transport are competitive options compared to ship, rail, and truck. For long distances, greater than 3,000 km, H_2 is converted to another carrier such as LOCH, ammonia, methanol, or SAF before being transported. All of these options involve costly and energy intensive conversion and reconversion processes as well as investment in new infrastructures or in the repurposing of existing assets (e.g., ports, pipelines etc.).[32] At present, one of the most promising options comes from dedicated pipelines connecting demand centres to close-by production sites and import terminals.[33] Another possible option is H_2 blending into existing NG pipeline networks. According to a study undertaken by the US National Renewable Energy Laboratory (NREL), many blending demonstrations internationally have proven that low-hydrogen-percent blending is possible under very specific scenarios with limited end-usage applications on both high-pressure transmission lines and low-pressure distribution lines.[34]

LAND AVAILABILITY ISSUE AND WATER ACCESS

Land availability is a great challenge for some densely populated countries such as South Korea, Japan, and some parts of Europe. Scaling up RH2 production requires large areas of land for renewable electricity generation (e.g., solar and wind installations),[35] although it is not an issue for some other regions of the world such as the 10 most promising countries for RH2 production stated by IRENA. To add to this, permitting processes for the installation of new renewable assets is a major bottleneck in some countries' production scale-up (e.g., Australia, Europe, and the US).[36]

Although there are some market reports stating that water supply is likely not to be a strong barrier to RH2, it is possible that it could be a major bottleneck in the years to come as the world is currently facing an exponential water scarcity crisis due to rapidly increasing demand. By 2030, the gap between the global demand for and the supply of fresh water is expected to reach 40%, and water scarcity in some regions could impact GDP growth by up to 11.5% by 2050.[37] The water consumption of RH2 production could therefore limit its deployment in water stressed areas such as in the Middle East and some parts of Africa. Water desalination projects to produce both drinkable water and H_2 are currently being deployed in most affected regions by water scarcity, such as in Saudi Arabia and the Middle East North Africa region.[38]

COMMERCIALISATION BARRIERS - LCOH

RH2 and LCH2 are currently expensive when compared to fossil hydrogen. RH2 is currently 2 to 3 times more expensive than LCH2 produced from fossil fuels in combination with CCS.[39]

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[31] Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

[32] Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

[33] Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

[34] Kevin Topolski, Evan Resnicek, Burcin Erdener, et. al., "Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology."

[35] Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

[36] Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

[37] Fiona Harvey, "Global fresh water demand will outstrip supply by 40% by 2030, say experts."

[38] Ide Maigret Jacopo, Edoardo Macchi, and Herb Blanco, "Global hydrogen trade to meet the 1.5 C climate goal: Part III – Green hydrogen cost and potential." 5-41.

[39] Petra Schwager, Luis Umanzor, Amparo González et. al., "Green Hydrogen Industrial Clusters Guidelines," 8-48; Truby, Johannes, Pradeep Philip, and Bernhard Lorentz, "Green hydrogen: Energizing the path to net zero," 3-74; Hydrogen Council and McKinsey & Company, "Hydrogen Insights 2023 – An update on the state of the global hydrogen economy, with a deep dive into North America," 1-27; International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity," 7-87; "International Energy Agency (IEA), "The State of Clean Technology

In some regions of the world, the electricity price may determine 40%–80% of the RH2 cost. Additionally, RH2 production costs are driven mainly by the high capital investment associated with the electrolyser cost, which requires high CAPEX.[iii]

In 2021, fossil hydrogen was produced at around US $2/kg, compared to RH2 US$4-9/kg and LCH2 US$2-5/kg.[40] Most countries target a clean hydrogen cost of less than €2/kg by 2030 or US $1/kg[iv] [41]. This target entails a vast increase in LCH2 production in volume, and more efficient and cost-effective H_2 production, distribution, and delivery technologies capacity.

At present, RH2 production is currently not-cost competitive unless there is public funding support or private capital. Additionally, its competitiveness is expected to depend on different cost reduction drivers, such as partially by the electrolyser CAPEX reduction (30-50% by 2030 to 70-80% by 2050) and mainly by the cost of electricity.[42] The optimal combination of RES and electrolysers is discussed in IRENA's 2022 report, "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part III – Green Hydrogen Cost and Potential," giving a roadmap of potential regional development in 2050 to reach the target of less than US $1/kg by 2050.[43] Additionally, H_2 logistics, such as transport and storage, final demand characteristics, and the stability requirement of the supply, will determine the competitiveness of H_2 use. Heavy investment in the "no regret sectors" such as industrial processes are needed. For example, green steel investment and operating costs are in the order of 30%- 50% higher compared to other traditional steel manufacturing routes.[44]

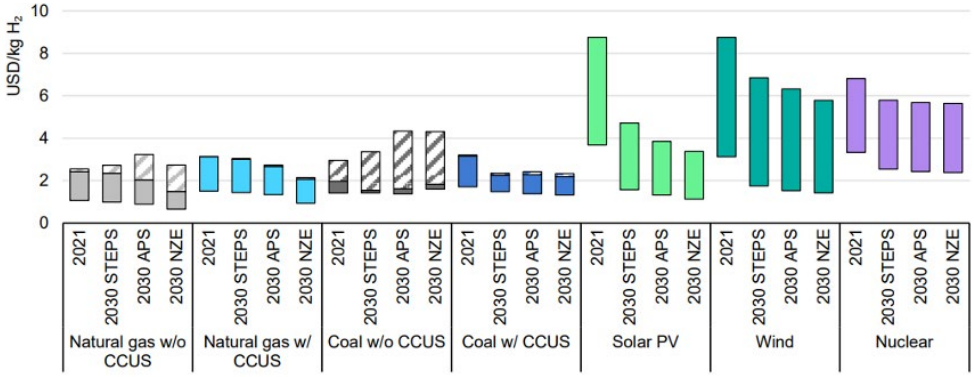


Figure 3: Levelized cost of hydrogen (LCOH) production by technology and scenario. Source: International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity, International Energy Agency." (IEA, 2023) 7-87.

Manufacturing," 4-33; International Energy Agency (IEA), "Global Hydrogen Review 2023," 11-171; International Energy Agency (IEA), "Net Zero by 2050," 29-187; United Nations Economic Commission for Europe (UNECE), "UNECE Technology Brief Hydrogen," 1-38; United Nations Economic Commission for Europe (UNECE), "UNECE Technology Brief Hydrogen," 1-38.

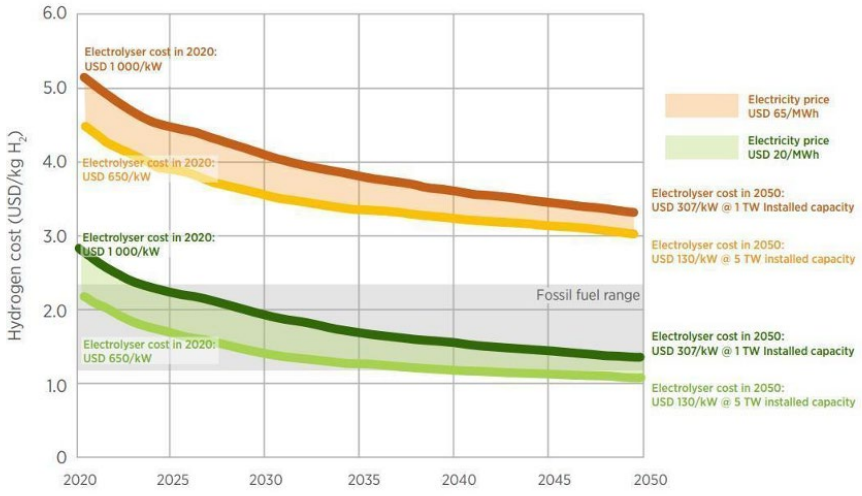
40. International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity," 7-87; International Energy Agency (IEA), "The State of Clean Technology Manufacturing," 4-33.

41. Office of Energy and Renewable Energy, "Hydrogen Shot – Hydrogen and Fuel Cell Technologies Offiice."

42. Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74; Emanuele Taibi, Herib Blanco, Raul Miranda, et. al., "Green hydrogen cost reduction, scaling up electrolysers to meet the 1.5oC climate goal," 8-102.

43. Emanuele Taibi, Herib Blanco, Raul Miranda, et. al., "Green hydrogen cost reduction, scaling up electrolysers to meet the 1.5oC climate goal," 8-102.

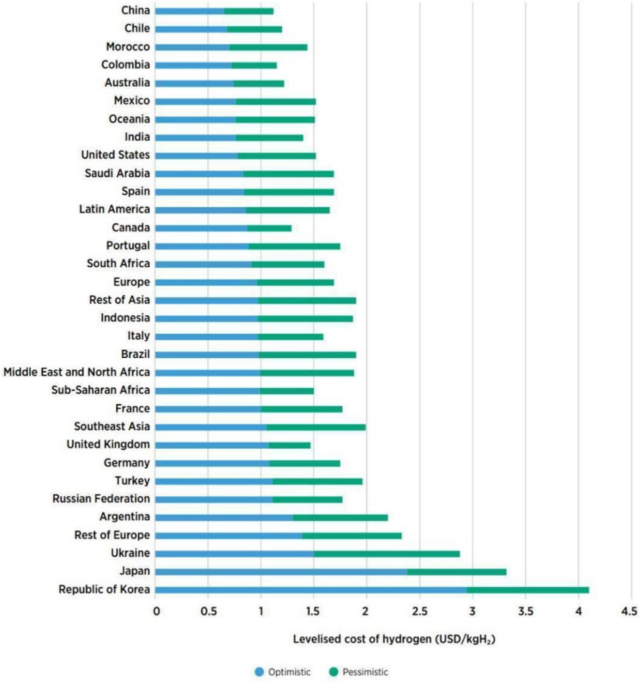
44. Truby, Johannes, Pradeep Philip, and Bernhard Lorentz, "Green hydrogen: Energizing the path to net zero," 3-47; International Energy Agency, "Electrolysers"; Emanuele Taibi, Herib Blanco, Raul Miranda, et. al., "Green hydrogen cost reduction, scaling up electrolysers to meet the 1.5oC climate goal," 8-102; Jacopo Ide Maigret, Edoardo Macchi, and Herib Blanco, "Global hydrogen trade to meet the 1.5 C climate gaol: Part III – Green hydrogen cost and potential," 5-41.



Note: Efficiency at nominal capacity is 65%, with a LHV of 51.2 kilowatt hour/kilogramme of hydrogen (kWh/kg H2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Based on IRENA analysis.

Figure 4 – Cost of RH2 production as a function of electrolyser deployment using average electricity prices in the period 2020-2050. Source: Emanuele Taibi, Herib Blanco, and Raul Miranda et. al., "Green hydrogen cost reduction - Scaling up electrolysers to meet the 1.5ºC climate goal, International Renewable Energy Agency." (IRENA, December 2020) 8-102.



Notes: Levelised cost of hydrogen derived from supply-cost curves of individual countries and regions based on their estimated hydrogen demand for 2050. Water availability for electrolysis is considered in the hydrogen supply-cost curves.

Figure 5 – Levelised cost of hydrogen (LCOH) range in 2050 derived from supply-demand analysis. Source: Emanuele Taibi, Herib Blanco, and Raul Miranda et. al., "Green hydrogen cost reduction - Scaling up electrolysers to meet the 1.5ºC climate goal, International Renewable Energy Agency." (IRENA, December 2020) 8-102.

REGULATORY BARRIERS

It is important to close the cost gap between fossil H_2 and clean H_2 to grow the sectors. Governments need to implement a wide range of policy instruments (e.g., by removing barriers to market entry, direct subsidies, fiscal incentives, public guarantees, CO_2 pricing/contracts for difference, and creating renewable pilot markets for H_2-based products such as green steel/green chemicals), address technical and regulatory pre-requisites, and align legal framework on a global level.[45] Differences between the three leading regions (Europe, USA, East Asia) and non-tariff barriers are hindering the development of RH2 production and slowing down the global energy transition.[46]

SKILL WORKFORCE ACCESS

Producing and using H_2 at scale requires a skilled and competent workforce that can overcome technical, economic, and social challenges and barriers for its adoption. The H_2 workforce needs a combination of technical, soft, and cross-cutting skills and competencies to perform various tasks and roles across the value chain.

SAFETY AND ENVIRONMENTAL ISSUES

The challenges surrounding H_2 are evident. One of the major difficulties is the youth of this industrial sector, which is still under development and has a deployment model which remains uncertain. H_2 is a highly flammable gas, and safety measures must be implemented throughout the production, storage, transportation, and distribution processes to mitigate the risk of accidents. Proper handling, storage, and adherence to safety standards are crucial to ensure the safe production and use of H_2. According to the industry loss investigation statistics, leaks are to blame for about one in four hydrogen fires, with about 40% of leakages going undetected before the loss. H_2 causes metal embrittlement, hence, any regulatory framework will need to incorporate these risks. There are several environmental risks associated with its production, storage and transport that need to be considered:

- Large-scale hydrogen production facilities could put additional pressure on water resources, potentially exacerbating water scarcity issues. Moreover, if water sources are contaminated due to improper handling or leakage of electrolysis reactants (e.g., KOH), it can have detrimental effects on aquatic ecosystems and human health.
- Intake and discharge of water during desalination processes can also have ecological consequences. The intake of seawater can trap and harm marine organisms, including fish and small invertebrates. Additionally, discharging brine with high salinity and altered temperature can disrupt local marine ecosystems, affecting marine life and biodiversity. Reverse osmosis (RO) plants' water recovery rates range from 35%-55%, drastically increasing the amount of brine discharged into the ocean each day.
- The extraction and processing of CRM for water electrolysers, fuel cells, and hydrogen storage materials can release pollutants.
- H_2 is not directly a GHG, but its chemical reactions change the abundances of methane (CH_4), ozone (O_3), and stratospheric water vapour. Leaked H_2 indirectly contributes to global warming by extending the lifetime of other GHGs. Recent studies suggest that H_2 has approximately 100 times stronger of a warming effect than CO_2 over a 10-year period.[v] [47] Unfortunately, the indirect global warming effect of H_2 leakage is rarely considered on a large scale.

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45. Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

46. Deloitte, "Green hydrogen: Energizing the path to net zero,"3-74.

47. Maria Sand, Ragnhild Skeie, Marit Sandstad, et. al., "A multi-model assement of the Global Warming Potential of hydrogen."

- Ammonia (NH_3) production requires a source of nitrogen (N_2), obtained from the air, natural gas, or other fossil fuel-based feedstocks. If the N_2 source is not derived sustainably, its oxide (N_2O – dinitrogen oxide) can contribute to GHG emissions and other environmental impacts. When it comes to warming the climate, N_2O is 300 times more powerful than CO_2. Additionally, it is active in the environment for more than a century. If renewable NH_3 or its by-products enter water bodies, such as rivers or lakes, it can contribute to eutrophication. Eutrophication is the excessive growth of algae and aquatic plants due to high nutrient levels, and can lead to oxygen depletion and harm to aquatic life.

- Chemically combining RH2 with CO_2 leads to eMethanol (CH_3OH) production.[48] Only CO_2 from biogenic sources or from Direct Air Capture (DAC) are eligible outside Europe to produce eMethanol, and other eFuels, for the European market.

BUSINESS MODELS AND OPTIONS TO BE ASSESSED BY DIFFERENT COUNTRIES

To result in a clean and robust H_2 development, countries should answer some relevant questions about the role of H_2 in the decarbonization pathway, especially with respect to the direct electrification of uses. There is a need to assess the current and future country-level industrial structure and end off-takers' needs, the availability of resources (RES potential, water availability, NG, biomass/biomethane, and more) and the robustness and reliability of electricity network and/or the availability of existing gas infrastructure. Cost evolution of electrolyser technology and manufacturing capacity development as well as renewable electricity availability and NG cost will pay a pivotal role in production models prevailing, in the choice of centralized and decentralized production, and in the development of the transport, storage and distribution model. Moreover, each energy conversion step leads to energy losses, such as energy to H_2 and to other carriers; as well as transport and storage, such as compression energy and carrier leakage. This increases the renewable capacity needed up stream.

As it stands, LCH2 is proposed as the "transition technology" towards 2050 Net Zero scenario (referring to NG production with CCS). It will be competitive in the short term for countries with low NG prices and where CO_2 storage sites are available (CO_2 emission intensity = 2-4 kgCO_2-eq/kg H_2 with CCS 93%[49]).

CENTRALIZED VS. DECENTRALIZED PRODUCTION

Decentralized RH2 production will facilitate its application by industrial and business off-takers avoiding the complexity and cost of transportation and storage infrastructure. Two H_2 production business models can be proposed:

- Co-location at the off-taker premise and connection to the grid. No H_2 transport infrastructure is needed;

- RES co-location of the electrolyser and H_2 transport to the off-taker premises. The proximity/distance with RES generation sites could heavily reduce the LCOH. Hybrid design combining solar PV and wind and the curtailment or the use of battery storage could be an option to manage the requirement of supplier stability and depends on the specific local conditions. Centralized RH2 production leads to relevant infrastructure development (e.g., transport by pipeline or shipping, storage, and distribution). Additionally, identifying places where the Levelized Cost of Energy (LCOE) is lower due to abundant

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[48] Dolf Gielen and Greg Dolan, "Innovation Outlook: Renewable Methanol," 4-96; BCC Research, "Green Methanol Market – A Global and Regional Analysis: Focus on End-Use Industry, Application, Methanol Type, and Region -Analysis and Forecast, 2022-2031"; Statista, "Production of methanol worldwide from 2017 to 2022"; IFP Energies Nouvelles, "Tableau de Bord Biocarburants 2022."

[49] International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions intensity," 7-87.

renewable energy resources or fossil fuel-based H_2 with CCS is essential to later bringing H_2 to the off-takers.

TRANSPORT AND STORAGE

The ability to transport H_2 in bulk will mean clean energy can be taken where it is needed, as easily as fossil fuels are today. But there is a cost involved in converting the H_2 into something easy to transport (and unconverting it at the destination). There are currently four attractive options: three use shipping for ammonia, LH2 (liquid), and LOHC, and the fourth using compressed CH_2 via pipelines, either newly laid or through upgraded existing gas pipelines.

Indeed, the most attractive options for shipping H_2 are in the form of ammonia, LH2, and LOHC which are oil derivatives that react reversibly with H_2. Furthermore, H_2 pipelines represent another option for large-scale transport, especially for regions with an existing NG network or with production sites close to consumption sites. It is foreseen that the options listed below will develop in parallel to one another to cover all transport needs:

- Shipping ammonia is the most attractive option for the widest range of size and distance combinations mainly because of the low transport costs. The highest energy and cost penalty of this pathway is the reconversion from ammonia to H_2 (e.g., cracking) which leads to a 13%-34% energy loss.[50] This can be avoided however by directly using ammonia for either existing applications, such as fertilisers, or future applications, such as bunkering fuel. The cracking step needs further development and demonstration at large scale that would be needed for global trade.

- The main challenge for LH2 is the cryogenic temperatures needed (-253°C) as it requires expensive equipment for transport, storage, and handling. It also requires 30%-36% of the energy contained in the H_2 for liquefaction. Due to the high capital intensity, LH2 becomes more attractive as the project size increases which leads to an overlap with the conditions where pipelines are the most cost-effective.

- LOHC can be attractive in a scenario with slower technology progress which leads to higher shipping costs overall and are the most attractive for relatively small projects.

- Pipelines are better suited for high-volume and transport; they are considered the most cost- efficient option for long distances. However, they require relevant investments (LCOH strongly affected by CAPEX and fixed OPEX). Refitting existing gas pipelines could lead to a reduction of 80% of pipeline component of the network CAPEX but the overall LCOH of T&S would be reduced just by 50% as compression and O&M costs would not change with respect to new infrastructure (e.g., specific codes for H_2 inland pipeline are more restrictive than for NG).[51] Furthermore, for H_2 pipeline, the maximum energy capacity could be up to 80%-90% of that of a NG pipeline. The largest common diameter for gas pipelines is about 48 inches (122 cm) which would have a transport capacity of about 13.5 GW at 80 bar. Levelized costs for pipeline transportation vary between US \$0.2-1/kg H_2/1,000 km.[52]

Hydrogen-repurposed pipelines are currently a better option to provide connection between core production and consumption points, but a few countries can rely on a distributed NG network or unused or under-used parallel pipeline to be refitted or refurbished. Regions such as North America, Europe, and Eastern China can potentially repurpose existing NG infrastructure to H_2, leading to a dual benefit of lower H_2 transport costs and avoiding stranded assets.

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[50] Trevor Brown, “Round-trip Efficiency of Ammonia as a Renewable Energy Transporation Media.”

[51] International Energy Agency (IEA), “Global Hydrogen Review 2022,” 11-171.

[52] International Energy Agency (IEA), “Global Hydrogen Review 2022,” 11-171.

However, H_2 may have different production centres and different end-users with respect to today's NG grid coverage.[53]

Two main types of H_2 storage can be assessed as alternatives between centralized and decentralized production: short-term distributed storage and long-term centralized storage.

- Short-term distributed storage would be situated close to the high demand locations to manage the requirement of supply stability and localized peak demand (to be intra-day storage). Assuming 30 years of useful life, pressurised tanks add costs of US $0.2-0.85/kg.[54]

- Long-term centralized storage involves very large H_2 volumes stored seasonally or strategically, such as in underground storage spaces such as salt caves and depleted oil and gas fields.[55] Presently, very limited practical experiences are available. Research projects in the EU are assessing the feasibility and the storage potentials. A fast-track option can be the use of existing NG storage facilities.

RH2 DERIVATIVES AND USES

From a decarbonization perspective, there are major uses of H_2 that appear necessary, such as producing low-carbon or carbon-neutral feedstocks, or process agents, to the chemical and steelmaking industries and delivering low-carbon or carbon-neutral fuels (ammonia, eMethanol, and SAF) to the great majority of planes and ships that cannot be electrified. This is important as steelmaking is responsible for 7% of GHG emissions, aviation, and maritime transportation for about 3% each.[56]

H_2 will likely be needed as a long- duration storage option in power systems dominated by variable renewables such as solar and wind.

Hydrogen allows vast quantities of clean energy to be stored for long durations for use in peak demand and seasonal energy balancing. Hydrogen generated from electrolysis using excess renewable electricity during peak production hours can be used in stationary fuel cells for power generation or stored as a compressed gas, cryogenic liquid, or a wide variety of loosely bonded hydride compounds for longer-term use. When the sun sets and the renewable energy stops coming in, grid operators can turn on hydrogen generators and keep the lights on until the energy supply recovers in the morning.

LCH2 may find other uses, though, but the perspectives are far from clear-cut. For ground transportation, notably long-range heavy-duty, H_2 may play a role to complement the more energy-efficient direct electrification, possibly in so-called "range-extenders," but this can take several forms.

Another often-quoted use of H_2 would be to deliver heat, which represents half the global energy demand. However, delivering low and even medium temperature heat from H_2 to buildings and industries is quite an inefficient proposition when compared to more efficient heat pumps.

Hydrogen–derived products are cheaper to transport long distances but require an expensive conversion process to extract H_2. Among the various eFuels, eMethanol stands out as a particularly promising platform fuel due to its versatility. eMethanol has a unique advantage in that it can seamlessly integrate into the existing infrastructure, without requiring any conversion or modification of technology and it can be used directly as a fuel

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53. Kevin Topolski, Evan Resnicek, Burcin Erdener, et. al., "Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology."

54. Ide Maigret Jacopo, Edoardo Macchi, and Herb Blanco, "Global hydrogen trade to meet the 1.5 C climate goal: Part III – Green hydrogen cost and potential." 5-41.

55. United Nations Economic Commision for Europe (UNECE), "UNECE Technology Brief Hydrogen," 1-38.

56. Anthony King, "Emissions-free sailing is full steam ahead for ocean-going shipping"; European Commission, "Reducing emissions from aviation."

in the maritime industry or feedstock for chemical applications. It can also be used in Direct Methanol Fuel Cell (DMFC) for niche applications. Additionally, eMethanol can be downstream-processed to other carbon-neutral fuels such as SAF, eGazoline, and others. This eMethanol option represents a great lever for the net-zero objective achievement as it could easily replace a large part of fossil fuels that represent today 60% of the global CO_2 emissions.

ENDNOTES

i Technology Readiness Levels are a method for estimating the maturity of technologies - The scale ranges from 1 to 9, where TRL 1 is the lowest and TRL 9 is the highest.

ii LCOH is defined as the total lifetime cost of the investment in a H_2 production technology divided by its cumulative delivered H_2 and its value reveals the average price that H_2 must be sold to break-even financially.

iii US $1-2 million per MW, depending on the electrolyser technology.

iv “1 1 1” – US$1 for 1 kg of clean hydrogen in 1 decade – the US DoE “Hydrogen Energy EarthShots” initiative.

v the GWP100 - Global Warming Potential over one century of H_2 is estimated at 11.6 ± 2.8.

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CEET SUBJECT MATTER EXPERT

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