Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options

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**Abstract:** Industrial decarbonization is a daunting challenge given the relative lack of low-carbon options available for “hard to decarbonize” industries such as iron and steel, cement, and chemicals. Hydrogen, however, offers one potential solution to this dilemma given that is an abundant and energy dense fuel capable of not just meeting industrial energy requirements, but also providing long-duration energy storage. Despite the abundance and potential of hydrogen, isolating it and utilizing it for industrial decarbonization remains logistically challenging and is, in many cases, expensive. Industrial utilization of hydrogen is currently dominated by oil refining and chemical production with nearly all of the hydrogen used in these applications coming from fossil fuels. The generation of low-carbon or zero-carbon hydrogen for industrial applications requires new modes of hydrogen production that either intrinsically produce no carbon emissions or are combined with carbon capture technologies. This review takes a sociotechnical perspective to examine the full range of industries and industrial processes for which hydrogen can support decarbonization and the technical, economic, social and political factors that will impact hydrogen adoption.

**Word count:** Approximately 30,000 (excluding citations)

**Keywords:** hydrogen; climate change; climate mitigation; anthropogenic emissions; industrial decarbonization
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Abbreviations or acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFOUL</td>
<td>agriculture, forestry and other land use</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ASU</td>
<td>air separation unit</td>
</tr>
<tr>
<td>ATR</td>
<td>autothermal reforming</td>
</tr>
<tr>
<td>BEV</td>
<td>battery electric vehicle</td>
</tr>
<tr>
<td>BF-BOF</td>
<td>blast furnace-basic oxygen furnace</td>
</tr>
<tr>
<td>BOG</td>
<td>boil off gas</td>
</tr>
<tr>
<td>CAPEX</td>
<td>capital expenditure</td>
</tr>
<tr>
<td>CCE</td>
<td>circular carbon economy</td>
</tr>
<tr>
<td>CeH₂</td>
<td>cryo-compressed hydrogen</td>
</tr>
<tr>
<td>CCS</td>
<td>carbon capture and storage</td>
</tr>
<tr>
<td>CCUS</td>
<td>carbon capture, utilization and storage</td>
</tr>
<tr>
<td>CfD</td>
<td>contract for difference</td>
</tr>
<tr>
<td>CGH₂</td>
<td>compressed hydrogen gas</td>
</tr>
<tr>
<td>CHP</td>
<td>combined heat and power</td>
</tr>
<tr>
<td>CNG</td>
<td>compressed natural gas</td>
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<tr>
<td>CO</td>
<td>carbon monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>CORSIA</td>
<td>Carbon Offsetting and Reduction Scheme for International Aviation</td>
</tr>
<tr>
<td>CRI</td>
<td>Carbon Recycling International</td>
</tr>
<tr>
<td>CSE</td>
<td>concentrated solar energy</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
</tr>
<tr>
<td>DAC</td>
<td>direct air capture</td>
</tr>
<tr>
<td>DRI</td>
<td>direct reduced iron</td>
</tr>
<tr>
<td>DRI-EAF</td>
<td>direct reduced iron-electric arc furnace</td>
</tr>
<tr>
<td>EAF</td>
<td>electric arc furnace</td>
</tr>
<tr>
<td>EECS</td>
<td>European Energy Certificate System</td>
</tr>
<tr>
<td>EOR</td>
<td>enhanced oil recovery</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>ETC</td>
<td>Energy Transitions Committee</td>
</tr>
<tr>
<td>FC</td>
<td>fuel cell</td>
</tr>
<tr>
<td>FCEV</td>
<td>fuel cell electric vehicle</td>
</tr>
<tr>
<td>FT</td>
<td>Fischer-Tropsch</td>
</tr>
<tr>
<td>G20</td>
<td>Group of Twenty</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas</td>
</tr>
<tr>
<td>GWI</td>
<td>global warming impact</td>
</tr>
<tr>
<td>H₂</td>
<td>hydrogen</td>
</tr>
<tr>
<td>H₂S</td>
<td>hydrogen sulfide</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrogen Council</td>
</tr>
<tr>
<td>HDT</td>
<td>heavy-duty truck</td>
</tr>
<tr>
<td>HESC</td>
<td>Hydrogen Energy Supply Chain</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IGU</td>
<td>International Gas Union</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>IRENA</td>
<td>International Renewable Energy Agency</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LaNi₅H₆</td>
<td>lanthanum-nickel alloy hydride</td>
</tr>
<tr>
<td>LDT</td>
<td>light-duty truck</td>
</tr>
<tr>
<td>LNG</td>
<td>liquefied natural gas</td>
</tr>
<tr>
<td>LPG</td>
<td>liquefied petroleum gas</td>
</tr>
<tr>
<td>LOHC</td>
<td>liquid organic hydrogen carrier</td>
</tr>
<tr>
<td>MDT</td>
<td>medium-duty truck</td>
</tr>
<tr>
<td>MgH₂</td>
<td>magnesium hydride</td>
</tr>
<tr>
<td>M(H₃B)₂</td>
<td>magnesium borohydride</td>
</tr>
<tr>
<td>MSW</td>
<td>municipal solid waste</td>
</tr>
<tr>
<td>N₂</td>
<td>nitrogen</td>
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<tr>
<td>NG</td>
<td>natural gas</td>
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<td>NH₃</td>
<td>ammonia</td>
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<td>OPEx</td>
<td>operational expenditure</td>
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<tr>
<td>PEM</td>
<td>proton exchange membrane</td>
</tr>
<tr>
<td>PEMFC</td>
<td>polymer electrolyte membrane fuel cell</td>
</tr>
<tr>
<td>PtL</td>
<td>power-to-liquids</td>
</tr>
<tr>
<td>PV</td>
<td>photovoltaic</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>research and development</td>
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<tr>
<td>RD&amp;D</td>
<td>research, development and demonstration</td>
</tr>
<tr>
<td>SAF</td>
<td>sustainable aviation fuel</td>
</tr>
<tr>
<td>SEWGS</td>
<td>Sorption Enhanced Water-Gas Shift</td>
</tr>
<tr>
<td>SH₂</td>
<td>slash or gelled hydrogen</td>
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<tr>
<td>SJR</td>
<td>Scimago Journal Rank</td>
</tr>
<tr>
<td>SMR</td>
<td>steam methane reforming</td>
</tr>
<tr>
<td>SO₂</td>
<td>sulfur dioxide</td>
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<tr>
<td>SOFC</td>
<td>solid oxide fuel cells</td>
</tr>
<tr>
<td>SOEC</td>
<td>solid oxide electrolysis cell</td>
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<tr>
<td>SOFC</td>
<td>solid oxide fuel cells</td>
</tr>
<tr>
<td>SPK</td>
<td>synthetic paraffinic kerosene</td>
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<tr>
<td>TEFC</td>
<td>total energy final consumption</td>
</tr>
<tr>
<td>TFC</td>
<td>total final consumption</td>
</tr>
<tr>
<td>TRC</td>
<td>technology readiness level</td>
</tr>
<tr>
<td>US DOE</td>
<td>United States Department of Energy</td>
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<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>VRE</td>
<td>variable renewable energy</td>
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<tr>
<td>WB</td>
<td>World Bank</td>
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<tr>
<td>WGS</td>
<td>water-gas shift</td>
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Units of measure

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>°C</td>
<td>degrees Celsius</td>
</tr>
<tr>
<td>atm</td>
<td>standard atmosphere</td>
</tr>
<tr>
<td>bbl</td>
<td>barrel</td>
</tr>
<tr>
<td>bbl/d</td>
<td>barrels per day</td>
</tr>
<tr>
<td>bcm</td>
<td>billion cubic meters</td>
</tr>
<tr>
<td>bcm/yr</td>
<td>billion cubic meters per year</td>
</tr>
<tr>
<td>cm/s</td>
<td>centimeters per second</td>
</tr>
<tr>
<td>CO₂ tot</td>
<td>total carbon dioxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>gram of carbon dioxide</td>
</tr>
<tr>
<td>gCO₂/kWh</td>
<td>grams of carbon dioxide per kilowatt hour</td>
</tr>
<tr>
<td>gCO₂/MJ</td>
<td>grams of carbon dioxide equivalent per megajoule</td>
</tr>
<tr>
<td>g/L</td>
<td>grams per liter</td>
</tr>
<tr>
<td>g/mol</td>
<td>grams per mole</td>
</tr>
<tr>
<td>GJ</td>
<td>gigajoule</td>
</tr>
<tr>
<td>Gt</td>
<td>gigatonnes</td>
</tr>
<tr>
<td>Gt CO₂</td>
<td>gigatonnes of carbon dioxide</td>
</tr>
<tr>
<td>Gt CO₂/yr</td>
<td>gigatonnes of carbon dioxide per year</td>
</tr>
<tr>
<td>Gt CO₂ eq/yr</td>
<td>gigatonnes of carbon dioxide equivalent per year</td>
</tr>
<tr>
<td>GW</td>
<td>gigawatt</td>
</tr>
<tr>
<td>M</td>
<td>million</td>
</tr>
<tr>
<td>M³</td>
<td>cubic meter</td>
</tr>
<tr>
<td>M³/kWe</td>
<td>square meter per kilowatt electrical</td>
</tr>
<tr>
<td>M³</td>
<td>million tonnes</td>
</tr>
<tr>
<td>MBtu</td>
<td>million British thermal units</td>
</tr>
<tr>
<td>MJ</td>
<td>megajoule</td>
</tr>
<tr>
<td>MJ/bbl</td>
<td>megajoule per barrel</td>
</tr>
<tr>
<td>MJ/L</td>
<td>megajoule per liter</td>
</tr>
<tr>
<td>MJ/kg</td>
<td>megajoule per kilogram</td>
</tr>
<tr>
<td>MJ/RTK</td>
<td>megajoule per revenue tonne kilometer</td>
</tr>
<tr>
<td>Mt</td>
<td>million tonnes</td>
</tr>
<tr>
<td>Mt/yr</td>
<td>million tonnes per year</td>
</tr>
<tr>
<td>MtH₂</td>
<td>million tonnes of hydrogen</td>
</tr>
<tr>
<td>Mt H₂/yr</td>
<td>million tonnes of hydrogen per year</td>
</tr>
<tr>
<td>Mt CO₂</td>
<td>million tonnes of carbon dioxide</td>
</tr>
<tr>
<td>Mt CO₂/yr</td>
<td>million tonnes of carbon dioxide per year</td>
</tr>
<tr>
<td>Mtoe</td>
<td>million tonnes of oil equivalent</td>
</tr>
<tr>
<td>Mtoe/yr</td>
<td>million tonnes of oil equivalent per year</td>
</tr>
</tbody>
</table>
1. Introduction

Hydrogen, which is the most abundant element in the universe, was first discovered by British scientist Robert Boyle in 1671 [1], and later confirmed as a distinct element in 1766 by another British scientist, Henry Cavendish [2]. In 1874, nearly 100 years after Cavendish’s discovery, Jules Verne set a vision for the use of hydrogen as a zero-carbon fuel when he wrote in his book the Mysterious Island, “water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable [3]”. Despite this long-known opportunity for hydrogen to be isolated from water and produce only water when combusted a fuel, techno-economic challenges hindered its widespread adoption as a clean fuel during the 19th and 20th centuries.

During the 20th century, interest in hydrogen as a fuel was sparked by the need for an energy dense and storable fuel for space travel, which became a topic of global interest in 1960s. In the early 1970s, interest in hydrogen again surfaced as the OPEC oil embargo crisis stimulated a search for alternatives to fossil energy. However, hydrogen never really gained traction as an energy source and by 2020 did not account for a measurable share of global energy consumption [4]. This has begun to change in recent years [5], however, as hydrogen production and utilization technologies have matured and a growing number of countries and organizations have made a commitment to net-zero carbon emissions by 2050 [6]. Hydrogen is increasingly being positioned as a key energy vector due to its versatility as a chemical store of energy for use the power, buildings, transport and industrial sectors (Figure 1), coupled with its potential to serve – alongside biomethane – as a versatile decarbonized gas (Figure 2).
Hydrogen has become a particularly attractive source of energy for the following reasons [4,8]:

- **Energy security**: because low-carbon hydrogen can be generated from both fossil and renewable energy resources, many countries can benefit from hydrogen for energy supply diversification.
- **Synergy with existing industries**: hydrogen production, storage, transmission, handling and consumption has many overlaps with the current oil & gas industry, and the manufacture of equipment for hydrogen production and utilization has synergies.
with existing industrial sectors. This offers the opportunity for a just low-carbon energy transition via hydrogen as many of the skills, jobs, infrastructure, assets and business models required for a “hydrogen economy” are transferable.

- **Viable and incremental transition pathway**: current infrastructure for natural gas, including pipelines, heaters and turbines, have the potential for conversion to hydrogen use. Hence costs associated with asset replacement, decommissioning and write-off can be avoided in many cases.

- **Sector coupling and renewable energy integration**: hydrogen can be used as a flexible store of intermittent renewable energy, particularly solar and wind energy, over long timescales and therefore can play an important role in achieving very-high shares of renewables in the power sector. Further, renewable electricity can be converted to hydrogen for the benefit of multiple end-use sectors.

- **Industrial decarbonization**: perhaps most importantly for this work, hydrogen is one of the limited options for many decarbonizing industrial sectors, particularly those that require chemical transformations that may not be amenable to decarbonization by other clean energy sources.

Despite these promising attributes, until recently, many global energy scenarios provided relatively limited coverage of hydrogen [7]. This has begun to change, however, with the following projections for hydrogen utilization in recent studies:

- Hydrogen Council: 18% Total Final Energy Consumption (TFEC) by 2050 [9]
- IEA (Sustainable Development Scenario): 13% TFEC by 2070 [10]
- International Gas Union (IGU): 7-24% TFEC by 2050 (policy dependent) [8]

Further, by early 2020, 18 countries had published hydrogen roadmaps [9] and several countries and regions have included hydrogen investment prominently in economic stimulus packages aimed at supporting economic recovery from the COVID-19 global health pandemic [12]. Hence, hydrogen is becoming recognized to be an important component for achieving ambitious climate targets, it is also central to the industrial and economic development plans of a growing number of regions and countries.

This review offers a critical, systematic and interdisciplinary assessment of industrial decarbonization via hydrogen. At a critical juncture for the industry and global climate, this study asks: How can hydrogen help decarbonize industrial processes? What are the most sustainable means of producing hydrogen? What current and projected technical solutions and innovations exist to make hydrogen production and uses low to zero carbon? What benefits will accrue from hydrogen use in industry, and what barriers will need to be addressed? To answer these questions, the paper undertakes a comprehensive and critical review of more than 2100 sources of evidence, and final referencing of over 700 papers and studies. It utilizes a sociotechnical lens that examines hydrogen production and utilization across multiple industries.

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1 Stabilizing global temperature rise to well below 2°C above pre-industrial temperatures by the end-of-century, while pursuing efforts to limit warming to 1.5 °C.
Section 2 provides background information about hydrogen that is important to understanding the opportunities and challenges for its use in industrial decarbonization, while Section 3 summarizes the literature review methodology. Section 4 explores the energy and climate impacts of industrial hydrogen use, and Section 5 looks at a number of current, emerging and breakthrough technologies across the hydrogen sociotechnical system. Section 6 discusses key policies and regulations related to industrial hydrogen adoption, while Section 7 the current barriers to hydrogen adoption. Section 8 presents a view toward future research agendas that may evolve from this work and finally in Section 9 provides concluding remarks.

2. Background: Definitions and attributes of hydrogen

Throughout this study, a number of terms and phrases are used that warrant upfront definition. Also, hydrogen is a fuel with many unique attributes that influence its acceptance and use, and hence these attributes are discussed in detail as well.

2.1 Definitions and terms

The study frequently uses the following phrases and terms [4,8,13]:

**Hydrogen**: in this paper, hydrogen refers to hydrogen in dimerized form, which is two hydrogen atoms combined into a hydrogen molecule (H₂). A single hydrogen molecule has a relatively high bond energy (436 kJ/mol) and hence is very stable and chemically inert at room temperature. H₂ only decomposes above roughly 6,000 degrees Celsius and hence hydrogen transformation reactions typically require catalysis.

**Fossil hydrogen**: hydrogen produced from fossil fuels, such as coal and natural gas, with the release of carbon dioxide (CO₂). Fossil hydrogen is sometimes referred to as **“brown”** (from lignite), **“black”** (from coal) or **“gray”** (from natural gas) hydrogen. Hydrogen produced from fossil fuels via methane pyrolysis, which produces solid carbon residue as the byproduct instead of CO₂ is referred to as **“turquoise”** hydrogen.

**Renewable hydrogen**: hydrogen produced via water electrolysis using renewable or zero-carbon emission electricity sources, such as solar and wind or produced from biomass gasification. Renewable hydrogen may also referred to as **“green”** hydrogen although there is in fact no unified definition yet of green hydrogen (Section 6) [14].

**Low-carbon hydrogen**: the EU CertifHy initiative has specified an upper limit of 36.4 g CO₂,eq/MJ for the carbon footprint hydrogen produced from renewable energy (this is called green hydrogen) or other low-carbon sources (this is called low-carbon hydrogen) [15,16]. The EU CertifHy upper limit represents a CO₂,eq reduction of 60% relative to the 91 g CO₂,eq/MJ specified for hydrogen produced from steam methane reforming (SMR). Hence, hydrogen produced from fossil fuels coupled with carbon capture and utilization or storage (CCUS) will, in most cases, qualify. Low-carbon hydrogen is referred to as **“blue”** hydrogen when produced from fossil fuels with CCUS and **“yellow”** or **“purple”** hydrogen when produced from water electrolysis using nuclear power. Hydrogen produced from water
Industrial decarbonization via hydrogen electrolysis using grid electricity is also sometimes referred to as “yellow” hydrogen. Renewable hydrogen also falls within the low-carbon hydrogen definition.

### 2.2 Distinguishing attributes

Hydrogen is the first and simplest element in the periodic table as it consists of only a positively charged nucleus (proton) and a negatively charged electron and therefore has the lowest atomic weight of any element (1.008 grams per mole, g/mol). At ambient temperature and atmospheric pressure atomic hydrogen does not occur and instead occurs as a highly stable hydrogen molecule (H₂). The key physical properties of hydrogen are summarized in Table 1 [4].

<table>
<thead>
<tr>
<th>Property</th>
<th>Hydrogen</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gaseous)</td>
<td>0.089 kg/m³ (0°C, 1 bar)</td>
<td>1/10 of natural gas</td>
</tr>
<tr>
<td>Density (liquid)</td>
<td>70.79 kg/m³ (-253°C, 1 bar)</td>
<td>1/6 of natural gas</td>
</tr>
<tr>
<td>Boiling point</td>
<td>-252.76°C (1 bar)</td>
<td>90°C below LNG</td>
</tr>
<tr>
<td>Energy per unit of mass</td>
<td>120.1 MJ/kg</td>
<td>3x that of gasoline</td>
</tr>
<tr>
<td>Energy density (ambient</td>
<td>0.01 MJ/L</td>
<td>1/3 of natural gas</td>
</tr>
<tr>
<td>con., LHV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific energy (liquefied, LHV)</td>
<td>8.5 MJ/L</td>
<td>1/3 of LNG</td>
</tr>
<tr>
<td>Flame velocity</td>
<td>346 cm/s</td>
<td>8x methane</td>
</tr>
<tr>
<td>Ignition range</td>
<td>4–77% in air by volume</td>
<td>6x wider than methane</td>
</tr>
<tr>
<td>Autoignition temperature</td>
<td>585°C</td>
<td>220°C for gasoline</td>
</tr>
<tr>
<td>Ignition energy</td>
<td>0.02 MJ</td>
<td>1/10 of methane</td>
</tr>
</tbody>
</table>

Under standard conditions, hydrogen is a colorless, odorless, non-toxic and environmentally benign gas with unique physical and chemical properties that play a key role in the ways in which hydrogen is produced, stored and utilized.

### 2.3 Physical Properties

As shown in Figure 3 and Table 1, hydrogen transitions from gas to liquid at –252.76°C (at atmospheric pressure) and has a critical temperature of –239.96°C, which means that above this temperature it cannot be liquefied, regardless of the pressure applied. Hydrogen’s critical pressure is 13.1 bar and so above this pressure and the critical temperature, hydrogen can only exist as a supercritical fluid with characteristics of both liquid and gas. Due to these properties, liquefaction of hydrogen is accomplished by cooling rather than pressurization. The compressed storage of hydrogen (often at 350 or 700 bar) always takes place with hydrogen existing as a supercritical fluid [13].
Hydrogen’s gaseous density is 0.089 grams per liter (g/L), which is approximately 14 times lower than that of air (1.29 g/L). For this reason, hydrogen has high buoyancy in the atmosphere and is highly volatile.

Hydrogen liquefaction is extremely important for hydrogen storage and transport. In the liquid state at -253°C and 1.013 bar, hydrogen has a density of 70.79 g/L, which is approximately 800 times its density as a gas. This massive reduction in volume per unit mass is much greater than that of other fuels, such as Liquefied Petroleum Gas (LPG), which undergoes an approximately 250-fold gas to liquid density increase (depending on the proportion of butane/propane) and methane, which when converted to Liquefied Natural Gas (LNG) undergoes an approximately 600-fold density increase. Because hydrogen undergoes a rapid phase change from liquid to gas and the associated volume increase is so substantial, robust ventilation and pressure relief devices must be built into hydrogen systems to ensure safety. In addition, hydrogen has a negative Joule-Thomson coefficient above –71°C, which means that, counterintuitively, it heats when expanded while most industrial gases, including air, nitrogen and oxygen, cool when expanded unless they are subjected to extremely high temperatures exceeding 300°C (i.e., their inversion temperatures). Due to this behavior, hydrogen liquefaction cannot take advantage of cryo-cooling cycles used by other industrial gases to exploit their cooling upon expansion [17,18].

Finally, hydrogen is the lightest gas and hence readily diffuses into other substances, passes through porous material and even passes into and through metals. This, in turn, can lead to hydrogen infrastructure embrittlement, which is also known as hydrogen assisted cracking or hydrogen-induced cracking. Such high diffusivity also requires the use of special materials for hydrogen storage containers to prevent hydrogen diffusion losses [19–21].
2.4 Chemical Properties

The key chemical attribute of hydrogen is its flammability, characterized by an ignition range that is very wide compared to other fuels, spanning a concentration of 4 vol% to 77 vol% (Figure 5).

![Figure 4: Ignition range of fuels [13]](image)

Although hydrogen has an autoignition temperature of 585°C, which is relatively high compared to conventional fuels, its ignition energy of 0.02 MJ at its stoichiometric concentration of 29% (volumetric) in air is low. For comparison, natural gas has an ignition energy of 0.29 MJ at its stoichiometric concentration of 9% (volumetric) in air [15]. While this would appear to make hydrogen a very dangerous gas, in practice hydrogen’s very high diffusivity in air makes achieving a high volumetric concentration (i.e., approaching 29%) difficult and hence the primary concern is mixing of hydrogen and air or oxygen in a confined space rather than in the open atmosphere [22].

When hydrogen is burned in ambient air, the flame is hardly visible in daylight as it is characterized by low heat radiation and a high ultraviolet component (Figure 4). This makes unintentional contact with hydrogen flames a concern in addition to potential UV overexposure that can result in sunburn-like effects. Hence, detection sensors are almost always installed with hydrogen systems to quickly identify any leaks and to minimize the potential for undetected flames.
In sum, hydrogen’s properties make it an excellent fuel, but also one that mandates considerable forethought with regard to processing and handling.

3. Research design and conceptual approach

Our review study design is critical and systematic with a sociotechnical perspective. Specifically, a sociotechnical lens is used to guide our assessment of industrial decarbonization via hydrogen and a critical review approach with a systematic searching protocol is to address the research questions stated in the introduction section. Despite an attempt at systematic coverage, and a broad sociotechnical frame to better capture the multifarious and often dynamic nature of hydrogen, our review does have some noted shortcomings. The most obvious is length. In order to be comprehensive in our assessment, we had to include a very large volume of evidence, and to adequately interpret that evidence necessitated a very long review (to which we secured special editorial approval). Secondly, we searched only publications in English, meaning we may miss important literature from other geographies (e.g., Asia, South America). Thirdly, we stopped collecting evidence systematically in January 2021, meaning that we may miss relevant studies published after this date. Lastly, as will be seen throughout the review, using the sociotechnical lens to assess industrial decarbonization via hydrogen occasionally requires investigating and discussing related hydrogen applications in other sectors such as transport, energy, or buildings. In line with our goal to generate a broad sociotechnical frame, such discussions are seen as necessary to develop a comprehensive assessment.

3.1 Critical and systematic review approach

We classify our review as both critical and systematic. A “critical review” seeks to demonstrate that a research team has extensively scoured the literature and critically evaluated its quality [24]. It goes merely beyond describing the literature to interpreting it and also making evaluative statements on the quality of evidence as well as possible research gaps. A critical review offers the chance to evaluate the literature in a given field across varying bodies of evidence in relation to a particular topic or research question. The critical aspect of our review is most evident in Section 9 on “gaps and future research agendas.”

Given that a weakness of critical reviews is that they do not always demonstrate a methodical review approach, we also made our review “systematic.” This approach offers a number of
advantages over a traditional literature review [25,26]. In particular, it has the advantage of offering:

- a focused exploration;
- the avoidance of selective and opportunistic evidence;
- replicability through documented study inclusion;
- the ability to discriminate between sound and unsound studies;
- increased transparency.

Systematic reviews also minimize unintentional bias and they can promote diversity. For these reasons, multiple studies have called for greater use of systematic reviews like this one in the domains of energy and the environment, climate change, and energy social science more broadly [27–29].

3.2 Searching protocol and analytical parameters

To guide our critical and systematic review, we relied on three distinct sets of search terms (shown in Figure 6) that encompass our focus on industrial decarbonization via hydrogen. This set results in 48 distinct search permutations. As Figure 6 summarizes, we executed these search permutations — 576 search strings in total — on twelve separate databases or repositories selected to capture the state-of-the-art across both scholarly and grey literature.

![Search string diagram](image)

Table 2 displays our results. It notes that while our generic searches resulted in more than 9.7 million potentially relevant documents, this fell to a final sample of the 4674 most relevant studies as determined via results sorting and screening. After screening this sample for recency (11 databases or search engines allowed for temporal restriction of search parameters, set to publication date “after 01/01/2000” or “2000-2021 period”, while the remaining database, National Academies Publications, had to be manually filtered), relevance
(they had to be highly relevant to the topic of mitigating the climate impacts of industrial processes), timeliness (many papers and reports update and expand upon earlier literature) and uniqueness (we adjusted the results to eliminate duplicates), this number dropped to 2134 studies with further short listing undertaken as the review developed. Our final citation count exceeds 700.

Table 2. Summary of critical and systematic review search results and final documents

<table>
<thead>
<tr>
<th>Database</th>
<th>Main topical area of database</th>
<th>Initial search results</th>
<th>Deemed relevant after screening titles, keywords and abstracts</th>
<th>Deemed relevant after scanning full study</th>
<th>Number of duplications</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ScienceDirect</td>
<td>General science, energy studies, geography, business studies</td>
<td>823,696</td>
<td>2052</td>
<td>885</td>
<td>-</td>
<td>885</td>
</tr>
<tr>
<td>JSTOR</td>
<td>Social science</td>
<td>44,753</td>
<td>401</td>
<td>399</td>
<td>0</td>
<td>399</td>
</tr>
<tr>
<td>Project Muse</td>
<td>Social science</td>
<td>119,427</td>
<td>21</td>
<td>15</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Hein Online</td>
<td>Law and legal studies</td>
<td>19,485</td>
<td>30</td>
<td>26</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>PubMed</td>
<td>Medicine and life sciences</td>
<td>5,282</td>
<td>34</td>
<td>34</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>SpringerLink</td>
<td>General science, business and area studies</td>
<td>676,972</td>
<td>276</td>
<td>269</td>
<td>10</td>
<td>259</td>
</tr>
<tr>
<td>Taylor &amp; Francis Online</td>
<td>General science</td>
<td>136,926</td>
<td>57</td>
<td>54</td>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td>Wiley Blackwell</td>
<td>General science, area studies</td>
<td>373,498</td>
<td>99</td>
<td>96</td>
<td>0</td>
<td>96</td>
</tr>
<tr>
<td>(Wiley Online</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Library)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sage Journals</td>
<td>General science, area studies</td>
<td>19,770</td>
<td>37</td>
<td>35</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>National Academies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Publications (nap.edu)</td>
<td>General science</td>
<td>379,926</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Targeted internet</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>searches</td>
<td>White papers, reports, grey literature (e.g., International Energy Agency, International Renewable Energy Agency, World Bank, UN agencies, and the online OECD library)</td>
<td>11,200</td>
<td>331</td>
<td>331</td>
<td>15</td>
<td>316</td>
</tr>
<tr>
<td>Google scholar</td>
<td>General science</td>
<td>7,136,530</td>
<td>1328</td>
<td>1328</td>
<td>1312</td>
<td>16</td>
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<tr>
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<td>9,747,465</td>
<td>4674</td>
<td>3480</td>
<td>1346</td>
<td>2134</td>
</tr>
</tbody>
</table>

Source: Authors

As shown in Figure 7 interest in the industrial use of hydrogen has grown sharply since 2018. Among the references selected in the meta-review, almost a quarter (23.5%) have been published since 2020. Both original research articles and book sections are the majority of publication types, while most of the grey literature of interest is in the form of reports (i.e., position papers, institutional reports, communications).
Figure 7: Left: results per year for publication period (2000-2021) considered in this systematic search. For searches conducted with no time of publication restriction (due to database search filtering limitations), results prior to 2000 were manually removed. Right: results selected in the systematic search classified by type of document. The category “Report” includes position papers, reports and communications that were not subjected to peer-review process. The category “Other” includes webpages and online databases publicly accessible at the time of the systematic search. Source: Authors

Topic-wise, the most numerous subject areas among articles selected in the meta-review are engineering and the natural sciences. While social science is well-represented in the breadth of journals, it represents a small fraction of the total number of papers when compared with engineering and the natural sciences. This suggests a very strong focus in the literature on technical matters concerning hydrogen use and hence much greater exploration of other sociotechnical aspects is possible.

3.3 Analytical frame of sociotechnical systems

To help guide and structure our results from this corpus of final documents on industrial decarbonization via hydrogen, we utilized the analytical frame, or conceptual approach, of sociotechnical systems [30,31]. This frame views hydrogen as far more than just a fuel as it considers the social and technical systems involved in making, distributing, and using hydrogen [32,33]. At the conceptual level, this includes not only the material and energy sources to produce hydrogen, but also all production technology platforms, relevant intermediates, co-generation and conversion alternatives, industrial and end-use applications, all while accounting for institutional and user inputs and drivers, from policy and regulatory frameworks to financial and economic enablers (Figure 8).
The hydrogen sociotechnical system can be described as the network of systems and interactions across five major elements, namely: hydrogen production (1|a); hydrogen supply chain (2|b); hydrogen industrial use (3|c); institutional drivers (4|d); and end-use drivers (5|e). In Figure 9, the actual hydrogen technological pathway (material and energy flows through the industrial systems) is highlighted in blue, while other relevant drivers and elements are highlighted in orange. Numbers are used to represent the origin element captured in the systems interactions, while the small letters represent the element impacted by the interaction. The diagrams have been created to indicate the intricacy of the hydrogen sociotechnical technical system dynamics.
Figure 9: Major elements defined in the sociotechnical system for industrial use of hydrogen. The top half of the diagram (blue) represents the sociotechnical elements where actual hydrogen flows are observed, from source to utilization. The bottom part of the diagram (orange) includes the relevant elements that are not part of the hydrogen technology pathways, but which are relevant for a holistic understanding of the sociotechnical system. Source: Authors

The major elements of hydrogen sociotechnical system evaluated at a higher level of detail are shown in Figure 10.
The production element (1|a) is divided into five sub-elements, namely: (1.1) material sources of hydrogen production (e.g., fossil, biomass, water), (1.2) energy sources (both for the production of hydrogen and its use as an energy vector), (1.3) processing of hydrogen into intermediates (e.g., ammonia, methanol, liquid organic hydrogen carriers – LOHC), (1.4) energy production, and finally (1.5) technology platforms that produce hydrogen. The energy and hydrogen production sub-elements form a coupled nexus, and material and energy flows across industrial systems can go in both directions between sub-elements. Likewise, there is a potential overlap between material and energy sources for certain hydrogen feedstocks of interest, such as biomass and fossil fuels, which can be used for both purposes.
While industrial systems such as steel and chemicals production, as well as oil and gas refining combine in situ production of hydrogen for self-use (flow 1c in Figure 9), enabling the hydrogen use at the global scale requires adequate supply chain processes and infrastructure. Evaluating this second major element of the sociotechnical system in greater detail (2|b), four sub-elements and associated drivers and flows are categorized: (2.1) transmission, (2.2) distribution, (2.3) storage and (2.4) conversion. Due to the heterogenous portfolio of material and energy sources for hydrogen production, coupled with multiple production pathways, technology platforms and use cases, a complex network of processes and industrial systems must be accounted for to fully capture hydrogen supply-chain dynamics. Between production and final use, hydrogen-related industrial systems can mobilize and convert this vector into and from other chemicals and intermediates. Likewise, hydrogen may be used as an intermediate for storage purposes, both within energy generation systems (i.e., to offset variable production and demand patterns), and to respond to production and consumption variability. Therefore, it is important to note that hydrogen can flow in any direction within these sub-elements, with potential industrial supply chains being capable of cycling more than once per flow or sub-element.

The third major element of the hydrogen sociotechnical system captures the main industrial applications for hydrogen (3|c). Some of the systems described rely on hydrogen to serve as either feedstock or fuel for the manufacture of products, such as steel, cement and chemicals, that have additional final applications. Other systems exclusively use hydrogen as an energy vector, such as the different transport industries and the heat, power and cooling sector, where hydrogen adoption co-exists with use of other energy vectors that can enable the adoption of renewable energy sources to fulfill the energy mix, phasing out current fossil-based production [34]. These industrial sectors and their characteristics are discussed in Section 4.

The first three major elements of hydrogen sociotechnical system that have been discussed represent the actual hydrogen flows from sources to end uses, and include the full spectrum of technological elements that are relevant. Other intangible drivers, such as policy, regulatory, and fiscal frameworks, as well as the relevant stakeholders and actors that inform these topics are captured in the fourth major element, Institutional drivers (4|d). Collectively, this portion of the sociotechnical system captures how governmental decision-making bodies (4.1) are shaping the hydrogen economy and managing the different opportunities and challenges in the implementation of hydrogen in industrial systems (4.2). A further detailed analysis of these sub-elements allows for the evaluation of interactions between drivers and enablers at supranational, national, regional and local levels.

Finally, the last major element of the hydrogen sociotechnical system focuses on drivers at the interface between industrial systems, applications and end users (5|e). These are the sociotechnical elements that relate to impacts on the development of hydrogen-based industrial systems and applications that originate from or are highly impacted by societal aspects that are either cultural and symbolic (5.2) or based on market or user preferences (5.3). The stimulation of market demands from changing social norms, increasing awareness of lifestyle footprints, as well as inertia from established behavior patterns are some of the elements captured. Understanding this part of the hydrogen sociotechnical system completes the overall picture of total industrial ecology that a transition to a hydrogen economy would create.
4. The energy and climate impacts of industrial hydrogen use

4.1 Current applications of hydrogen in industry

As shown in Figure 11, industrial use of pure hydrogen (i.e., hydrogen with minimal contaminant or impurities) is currently dominated by oil refining and ammonia production, primarily for fertilizer [4]. Global demand for pure hydrogen was approximately 75 million tonnes (Mt) in 2019 along with an additional 45 Mt per year of hydrogen that is part of gas mixtures for fuel or feedstock (i.e., non-pure) [10]. The main applications for this “non-pure” hydrogen are methanol and steel production.

As shown in Figure 12, nearly all of the pure hydrogen is fossil hydrogen with most of it produced from natural gas (i.e., grey hydrogen) and coal (i.e., black or brown hydrogen). This 275 Mtoe of fossil energy is approximately 2% of total global primary energy demand and yields considerable CO₂ emissions: 10 tonnes of carbon dioxide per tonne of hydrogen from natural gas, and 19 tonnes of carbon dioxide per tonne of hydrogen from coal. In all, CO₂ emission from hydrogen production results is approximately 830 Mt CO₂/yr, which is equal to the combined CO₂ emissions of Indonesia and the United Kingdom [4]. While much of the CO₂ is emitted to the atmosphere, CO₂ produced for ammonia and/or urea production can be used in fertilizer production.
Figure 12: Hydrogen value chain 2020. Notes: Other forms of pure hydrogen demand include the chemicals, metals, electronics and glass-making industries. Other forms of demand for hydrogen mixed with other gases (e.g., carbon monoxide) include the generation of heat from steel works arising gases and by-product gases from steam crackers. The shares of hydrogen production based on renewables are calculated using the share of renewable electricity in global electricity generation. The share of dedicated hydrogen produced with CCUS is estimated based on existing installations with permanent geological storage, assuming an 85% utilization rate. Several estimates are made as to the shares of by-products and dedicated generation in various end uses, while input energy for by-product production is assumed equal to energy content of hydrogen produced without further allocation. All figures shown are estimates for 2018. The thickness of the lines in the Sankey diagram are sized according to energy contents of the flows depicted. [4]

4.2 Energy impacts

Although the use of hydrogen is somewhat limited in scope today, a very different future may be on the horizon. As shown in Figure 13, the Hydrogen Council, which is an industry-led initiative whose members are current fossil hydrogen producers, investors in the sector and heavy industry hydrogen users, has identified 35 applications where hydrogen can have a strong impact now and into the future [9]. These applications, which are both new and existing across transport, buildings, industry heat and industry feedstock are currently responsible for 60% of the world’s energy- and process-related emissions.
As shown in Figure 14 and Figure 15 the IEA Sustainable Development Scenario (SDS) suggests that by 2070, the uses of hydrogen may look very different from today: direct use of hydrogen, synthetic fuels from hydrogen and ammonia from hydrogen are expected to contribute to meeting various transportation fuel demands and to account for nearly 70% of all hydrogen use, which may exceed 500 Mt [10]. If the SDS projections are realized, low-carbon hydrogen produced from a balanced mix of fossil fuels with CCUS and water electrolysis may be able to meet more than 20% of final energy demand for chemicals production, and roughly 15% of final energy demand for iron and steel. The major opportunity, however, would be in the use of hydrogen and/or its derivatives in shipping. Hydrogen and hydrogen-derived fuels may be able to meet more than 70% of final energy demand in this transportation sector.
Figure 14: 2070 Global final energy demand for hydrogen by sector and share of hydrogen in the final energy demand of selected sectors in the IEA Sustainable Development Scenario. Notes: TFC = total final consumption. Synfuels refer to synthetic hydrocarbon fuels produced from hydrogen and CO2. Shares of hydrogen in the final energy demand include for transport modes ammonia and synthetic hydrocarbon fuels [10].

Figure 15: Global hydrogen production and demand in the Sustainable Development Scenario (SDS), in the year 2070. CNR: hydrogen as by-product from catalytic naphtha reforming in refineries; prod.: production; NH₃: ammonia; H₂: hydrogen. [10]
4.3 Climate impacts

Industrial emissions can be segregated into three categories, although not all sectors have emissions associated with all categories. The first category is direct energy-related emissions, which are emissions associated with industrial use of fuels for power and heat (Figure 16). The second category is indirect emissions, which are emissions associated with sourced electricity and heat. The last category is direct process emissions, which are emissions resulting from chemical transformations occurring in industrial processes (e.g., metal oxide reduction processes in both cement and steel manufacturing). To mitigate these emissions, fundamental alterations to industrial processes are needed, such as replacement of feedstocks, novel production pathways, and novel product formulations. In heavy industries (Figure 17), both direct and process emissions are considered hard to abate, and represent the bulk of industrial emissions that remain long-term in the IEA Sustainable Development Scenario (SDS) [10].

Figure 16: CO₂ emissions from fuel combustion in industrial sectors in 2018. ¹: emissions from manufacturing and construction industries; ²: emissions from own use in petroleum refining, the manufacture of solid fuels, coal mining, oil and gas extraction and other energy-producing industries; ³: emissions from agriculture, fishing and other final consumption not specified elsewhere. Adapted from [35–38]
For hydrogen-dependent industrial activities (i.e., where hydrogen is used as a feedstock, such as refining and chemicals), decarbonizing hydrogen production itself is one of the primary ways to reduce the carbon intensity of industrial processes. For industrial high-temperature heat applications in industries such as cement, metals, glass and ceramics, decarbonization via low-carbon hydrogen is also possible. Figure 18 compares the potential CO₂ emissions reduction per unit of produced hydrogen achievable by using renewable or low carbon hydrogen in different applications. In industrial heat applications and in transport sector fuel use, emissions avoidance is related to existing fossil energy combustion emissions. In industrial process applications using hydrogen as feedstock, the decarbonization potential is related to decarbonizing existing fossil hydrogen production (Section 4.1). Thus, it is important to note that in applications where decarbonized hydrogen or one its derivatives is incorporated into a new product (such as in chemicals sector, e.g., methanol and urea production), the decarbonization potential of renewable or low-carbon hydrogen is proportionally smaller. Thus, both hydrogen feedstock demand and overall energy requirements may be met with the low-carbon hydrogen to reach the full decarbonization potential.
The full potential impact of decarbonized hydrogen on global industrial emissions is revisited in Section 6.3.3 (Figure 33), where we discuss carbon pricing and the cost of emissions abatement for industrial sectors.

5. Current and emerging technologies and practices for decarbonization via hydrogen

In this section, the potential for industrial decarbonization via hydrogen is discussed with consideration of the hydrogen production, transmission and distribution and industrial end use. Following our sociotechnical system approach, the potential technology drivers, interventions, and applications in decarbonizing hydrogen for its use as both a low or zero-carbon feedstock as well as energy vector are evaluated. As discussed in Section 4, hydrogen use presently is overwhelmingly reliant on production pathways that have fossil fuels as material and energy sources. These fossil hydrogen sources are not expected to provide long-term solutions for industrial decarbonization applications, unless carbon mitigation strategies (preferentially utilizing renewable energy sources) are able to meet zero- or low-carbon emissions standards [41–43].

The hydrogen sociotechnical system is uniquely positioned to impact the industrial decarbonization of these sectors, as the use of hydrogen as an energy vector supports the four main drivers for net-zero sector emissions (i.e., end-user electrification, carbon capture and storage, low-carbon fuels and large-scale bioenergy production and use). Furthermore, the interactions between the value chains of each industrial sector provides an opportunity for reduced embodied emissions in one sector via the use of hydrogen for decarbonization in an upstream process.
For these sectors, low-carbon transitions based on hydrogen production are feasible. Other potentially relevant sectors, such as food, paper, and rail transport, may also benefit from hydrogen, although both bioenergy (food, paper industries) and direct electrification (rail transport) are perhaps better alternatives in the near future [44].

### 5.1 Options for hydrogen production

While there are an extensive number of ways that hydrogen can be produced [45], we focus on industrial hydrogen production according to the 11 technology pathways listed in Table 3. When discussing the multiple production pathways, it is possible to classify them according to the main energy form used to drive the conversion of material sources into hydrogen, namely: thermochemical, biochemical, electrochemical, and photochemical [46]. Further, using the redox potential perspective to analyze the reactions involved, in the first two groups the material source is a hydrocarbon or other organic molecule that must be oxidized to generate hydrogen, while in the latter two the material sources is water that is reduced to liberate oxygen and hydrogen, which leads to the often-used term “water splitting”.

---

**Table 3. Overview of hydrogen production pathways classified by transformation process**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Transformation process</th>
<th>Material source</th>
<th>Low-carbon, material source options</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam-reforming</td>
<td>Thermochemical</td>
<td>Natural gas, oil (naphtha), other hydrocarbons</td>
<td>Biomass, biomass waste</td>
<td>[41,47–62]</td>
</tr>
<tr>
<td>Partial oxidation</td>
<td>Thermochemical</td>
<td>Natural gas, naphtha, other hydrocarbons</td>
<td>Biomass, biomass waste</td>
<td>[41,55,63,64]</td>
</tr>
<tr>
<td>Autothermal reforming</td>
<td>Thermochemical</td>
<td>Natural gas, naphtha, other hydrocarbons</td>
<td>Biomass, biomass waste</td>
<td>[41,55,65–67]</td>
</tr>
<tr>
<td>Gasification</td>
<td>Thermochemical</td>
<td>Natural gas, oil, coal, other hydrocarbons</td>
<td>Biomass, biomass waste, MSW*</td>
<td>[47,49,51,55,68–76]</td>
</tr>
<tr>
<td>Methane pyrolysis</td>
<td>Thermochemical</td>
<td>Natural gas</td>
<td>Biogas</td>
<td>[77–81]</td>
</tr>
<tr>
<td>Biomass-derived liquid reforming</td>
<td>Thermochemical</td>
<td>Ethanol, isobutanol, bio-oleins</td>
<td>N/A</td>
<td>[47,67,82–84]</td>
</tr>
<tr>
<td>Fermentation</td>
<td>Biochemical</td>
<td>Biomass, biomass waste, wastewater</td>
<td>N/A</td>
<td>[47,70,85–106]</td>
</tr>
<tr>
<td>Microbial electrolysis cells</td>
<td>Biochemical and electrochemical</td>
<td>Biomass, biomass waste, wastewater</td>
<td>N/A</td>
<td>[70,97,107–112]</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>Electrochemical</td>
<td>Fresh water, seawater, brine, wastewater, hydrogen sulfide</td>
<td>N/A</td>
<td>[113–131]</td>
</tr>
<tr>
<td>Photo-biological</td>
<td>Photochemical</td>
<td>Fresh water, seawater, brine, wastewater</td>
<td>N/A</td>
<td>[41,100,102,111,132–138]</td>
</tr>
<tr>
<td>Photoelectrochemical</td>
<td>Photochemical</td>
<td>Fresh water, seawater, brine</td>
<td>N/A</td>
<td>[41,62,101,139–146]</td>
</tr>
</tbody>
</table>

*MSW: Municipal solid waste. Source: Authors

Hydrogen production is expected to increasingly move away from fossil hydrogen. Thus, interventions that specifically address the material source of hydrogen are relevant to thermochemical energy-dependent pathways. In order to leverage the existing infrastructure for fossil hydrogen, replacement with biomass feedstocks (fuel crops, biomass waste streams, and biomass-derived fuels), other waste streams (MSW, de-watered effluent sludge) [147–149], and co-processing are possible decarbonizing interventions.

Electrochemical and photochemical energy-dependent pathways both operate with aqueous feedstocks, and interventions favor the use of non-fresh water resources (such as seawater,
wastewater and desalination brine) instead [119,121,150]. For biochemical energy-dependent pathways, the material source is already considered low-carbon or carbon-neutral (biomass) or the production process is intended to operate using biomass waste streams from other industrial systems, thus limiting the potential for decarbonization interventions.

Alternative waste sources are a potential feedstock opportunity for hydrogen production. Among the suitable industrial waste streams, effluent from sour gas (i.e., natural gas with high sulfur content) desulfurization is particularly relevant for the oil and gas sector as sour gas, which is abundant in some geographies, can provide a novel source of hydrogen production [131]. However, while the potential for hydrogen production from sour gas has been investigated, existing conversion processes are still not viable at industrial scales [130].

Interventions that lead to energy source decarbonization for hydrogen production will cluster depending on the main energy form used in the technology pathways. Figure 19 shows the potential renewable and nuclear energy replacements for fossil fuels. The electrochemical energy-dependent pathways are capable of using all energy sources, while wind and hydropower are not suitable for thermochemical energy-dependent pathways [46]. Both biochemical and photochemical energy-dependent pathways can only be pursued with renewable energy sources, and thus interventions for those pathways are not envisioned. Among all energy sources, solar is the only energy source capable of decarbonizing all four energy forms, and is the sole source for photochemical energy-dependent pathways [151,152].

**Figure 19:** Comparison between fossil and renewable and nuclear sources for hydrogen production. Colored boxes indicate which main energy form each of the listed sources is capable of supplying for the technology pathways evaluated. Source: Authors
These energy sources can most significantly contribute to the decarbonization of hydrogen production when zero-carbon electricity is used for electrolysis [153–158]. The hydrogen production technology pathways that use electricity are energy carrier-agnostic, as far as input energy vectors are considered, and can be deployed both under centralized and distributed systems. Their application for energy load balancing and power storage is also another crucial aspect, which is further explored in Sections 5.2 and 5.3. Because electrolysis is somewhat energy-intensive, adoption at large scale will be coupled with the widespread production of renewable power. For thermochemical energy-dependent pathways, adoption of renewable energy sources is possible to drive the hydrogen production using power of mixed origin (which has been referred to in the grey literature as “yellow hydrogen” [159,160], in an overlap of nomenclature with nuclear energy-derived hydrogen). Alternatively, the secondary unit operations systems associated with thermochemical energy-dependent pathways may themselves be powered using renewables, partially offsetting the energy demand from the fossil feedstocks [161]. Carbon capture and storage interventions to mitigate emissions from fossil fuel-based power stations are also included here.

Regarding feedstocks that serve as sources of hydrogen, adoption of low- and zero-carbon alternatives for thermochemical energy-dependent hydrogen production processes may result in added unit operations needed to condition these replacements as drop-in feedstocks. Pretreatment of feedstocks includes processes such as de-watering/drying, torrefaction, gasification as well as other fractioning activities. With regard to the use of aqueous effluents in the biochemical, electrochemical and photochemical energy-dependent pathways, interventions may combine the hydrogen-producing feedstock pre-treatment requirements with existing unit operations (filtration and membrane separation) or industrial systems (desalination, chlor-alkali, wastewater treatment).

A summary overview of industrial pathways for hydrogen production along with their compatibility with CCS (or CCUS if utilization is considered as well) applications is shown in Figure 20. Technological interventions that impact multiple pathways include both CCS (thermochemical and biochemical energy-dependent pathways) [162] and redox-based chemical looping cycles (thermochemical) [50,68,163–166]. Industrial adoption of these pathways ranges from established processes to experimental and frontier technologies at lab-scale [167] (for each pathway, an expanded diagram of current and potential material and energy sources are presented in Figure 21).
Figure 20: Overview of technology pathways for industrial hydrogen production. Existing industrial production capacity (dark grey) is concentrated on the fossil fuel-based, thermochemical processes, while electrochemical systems are currently in the early adoption phase (light grey). Alternative pathways still in the experimental and pilot-scale phase (white) are also considered for medium- and long-term adoption. The “water, other” material source category includes saline water (brine, seawater), wastewater and other waste effluents (e.g., hydrogen sulfide in sour gases). Source: Authors
Figure 21: Energy and material couplings for all hydrogen production pathways considered in this review. Low-carbon production is inherently possible in the renewable energy-based pathways, while decarbonizing fossil-fuel based pathways can be achieved via energy mix replacement (i.e., renewables and nuclear), CCS use, renewable feedstock use, or a combination of these options.
In addition, Figure 22 illustrates the current use and potential future compatibility of the pathways with industrial sectors where hydrogen is relevant. In this figure, the current status and forecast for hydrogen adoption in industrial sectors is presented in the context of favorable technological pathways and synergy with primary industrial processes. Both peer-reviewed [41,45,55,75,104,109,112,152,155,156,167–182] and grey literature [4,9,10,183–186] were evaluated to provide a foundation for this snapshot. Major technological drivers for selection between the different pathways can be summarized as:

- For existing thermochemical production pathways, decarbonizing hydrogen production will rely on adoption of renewable and waste feedstocks [42,71,148,149,187], use of CCS technologies [162,171,188–190], switch to renewable and nuclear energy [191], or a combination of these interventions [152,161,169,182,192];
- In case thermochemical production coupled with CCS technology does not meet regulatory criteria for classification as low-carbon hydrogen (further discussed in Section 6) or are unacceptable for other reasons, methane pyrolysis and high-temperature electrolysis may be suitable for hydrogen production with high heat processes [43,80,81,123,128,179,193,194];
- Electrolysis produces high-purity hydrogen and can be directly used for fuel cell applications (electric vehicles, electricity generators, distributed heat and power units) [120,195–197];
- Biohydrogen pathways have much lower hydrogen production yields than other alternatives and will therefore have niche applications when coupled with the treatment of wastewater and industrial effluents, as well as the uptake of recalcitrant biomass feedstocks [86,93,102,138,172,198–201];
- Renewable energy availability (in particular solar and wind energy) will impact technology adoption [126,170,202–205].
Figure 22: Current and expected medium- and long-term production pathways for different industrial sector demands (colored boxes). By-product hydrogen production in main sectors is not covered. Diagram generated based on [4,9,10,41,45,55,75,104,109,112,152,155,156,167–186]. Source: Authors
Industries where hydrogen feedstock use can be integrated into optimized heat management favor hydrogen production pathways operating at high-temperature conditions (Figure 20). Chlor-alkali industry is expected to continue to rely on electrolysis with hydrogen production resulting, while long-term biohydrogen production (fermentation, MEC and photo-biological) will be coupled with wastewater and effluent treatment technologies, favoring industrial sectors where both activities can be co-located (i.e., food industry). Low-carbon hydrogen from current thermochemical processes will depend on conversion to renewable and waste feedstocks or use of CCS technologies. In the ammonia industry, thermochemical production of hydrogen coupled with CCS affords the opportunity to beneficially use captured carbon dioxide in the production of urea, which is a commodity chemical made from ammonia and carbon dioxide.

5.2 Options for hydrogen transmission, distribution and storage

As the industrial use of hydrogen grows, the movement of large volumes of hydrogen between sources and end-uses will become an increasingly important concern. Interventions that target the supply-chain element of the hydrogen sociotechnical system are discussed in Table 4 below along with inclusion of the key literature references. The remainder of this section elaborates on these elements.

<table>
<thead>
<tr>
<th>Sociotechnical element</th>
<th>Hydrogen form</th>
<th>Advantage in sociotechnical context</th>
<th>Key application considerations</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas pipeline conversion or newly built hydrogen pipelines</td>
<td>Transmission Compressed</td>
<td>Enables long-distance transport of zero-carbon or low-carbon hydrogen between producers and consumers; Leverages existing infrastructure for NG while attenuating existing energy carbon footprint</td>
<td>Hydrogen embrittlement; leakages</td>
<td>[206–210]</td>
</tr>
<tr>
<td>Co-transmission with natural gas (NG) pipelines</td>
<td>Transmission Compressed</td>
<td></td>
<td>Optimum hydrogen-to-CNG ratio (i.e., lower methane concentrations) for end-use applications</td>
<td>[211–217]</td>
</tr>
<tr>
<td>Liquified hydrogen tankers</td>
<td>Transmission Liquified and cryo-compressed</td>
<td></td>
<td>Storage, minimization of transport losses via boil off gas recovery (as energy or as product)</td>
<td>[218–223]</td>
</tr>
<tr>
<td>Tube trailer trucks</td>
<td>Distribution Compressed</td>
<td>Distribution of hydrogen to local end-use applications</td>
<td>Safety, regulatory limits on weight of hydrogen transported</td>
<td>[224–229]</td>
</tr>
<tr>
<td>Cryogenic trailer trucks</td>
<td>Distribution Cryo-compressed and liquified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen storage tanks</td>
<td>Storage Compressed, cryo-compressed and liquified</td>
<td>Enable long-term hydrogen storage at scale</td>
<td>Demand for large-scale and/or long-term storage in absence of geologic storage options</td>
<td>[208,230–234]</td>
</tr>
<tr>
<td>Geologic storage in salt caverns, depleted gas fields, rock caverns and aquifers</td>
<td>Storage Compressed</td>
<td></td>
<td>Geological site surveys, emissions and leakage detection and management</td>
<td>[233–239]</td>
</tr>
</tbody>
</table>
Transmission and distribution of hydrogen may be feasible using different physical and chemical states. The first set of transformations involve altering the physical properties of the transferred hydrogen, via compression or liquefaction. These unit operations aim to increase the volumetric density of the hydrogen gas, which is extremely low at standard operating conditions (1 atm, 25 °C). Alternatively, hydrogen can be chemically converted into other intermediates, such as ammonia or liquid organic hydrogen carriers (LOHC). The conversion of hydrogen into other energy vectors is pursued when they possess supply-chain advantages, such as the ability to use existing infrastructure, meet an existing industrial demand, and/or provide better physical properties for ease of storage and safer handling. Both physical and chemical transformations of hydrogen for transmission and distribution require added energy inputs, and in case of conversion into intermediates, hydrogen regeneration is also necessary. In certain applications, such as use of hydrogen-derived fuels, the intermediate energy vector may be used without the regeneration step. Therefore, the decision between the different transmission and distribution chain approaches must take into consideration both the efficiency of the supply chain (i.e., opportunities to minimize hydrogen losses or improve hydrogen recovery) and the energy penalty associated with the unit operations (i.e., adopting multiple conversion and transformation steps adds to the overall energy yield losses from hydrogen production until use) [246]. An overview of the main properties and characteristics of the hydrogen supply-chain options is presented in Figure 23, while the technology status for different supply-chain options in the context of the hydrogen sociotechnical system is summarized in Figure 24.
Figure 23: Overview of main options for hydrogen supply-chain using the sociotechnical system context. Figure based on [45,246–254]. Source: Authors
Figure 24: Technology status for different supply-chain options. Figure based on [45,246–254]. Source: Authors
Current hydrogen supply-chain elements have different technology readiness levels, with most mature technologies associated with existing infrastructure uses and industrial applications. However, the main challenge with scaling-up the hydrogen supply-chain is to lower transport-associated costs, as transmission and distribution using existing technologies is still significantly higher than that of other fuels, such as oil and natural gas. This is due to both the maturity and scale of the other energy vectors, as well as the added technical challenges with hydrogen transport due to added energy requirements (for compression, liquefaction or conversion) and inherent physical properties (such as leakage due to small molecule size, or metal embrittlement).

Many of the sub-elements detailed in Figure 24 are technologies related to the infrastructure currently in place for related energy sources and vectors, such as natural gas, methanol, ammonia, and liquid hydrocarbon fuels [255]. Further infrastructure development specifically for hydrogen scale-up will require advances in certain technologies that are targeted specifically toward the transport and storage of hydrogen.

Selecting between the different transmission and distribution options for hydrogen supply chain is a function of both distance and volume of hydrogen moved between production and consumption sites. Figure 25 shows the estimated cost of transporting different quantities (vertical axis) over select distance ranges (denoted in the horizontal axis), with the least expensive mode illustrated. In addition to the terrestrial hydrogen transport systems, which are based on pipelines and trucks, dedicated tanker ships will enable maritime shipping for international overseas transport.

Figure 25: H₂ transport costs based on distance and volume, $/kg, 2019. Notes: figures include cost of movement compression and associated storage (20% assumed for pipelines in a salt cavern). Ammonia assumed unsuitable at small scale due to its toxicity. While LOHC is cheaper than LH₂ for long-distance trucking, it is less likely to be used than the more commercially developed LH₂ [256]
When considering the hydrogen supply chain, the key issue determining the most efficient and effective means of moving hydrogen as a solid, liquid or gas via truck, train, pipeline or ship. As shown in Figure 26, 1 kg of hydrogen stored in various states has significantly different volumes and so new means of volumetrically efficient movement and storage of hydrogen are constantly being sought. Indeed, the means by which hydrogen can be economically transported at scale has a significant impact on the organization of dedicated hydrogen ecosystems, such as industrial clusters, as well as the form in which hydrogen is exported and ultimately utilized. The latter point is demonstrated by the growing use of ammonia directly in power generation [257,258].

![Figure 26. Hydrogen density using different states and carriers.](image)

The overseas shipping element of the hydrogen supply-chain may leverage existing infrastructure for the transport of other liquified gases (in particular natural gas), and exist within a wider context of transitions in the maritime transport sector [220]. The choice of fuel to propel these vessels is relevant to the overall carbon footprint of hydrogen supply [221] and so hydrogen or one of its derivatives, particularly ammonia, may play a prominent role in hydrogen transportation. Similar to the transport of LNG, transported hydrogen will invariably have boil off gases (BOG) that can be either recovered (thus reducing product losses during transport) or used as fuel (thus fulfilling part of the clean fuel demand of the ship).

Depending on routes, operation times and weather conditions, different propulsion systems may be preferred from economic, technological, and environmental perspectives [219]. As already noted, ammonia and other hydrogen derivatives are emerging as promising clean fuel candidates for shipping [218,222,223]. In the case of ammonia, ammonia-fueled engines
could drive hydrogen BOG recovery in hydrogen tankers, or the vessels could be fitted with engines capable of accepting ammonia-hydrogen mixtures as fuel.

Large-scale terrestrial transmission of hydrogen is common using pipelines. In this case, compressed hydrogen can use converted natural gas pipeline infrastructure, or newly-built ones. The possibility to leverage existing infrastructure for natural gas transmission is one of the stronger drivers for co-transmission of hydrogen and natural gas (i.e., blending small amounts of hydrogen in conventional natural gas distribution systems) to partially decarbonize existing natural gas use in the energy sector [206–209,211,248,260,261].

The distribution of smaller quantities of hydrogen is possible using dedicated tanker trucks, either tube trailers (for compressed gas) or insulated, cryogenic tanker trucks (for liquefied and cryo-compressed hydrogen). Other modes of transport, such as railcars, barges or container-ferrying ships could be fitted with tube trailers, although the use of these alternative transport modes is less common. The distance needed to be covered during transport is the economic driver for choosing between compressed and liquefied hydrogen states, as the latter becomes financially preferable with increased distances [225,227,229,230,261].

In the hydrogen storage context, options include naturally occurring geological formations (salt caverns, aquifers), engineered geologic sites (depleted oil and gas reservoirs), dedicated facilities and vessels (compressed, liquid storage tanks), and material-based solutions (both via conversion into other intermediates or in regenerating liquid and solid carriers). The most technologically mature options relate to hydrogen storage as a compressed gas, and similar to the transmission and distribution elements, existing infrastructure and know-how from related energy vectors is relevant. While this trend holds for stationary storage needs, storage requirements in mobility applications (such as in light- and heavy-duty vehicles) is driving research into technologies with medium- and long-term horizons for commercial maturity. Both LOHC and metal hydrides are seen as suitable solutions, due to the possibility to provide hydrogen storage in line with road transport sector needs. In order to arrive at a mature technology readiness level, however, both hydrogen carriers will have to achieve technological breakthroughs in the following areas: increased hydrogen density and energy density per unit of carrier (volume and weight, respectively); improved hydrogen regeneration at lower temperatures (below 100 °C), lower carrier degradation and loss during re-hydrogenation, greatly improved economic performance and lower costs per unit of hydrogen stored [233,250,252,254,262]. Table 5 provides a comparison of storage costs associated with the different hydrogen states and intermediates.

Table 5. Current hydrogen storage options. Adapted from [256]

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>Salt caverns</th>
<th>Depleted gas fields</th>
<th>Gaseous Rock caverns</th>
<th>Pressurized containers</th>
<th>Liquid hydrogen</th>
<th>Liquid Ammonia</th>
<th>LOHCs</th>
<th>Solid Metal hydrides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>300-10,000 t H₂ per cavern</td>
<td>300-100,000 t H₂ per field</td>
<td>300-2,500 t H₂ per cavern</td>
<td>5-1,100 kg H₂ per container</td>
<td>0.2-200 t H₂</td>
<td>1-10,000 t H₂</td>
<td>0.18-4,500 t H₂ per tank</td>
<td>0.1-20 kg H₂</td>
</tr>
<tr>
<td>Duration</td>
<td>Weeks to months</td>
<td>Months (seasonal)</td>
<td>Weeks to months</td>
<td>Daily</td>
<td>Days to weeks</td>
<td>Weeks to months</td>
<td>Weeks to months</td>
<td>Days to weeks</td>
</tr>
<tr>
<td>Benchmark LCOS ($/kg)</td>
<td>0.23</td>
<td>1.90</td>
<td>0.71</td>
<td>0.19</td>
<td>4.57</td>
<td>2.83</td>
<td>4.50</td>
<td>Not evaluated</td>
</tr>
<tr>
<td>Forecast LCOS ($/kg)</td>
<td>0.11</td>
<td>1.07</td>
<td>0.23</td>
<td>0.17</td>
<td>0.95</td>
<td>0.87</td>
<td>1.86</td>
<td>Not evaluated</td>
</tr>
<tr>
<td>Geographical availability</td>
<td>Limited</td>
<td>Limited</td>
<td>Limited</td>
<td>Not limited</td>
<td>Not limited</td>
<td>Not limited</td>
<td>Not limited</td>
<td>Not limited</td>
</tr>
</tbody>
</table>
Another dimension to differentiate between storage solutions is the expected residence time of hydrogen in each technology alternative. For short-term turnover (i.e., fast loading and consumption) at small volumes, dedicated vessels (e.g., compressed and liquid tanks) and metal hydrides provide suitable platforms. At the other end of the scale, hydrogen storage in a depleted gas reservoir or in an aquifer offers the potential for the seasonal storage for multiple applications, including the storage of inherently variable renewable energy. There appears to be no insurmountable technical barrier to the storage of hydrogen in a depleted gas reservoir. Hydrogen losses from dissolution and diffusion could be reduced to less than 0.1%. Losses from biological conversion of residual CO₂ are considered limited, even considering calcium carbonate dissolution. However, the biological reduction of sulfur minerals to hydrogen sulfide remains a potential problem to address [235].

5.3 Options for hydrogen industrial use

The transition towards net-zero emissions via hydrogen, wherever possible, will also have to take into consideration the expected investment cycles for the heavy industries, as older unit operations and facilities reach the end of their expected operation lifetimes and can be replaced. Nonetheless, hydrogen and its derivatives, particularly ammonia, play a key role in net-zero strategies (Figure 14). As already discussed in Section 4, decarbonizing hydrogen is the key to decarbonizing the chemical and refining industries while decarbonized hydrogen will be a new means of decarbonization for a breadth of other industries. Such opportunities are elaborated in the following sections.

5.3.1 Hydrogen use in industry

Oil and gas refining: this industrial sector is one of the major industrial users of hydrogen and is also a producer of hydrogen as an on-site by product of catalytic naphtha reforming and steam cracking of hydrocarbons. The refining sector alone accounted for 33% of global hydrogen demand in 2018 (mixed and pure forms of hydrogen) and approximately two-thirds of hydrogen consumed was produced at dedicated on-site facilities or acquired from merchant suppliers (Figure 27) [4].
Consumption of hydrogen in the refining sector is primarily attributed to the removal of impurities, particularly sulfur, from hydrocarbons (i.e., hydrotreatment) and the upgrading of heavy oils into lighter, higher value products (i.e., hydrocracking). The hydrogen utilized from on-site production and merchant supply is mainly from steam methane reforming from natural gas (48% in 2014), with the balance from refining operations, in particular naphtha reforming for higher octane products [263,264]. Given the industrial relevance of hydrogen in the oil and gas refining industry, multiple projects for low-carbon hydrogen production have been implemented [265].

Selected initiatives targeting the oil and gas refining sector (exclusively or as a part of interventions across multiple hard-to-decarbonize sectors) are presented in Table 6. These initiatives focus on the existing major industrial users of hydrogen (chemicals, iron and steel and refining), and couple these sectors with other energy-related applications, such as cement and buildings (i.e., high heat applications), to provide a unified vision of hydrogen-based transitions.

Table 6. Overview of proposed hydrogen industrial uses in the oil and gas refining industry and other cross-sector uses

<table>
<thead>
<tr>
<th>Technology/Project</th>
<th>Developers and location</th>
<th>Advantage in sociotechnical context</th>
<th>Scale and timeframe</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Carbon Humber partnership (Drax Humber Cluster)</td>
<td>Drax Group, Equinor, National Grid Ventures; Humber, UK</td>
<td>Complete industrial ecology development targeting multiple hard-to-decarbonize sectors using hydrogen and CCS</td>
<td>UK’s first low carbon cluster by 2040, capture of up to 53 Mt CO₂eq/yr</td>
<td>First hydrogen production demonstrator by 2026; full cluster development by 2040</td>
<td>[266]</td>
</tr>
<tr>
<td>Silver Frog</td>
<td>Hydrogenics, Meyer Burger, Ecosolife, European Energy; production sites in Italy (modular)</td>
<td>Renewable hydrogen production and transmission</td>
<td>Start date 2030 with 10GW solar and 5GW wind power plants, 10GW water electrolyzer; 8 Mt/yr CO₂ emissions reductions</td>
<td>Renewable hydrogen production up to 800 kt/year</td>
<td>[267]</td>
</tr>
<tr>
<td>Technology/Project</td>
<td>Developers and location</td>
<td>Advantage in sociotechnical context</td>
<td>Scale and timeframe</td>
<td>Comments</td>
<td>References</td>
</tr>
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</tr>
<tr>
<td>HESC (Liquefied hydrogen energy supply chain)</td>
<td>Kawasaki Heavy Industries (KHI), J-POWER, Iwatani Corporation, Marubeni Corporation and AGL, Australia and Japan</td>
<td>Long-distance, maritime supply-chain between Australia and Japan</td>
<td>Pilot phase by 2021, target 2030 start of commercial operations</td>
<td>Joint Australian and Japanese government partnership with industrial partners</td>
<td>[268]</td>
</tr>
<tr>
<td>NorthH2 green hydrogen</td>
<td>Gasunie, Groningen Seaports, Shell Nederland, Equinor; Netherlands</td>
<td>Hydrogen as a buffer for renewable energy production fluctuations and use of existing natural gas infrastructure for hydrogen transmission and distribution</td>
<td>3-4 GW wind energy by 2030, 10 GW by 2040 for 800 kt/yr hydrogen production, with 7 Mt CO₂ emissions reduction per year</td>
<td>First wind power stations operational by 2027</td>
<td>[269]</td>
</tr>
<tr>
<td>Hi-Vision</td>
<td>Deltalinqs, Air Liquide, BP, Gasunie, Port of Rotterdam Authority and partners; Netherlands</td>
<td>Replacement of existing natural gas infrastructure with blue hydrogen</td>
<td>2.7 Mt CO₂ emissions reductions by 2030</td>
<td>750 MW Hydrogen production plant by end of 2026</td>
<td>[270]</td>
</tr>
<tr>
<td>HyNet North West</td>
<td>North West Hydrogen Alliance; UK</td>
<td>Natural gas grid use replacement with hydrogen (30 TWh/yr) by 2035, 10 Mt CO₂ emissions reductions per year</td>
<td>3 TWh/year low-carbon hydrogen production capacity, with 1 Mt CO₂ emissions reduction during initial phase by 2025</td>
<td></td>
<td>[271]</td>
</tr>
<tr>
<td>Acorn Hydrogen</td>
<td>Pale Blue Dot Energy and partners; UK</td>
<td>400 kt CO₂ emissions reductions at 2% blend into natural gas grid by 2025, eventual 100% hydrogen distribution</td>
<td></td>
<td>Based on Acorn CCS project and part of Hydrogen Coast project</td>
<td>[272]</td>
</tr>
<tr>
<td>GreenHydroChem Central Germany</td>
<td>Siemens AG, Linde AG, the Fraunhofer Institute for Microstructure of Materials and Systems IMWS; Germany</td>
<td>Renewable hydrogen production</td>
<td>100 MW PEM electrolyzer operation start by 2024, 91% GHG emissions reduction as CO₂ equivalent</td>
<td>Large-scale demonstrator of renewable hydrogen production from industry-academia partnership</td>
<td>[273]</td>
</tr>
<tr>
<td>Hybridge</td>
<td>Amprion, Open Grid Europe; Germany</td>
<td>Power-to-gas for hydrogen production</td>
<td>100 MW electrolyzer operation tart by 2023</td>
<td>Potential for synthetic natural gas production via CCS</td>
<td>[274]</td>
</tr>
</tbody>
</table>

Ammonia (chemicals industry): industrial production of ammonia from hydrogen follows the established Haber-Bosch process, which involves the reaction of nitrogen and hydrogen gas over an iron catalyst at elevated temperatures and pressures. Ammonia production is the largest contributor to chemical industry GHG emissions with average direct emissions globally from ammonia production of 2.4 tonnes CO₂ per ton produced [4]. These significant emissions are largely from hydrogen feedstock production, which is primarily based on the steam methane reforming (SMR) of natural gas, with naphtha and coal gasification also used. Electrolysis-based hydrogen production is still in the large-prototype and early adoption phase, due to economic constraints of existing technologies (associated with the electricity cost trend of renewable energy production at market conditions) [275]. Due to a synthesis
reaction based on catalysts, hydrogen feedstock must contain low-levels of additives or contaminants to prevent production slowdowns due to catalyst inhibition or inactivation [4, 223]. As a product, ammonia is mainly used as a chemical fertilizer (nitrogen source for agriculture), either in its ammonium nitrate salt from or as other related chemicals, such as urea (where concentrated CO₂ streams from hydrogen production via SMR of natural gas are used in the production process). Other industrial uses include as a refrigerant gas and as a feedstock for other chemicals production [276]. Due to its chemical and physical properties, ammonia, which is 17-18% hydrogen by weight, is increasingly explored as an energy vector (in direct combustion power systems or fuel cell applications) [218, 222, 277, 278] and as a hydrogen carrier (for long distance transmission and distribution as an intermediate) [262, 279–287]. The decarbonization of maritime transport (further discussed below) is suggested to benefit from renewable hydrogen-derived ammonia as its primary decarbonizing fuel option in the medium-term [223], as falling electricity prices from renewable and nuclear energy will lower production costs of green ammonia, bringing it in line with current fossil-derived hydrocarbon fuels [4].

An overview of reported interventions for ammonia production decarbonization via hydrogen is presented in Table 7.

Table 7. Overview of proposed hydrogen industrial uses in the ammonia industry

<table>
<thead>
<tr>
<th>Technology/Project</th>
<th>Flows and elements</th>
<th>Developers and location</th>
<th>Advantage in sociotechnical context</th>
<th>Scale and timeframe</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2U Eyre Peninsula Gateway</td>
<td>Water, solar and wind energy, electrolyzer, hydrogen gas turbines, compressed storage, green ammonia, liquified ammonia tankers, industrial use</td>
<td>H2U, Australia</td>
<td>Renewable hydrogen production and transmission via green ammonia for direct use and long-distance market demand</td>
<td>75 MW electrolysis plant, 40,000 t green ammonia production per year</td>
<td>Targeting market demand in Japan for maritime and fuel cell applications</td>
<td>[288]</td>
</tr>
<tr>
<td>Yara</td>
<td>Water, renewable energy, electrolyzer, hydrogen green ammonia, ammonia storage, liquified ammonia tankers, industrial use</td>
<td>Yara, Engie; Norway</td>
<td>500 kt of green ammonia production per year; 800 kt CO₂ emissions reduction; target year 2026</td>
<td>Electrolyzer installation and start-up at Porsgrunn ammonia plant (20 kt green ammonia per year), 2023</td>
<td></td>
<td>[289]</td>
</tr>
<tr>
<td>NEOM</td>
<td>Water, solar and wind energy, alkaline water electrolyzer, green ammonia, liquified ammonia tankers, industrial use</td>
<td>Air Products &amp; Chemicals, ACWA Power, NEOM; Saudi Arabia</td>
<td>4 GW solar and wind power plant for 650 t/day green hydrogen production; target year 2025</td>
<td>Ammonia production for transmission via shipping by 2025</td>
<td></td>
<td>[290]</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>Technology/Project</th>
<th>Flows and elements</th>
<th>Developers and location</th>
<th>Advantage in sociotechnical context</th>
<th>Scale and timeframe</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asian Renewable Energy Hub</td>
<td>Water, renewable energy, electrolyzer, green ammonia, ammonia storage, liquified ammonia tankers, industrial use</td>
<td>Intercontinental Energy, CWP Energy Asia, Vestas, Australia</td>
<td>26 GW wind and solar power plants, 23 GW for green hydrogen and green ammonia production,</td>
<td>Start of exports by 2028</td>
<td></td>
<td>[291]</td>
</tr>
<tr>
<td>HyEx (Enaex)</td>
<td>Seawater, solar energy, electrolyzer, green ammonia, ammonia nitrate production</td>
<td>ENAEX, Engie; Chile</td>
<td>2GW solar farm, 1.6 GW electrolyzer, 124 kt green hydrogen into 700 kt green ammonia production per year; 600 kt CO₂ emissions reduction by 2030</td>
<td>36 MW solar, 26 MW electrolyzer, 18 kt green ammonia production per year pilot-plant by 2024</td>
<td></td>
<td>[292]</td>
</tr>
</tbody>
</table>

### Methanol (chemicals industry): the state-of-the-art for methanol production is almost exclusively based on the use of hydrogen from fossil resources and hence average direct emissions globally from methanol production stand at 2.3 tonnes CO₂ per ton produced [4]. A switch towards “green” production pathways is focused on alternative syngas sources, such as biogas and gaseous waste streams from other industrial processes (e.g., cement, steel) or from direct air capture of CO₂ [293]. These gaseous feedstocks are used for methanol synthesis using thermochemical pathways, while a prior step of syngas generation (either via gasification or reforming) might be necessary for solid and liquid fuels [294–296].

Replacing fossil sources with these alternative syngas feedstocks will affect the design and operation of existing and future methanol production systems, as the different compositions and gas species ratios (between carbon-containing molecules, hydrogen and inert gases) will impact reaction rates and stoichiometric balances (mass and energy) [294,295,297,298].

As seen in Section 5.2, methanol can play a role in the hydrogen supply-chain as an energy vector intermediate, with the hydrogen-methanol-hydrogen conversion driven by the possibility of long-distance transmission and distribution using liquid carriers and infrastructure [59,62,63,296,299]. In fact, the potential advantages of using methanol as the main energy vector (rather than hydrogen) have been discussed by Gumber and Gurumoorthy [300].

Another potentially important sectoral interaction when discussing industrial decarbonization is with steel production [293]. Methanol could be either produced using conventional steel production waste gases (under a CCU implementation) [295], or used as feedstock for direct reduction of iron [301]. Adoption of these cross-sectoral decarbonization strategies will require coordination between industries and governments, as medium- and long-term transitions will alter the availability of feedstock gases, whether from emissions avoidance or from renewable production [302,303].
An overview of reported interventions for methanol production decarbonization via hydrogen is presented in Table 8.

### Table 8. Overview of proposed hydrogen industrial uses in the methanol industry

<table>
<thead>
<tr>
<th>Technology / Project</th>
<th>Flows and elements</th>
<th>Developers and location</th>
<th>Advantage in sociotechnical context</th>
<th>Scale and timeframe</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>FReSMe</td>
<td>Water, coal-fired power station, CCU plant, PEM electrolyzer, methanol synthesis</td>
<td>CRI (technology), SSAB and Tata Steel (steel) Swerim, (engineering), multiple European sites</td>
<td>Simultaneous CCU integration and hydrogen use for methanol as energy vector</td>
<td>20% CO₂ emissions reductions at 110MW of water electrolysis capacity</td>
<td>1 ton methanol per day Pilot plant in Luleå, Sweden</td>
<td>[304]</td>
</tr>
<tr>
<td>Carbon2Chem®</td>
<td>Water, renewable energy, alkaline water electrolyzer, compressed storage, CCU of waste gases, methanol synthesis</td>
<td>German Federal Ministry of Education and Research (BMBF), Thyssenkrupp and industrial partners, Germany</td>
<td>Simultaneous CCU integration with other hard-to-decarbonize sectors (steel, cement, power)</td>
<td>Integrated steel and methanol production with 41-42% lower Global Warming Impact (GWI) than conventional processes by 2030</td>
<td>2MW alkaline water electrolyzer Pilot-scale plant in Duisburg, Germany. Methanol as intermediate for energy and chemicals production (ammonia, urea, liquid hydrocarbons and polymers)</td>
<td>[305–307]</td>
</tr>
<tr>
<td>mefCO2</td>
<td>Water, coal-fired power station, CCU plant, PEM electrolyzer, methanol synthesis</td>
<td>Mitsubishi Hitachi Power Systems Europe (engineering), STEAG (power utility), CRI (technology), Hydrogenics Europe (technology), multiple European sites</td>
<td>Simultaneous CCU integration and hydrogen use for methanol as energy vector</td>
<td>11.2% of transport fuel energy demand in Europe (2012 reference)</td>
<td>1MW, 1 ton methanol per day Pilot plant in Niederaussem, Germany</td>
<td>[308]</td>
</tr>
<tr>
<td>Vulcanol</td>
<td>Water, geothermal energy, electrolyzer, CCU of geothermal flue gases, methanol synthesis</td>
<td>CRI, Iceland</td>
<td>Power-to-methanol via hydrogen electrolysis intermediate</td>
<td>5500 tonnes of CO₂ emissions avoided per year, current performance</td>
<td>4000 ton per year pilot production in Svartsengi, Iceland</td>
<td>[309,310]</td>
</tr>
</tbody>
</table>

**Iron and Steel:** The industrial production of steel is considered one of the heavy industries where industrial inertia (i.e., path dependency and technological “lock-ins”) limits sustainability transitions [311]. Steel production technologies have evolved slowly over the 20th century, and current technology platforms for primary and secondary steel production, namely blast furnace-basic oxygen furnaces (BF-BOF) and electric arc furnaces (EAF), favor different feedstocks (iron ore and scrap steel, respectively) and are either dependent on coke (in the case of the BF process) or natural gas (in case of direct reduction processes in the ironmaking step) as the reducing reactant [176,302]. As shown in Figure 28, BF-BOF and EAF with direct reduction of iron (DRI-EAF) both consume hydrogen although on DRI-EAF pure hydrogen is used as a reducing agent while in BF-BOF hydrogen is mostly used as fuel.
Decarbonizing the BF-BOF process is limited by the current role of coal, which provides energy (i.e., heat), material (i.e., coke making carbon feedstock), and carbon monoxide reductant for the reaction within the BF. Consequently, complete switching to hydrogen in BF-BOF processes is not a valid strategy, as decarbonized hydrogen would only be employed to partially reduce the amount of coke used [40]. Due to the basic chemistry inside the BF, hydrogen content in the gas mixture used in the BF is limited to 5-10% with resulting carbon emissions reductions of just more than 20% relative to the conventional BF-BOF process [312].

Decarbonizing the iron and steel sector will require the deployment of CCS technologies (where steel production processes are not changed), replacement of coke as the reducing agent (which is CO2-emitting), either with renewable hydrogen or biomass-derived charcoal, or development of novel technologies for direct iron ore electrolysis, which are currently still at lab scale [313].

Decarbonizing steel production also has direct impacts on the carbon footprint of hydrogen production itself. The increase in industrial hydrogen production using thermochemical pathways is expected to drive demand for steel alloys capable of withstanding degradation due to exposure to reaction conditions, i.e., carbon-rich gaseous atmospheres under high temperature conditions. Such operating conditions may lead to material faults due to oxidation and carburization (e.g., metal dusting) processes on metal surfaces, impacting industrial long-term use and resulting in safety issues and increased maintenance costs [314]. Additionally, hydrogen embrittlement can occur both during steel processing and use, thus mitigation of and resistance to hydrogen ingress is needed to prevent material degradation. Industrial applications of steel relevant to the hydrogen sociotechnical system where this problem is relevant include nuclear energy generation, gas transmission, distribution (compressed and liquified tankers), and storage. An overview of reported interventions for steel sector decarbonization via hydrogen is presented in Table 9.
Table 9. Overview of proposed hydrogen industrial uses in the steel industry

<table>
<thead>
<tr>
<th>Technology/Project</th>
<th>Flows and elements</th>
<th>Developers and location</th>
<th>Advantage in sociotechnical context</th>
<th>Scale and timeframe</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYBRIT (direct reduced iron – DRI – using hydrogen for steel production)</td>
<td>Water, renewable energy, electrolysis, compressed storage or geological storage, DRI-EAF steel production</td>
<td>LKAB (iron ore mining), SSAB (steel manufacturer) and Vattenfall (power utility), Sweden</td>
<td>Integration of dynamic hydrogen production and storage in line with variability in renewable energy production and with hydrogen feedstock demand; addresses 85 to 90% of total CO₂ emissions in the steelmaking value chain</td>
<td>Long-term industrial transition; reduction in CO₂ emissions from 1.6-1.7 ton per ton of steel (current emissions) to 0.025-0.053 ton per ton of steel (target date 2045)</td>
<td>HYBRIT steel production costs 20-30% higher than conventional steel at current energy and feedstock prices</td>
<td>[302,311,313]</td>
</tr>
<tr>
<td>ArcelorMittal’s hydrogen-DRI</td>
<td>Water, renewable energy, electrolysis, compressed storage or geological storage, DRI-EAF steel production</td>
<td>ArcelorMittal Hamburg (steel manufacturer), Germany ArcelorMittal Dunkirk (steel manufacturer), Air Liquide (hydrogen supplier, CCS), France</td>
<td>Integration of green hydrogen in large-scale DRI facilities that currently are designed to operate using natural gas (i.e., “hydrogen-ready” installations)</td>
<td>Long-term industrial transition, with 30% emissions reduction by 2030 and carbon-neutral production of steel by 2050 MoU for Dunkirk facility signed in March, 2021</td>
<td>Current 6MW pilot scale PEM electrolyzer under testing; use of natural gas direct reduction envisioned as a bridge technology</td>
<td>[315–317]</td>
</tr>
<tr>
<td>H₂FUTURE</td>
<td>Water, renewable energy, electricity grid, PEM electrolyzer</td>
<td>Verbund (power utility), Voestalpine (steel manufacturer) and Siemens (technology), Germany</td>
<td>In situ, on demand hydrogen production from grid electricity (with energy source decarbonization)</td>
<td>Pilot scale, 26-month project length</td>
<td></td>
<td>[176,313,318]</td>
</tr>
<tr>
<td>SALCOS, WindH₂ and GrInHy</td>
<td>Water, renewable energy, PEM electrolyzer and high temperature electrolyzer, compressed storage, DRI-EAF steel production</td>
<td>Salzgitter Flachstahl (steel manufacture), Linde AG (gas supplier), Avacon Natur (gas and electricity utility), Germany</td>
<td>Stage-gate transition from existing infrastructure to hydrogen-based DRI using natural gas as bridge technology</td>
<td>Reduction of 10% to 95% CO₂ emissions by 2050, depending on project phase</td>
<td>720 kW SOEC electrolyzer currently under testing</td>
<td>[302,313,318–320]</td>
</tr>
</tbody>
</table>

**High-temperature heat (other industry):** excluding the iron and steel and the chemicals sectors, industrial high-temperature (i.e., > 400 °C) and very-high-temperature (i.e., > 1,000 °C) heat is responsible for approximately 50% of industrial heat demand (Figure 29) and 3% of global energy-sector CO₂ emissions (1.1 Gt CO₂ per year of direct emission) [4].
Although hydrogen combustion is a low-carbon option for high-temperature industrial processes [321], its utilization for this application faces several potential challenges that are sector specific:

- Hydrogen’s high combustion velocity relative to carbon-based fuels, and a non-luminous flame, makes it difficult to monitor optically and hence a safety issue.
- Hydrogen flames have low radiation heat transfer compared to other fuels, requiring fuel additives for use in kiln-based heating processes and potentially leading to burner redesigns.
- Hydrogen can cause corrosion and brittleness in some metals, potentially requiring new coatings and other protective measures.
- Due to hydrogen’s explosive properties, handling and storing hydrogen can present difficulties compared with traditional fuels.

Further, with the exception of chemicals, primary steel and cement production, the majority of industrial heating decarbonization can likely be achieved via power-to-heat using renewable energy power sources and established heating technologies [322]. When further including consideration of technologies with low technological maturity, research suggests that 99% of the heat demand from industry may be amenable to electrification in the future and therefore decarbonized via renewable power. Thus, in high-temperature heat process, low-carbon hydrogen fuel switching is an option but not considered in industrial decarbonization roadmaps [323]. In the case of cement industry, alternative waste resources, combined with novel cement formulations, are expected to provide decarbonization options in the short- and medium term, combined with increase in bioenergy and waste-to-energy adoption [324,325].

*Other industrial uses of hydrogen feedstock:* in the non-steel metallurgy sector, decarbonization via hydrogen is also being investigated. A renewable energy-based smelting unit operation with combined hydrogen production for use as a reducing agent may be suitable for copper production. In particular, concentrated solar energy (CSE) for heat and electricity is posited as a net-zero carbon energy source replacement to drive the
Industrial decarbonization via hydrogen 48

5.3.2 Hydrogen use in transportation

Hydrogen adoption will follow the development of infrastructure for fuel delivery to end-use applications, coupled with long-term replacement of current fleets, as current power trains have in the near-term better drop-in alternatives for CO₂ emissions reductions in the form of biofuels [264,327–331]. In addition, battery-based electric vehicles (BEV) will compete with hydrogen- and ammonia-based fuel cell electric vehicles (FCEV) in light-duty terrestrial transport, where energy density per mass of stored fuel is a less restrictive criterion and refueling infrastructure is possible. This contrasts with maritime transport, aviation and space sector, where mid-voyage refueling logistics are not the norm, and a full fuel load is expected to be carried by the vessels [332].

Maritime transport: the maritime transport sector, already discussed in some detail with regard to the hydrogen supply chain (Section 5.2), is responsible for 90% of the physical trade in goods globally (when measured by volume), a third of which is in the form of oil products and fuels [333]. Sectoral GHG emissions have increased 9.6% in the 2012-2018 period (1075 Mt CO₂ equivalent in year 2018), leading to an increase in the share of global anthropogenic emissions as well (from 2.76% to 2.89% of total emissions in the same period) [334]. Current use of hydrogen in the maritime industry is limited to pilot projects and experimental use [335,336], but replacement of fossil fuels with hydrogen and hydrogen-based fuels is expected to occur in the medium-term [337]. Among the hydrogen-based fuels, different liquid organic hydrogen carriers (LOHC) and, in particular, green ammonia, are being investigated for their potential as zero-carbon maritime fuels [222,249,254,282]. The transition to LOHC and green ammonia in the maritime sector is expected to be driven in part by the increase in hydrogen and hydrogen-based fuel demand by industries, which will require use of tankers for transmission, potentially replacing existing hydrocarbon shipping lanes [208,223,338]. The other driver for this transition is the development of power train technologies that can use these fuels [222], which can either increase fuel efficiency by onboard use of LOHC and green ammonia products, or reduce transmission losses by regenerating boil off gases of the stored intermediates [219].

Aviation: demand for international travel has been heavily impacted by the COVID-19 pandemic [339], and return to pre-pandemic levels of passenger demand is not expected until 2024 [340]. As a result, the implementation of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a global market-based mechanism (MBM) to guide carbon neutral growth and reduce total CO₂ emissions in the aviation sector to half of 2005 CO₂ emissions by 2050, has been impacted as well [341]. Despite an actual reduction on CO₂ emissions due to depressed demand in 2020, the aviation sector must still address and find long-term solutions for its emissions, as fewer technological pathways are available when compared with other transportation modes [342–344]. As seen with other heavy industries, technological “lock-ins” (e.g., liquid hydrocarbon fuel-based power trains and jet turbines) and longer operational lifetimes for aircrafts will require decarbonizing solutions that take into consideration current-technology vehicles still being in operation in the medium- and long-term (i.e., in the year 2050 and beyond) [345].
Current use of hydrogen in the aviation sector occurs mainly in the auxiliary power unit (APU) system of aircrafts, which uses natural gas-derived hydrogen for onboard power generation as a stand-alone, separate system (for redundancy from the main power station) [346]. In addition, ground operations at airports can be converted for hydrogen use (see light- and heavy-duty transport) [347].

Hydrogen use in the aviation sector is expected to occur under two different pathways. First, for small planes aircraft electrification and hydrogen-based fuel cells may be possible. These small aircraft would be employed in very specific geographical and use cases, such as: sparse networks in remote areas (e.g., near Arctic communities, such as in Alaska, USA, or European Nordic countries), small island countries (e.g., archipelagos) and mountainous locations (e.g., Himalayas and Andes mountain ranges), where jet fuel transmission and distribution may be costly and demand patterns favor these electrified aircraft; as urban air taxis, where cargo lift, speed and travel distance requirements are appropriate for fuel cells [346,348]. The second hydrogen use pathway, which encompasses the majority of the aviation sector, is production and use of low-carbon synthetic liquid fuels. Such fuels are currently dominated by synthetic paraffinic kerosene (SPK) from renewable sources using biomass-based feedstocks, and can be blended up to 50% (volume or mass ratio) into conventional aviation fuels [349]. Hydrogen-based synthetic fuels could contribute to production capacity in the long-term, but remain economically unfeasible in the near- and medium-term due to higher production costs [348,350,351].

**Heavy- and light-duty transport**: terrestrial road transport is responsible for almost three quarters of emissions associated with transport sector (Figure 16), and the main interventions proposed for decarbonizing this sector include: shifting use patterns to more efficient modes (e.g., increase in rail transport, public transportation); wide-scale replacement of conventional internal combustion engine (ICE) vehicles with battery-based electric vehicles and plug-in hybrid electric vehicles; wide-scale supply and use of low-carbon biofuels (for ICE vehicles and for hybrids), and wide-scale replacement of ICE vehicles with fuel cell electric vehicles (FCEV) [352–354]. Hydrogen and hydrogen-based fuels are relevant in the latter two interventions, as without adequate fuel production and supply infrastructure the adoption of zero-emission vehicles will face market resistance (further discussed in Section 9) [355–359]. In addition, both BEV and FCEV provide better traceability and emissions quantification frameworks to guarantee zero-carbon fuels, when compared with biofuels for ICE vehicles, which have more complex emissions quantification requirements (from a technical and regulatory perspective) [360–364]. Hydrogen and hydrogen-based fuels also avoid other potential environmental impacts associated with bioenergy fuels (e.g., land use change, water demand, competition with food production) [332,365–367]. The supply chain element for hydrogen use in terrestrial transport is still under development, and small-scale pilot and demonstrator projects are exploring both central production with transmission and distribution to fueling stations, as well as distributed production in situ at the fueling station [368]. In addition to production and supply infrastructure, technical challenges with hydrogen use in light and heavy-duty transport include improving vehicle range, and safe handling and storage (which has implications captured by the fifth sociotechnical element, end-user drivers, further discussed in Section 9) [369].

**Space industry**: use of liquid hydrogen and liquid oxygen (LH2/LO2) propellants dates back to 1963, as these reactants were identified as yielding the high-energy release reactions to
generate the necessary thrust [370]. Although it has been replaced in large part by other fuels, such as RP-1, which are easier to handle and do not require cryogenic storage, it remains in use in upcoming rocket launch systems, such as European Space Agency’s Ariane 6 and NASA’s Space Launch System [371]. The development of commercial Near-Earth launch industry is expected to drive an increased demand for rocket fuel, and the choice of propellant and propulsion system can have deep implications on mission design and possible travel distances [372,373]. In addition, as the Near-Earth orbit industry develops, spacecraft manufacturing will require advanced materials capable of coping with hydrogen embrittlement, as these R&D breakthroughs will both support and be based on technology development for other industrial processes in the hydrogen economy [374]. Other relevant sectoral interactions include extractive mining, which is a frontier industry in the space sector in the form asteroid mining. Both natural hydrogen deposits and hydrogen production from ice water electrolysis may provide feedstocks for rocket fuel production in space [375,376]. Other frontier industries, such as moon-based regolith extraction and space manufacturing, will likely use hydrogen as both fuel and feedstock (i.e., reducing agent) [377], similar to earth-based industries in the cement, steel and chemicals sectors. The vastly different environmental conditions between systems, however (e.g., gravity, temperature, atmospheric pressure and composition), will significantly change the performance and feasibility of hydrogen-related processes and unlock new opportunities.

For prolonged and deep space missions, onboard generation of fuel and oxidant via solar hydrogen pathways coupled with habitability recycling systems is also suggested as a mechanism to reduce mission payloads [378].

5.3.3 Hydrogen use in other electricity, heat and cooling applications

Given its large contribution to direct energy use, at around 30% [4] and associated CO₂ emissions (Figure 16), decarbonizing the energy use in buildings sector is possible with direct substitution of fossil fuels for renewable energy, in which the hydrogen sociotechnical system can play a role. Co-generation (for heat and power) and tri-generation (for heat, electricity and cooling) systems improve energy efficiency of industrial processes by re-using waste heat sources, either directly or in coupled applications, such as climate conditioning in buildings. Both centralized and distributed solutions are possible, in a trade-off of where conversion occurs between the energy vectors and end-use applications (i.e., whether energy as electricity, heat or fuel is transmitted and distributed via grids and networks). As such, although as noted previously, industrial use of hydrogen in this sector is negligible and mostly in the experimental and conceptual stages, the buildings sector will follow the other large-scale decarbonization transitions of fossil-based energy systems and be influenced by social and political considerations that transcend pure techno-economic analysis (Table 6). This combined cross-sectoral transition is supported by the same interactions and drivers present in the relationships between the sectoral sociotechnical systems today. Further, the use of existing infrastructure and market dynamics to facilitate hydrogen adoption also incentivizes a staged approach to the transition, with blending into exiting natural gas systems being a stepping stone towards 100% hydrogen systems.
5.4 Recent breakthroughs and emerging technologies

The surging interest in hydrogen in recent years has accelerated the rate of technological innovation in the field, with novel technologies and scale-up and demonstration-scale initiatives being announced at a rapid pace. This constantly evolving field has already made some forecasts and analyses published in the earlier 2000s obsolete. An overview of relevant and notable breakthroughs and emerging technologies is summarized in Table 10. This table, while non-exhaustive, illustrates the evolving nature of technology development for the hydrogen sociotechnical system. Technologies listed 1 through 6 represent production pathways discussed in Table 3 (pathway name added in parenthesis).

Table 10. Ten emerging and breakthrough technologies in the hydrogen sociotechnical system

<table>
<thead>
<tr>
<th>Technology</th>
<th>Type</th>
<th>Description</th>
<th>Institutions and partners</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Seawater electrolysis</td>
<td>Production (breakthrough technology)</td>
<td>Novel nickel-iron- (oxy)hydroxide catalyst for direct seawater electrolysis</td>
<td>University of Houston and Central China Normal University</td>
<td>[379]</td>
</tr>
<tr>
<td>2. Methane pyrolysis</td>
<td>Production (breakthrough technology)</td>
<td>Molten metal mist reactor for methane splitting into hydrogen and solid carbon (potential for carbon nanotube production)</td>
<td>Susteon, Stanford University, Palo Alto Research Center, SoCalGas</td>
<td>[380]</td>
</tr>
<tr>
<td>3. Solar photocatalysis (photoelectrochemical)</td>
<td>Production (breakthrough technology)</td>
<td>Improved corrosion resistance of photocatalytic semiconductor for H₂ and O₂ co-evolution using a TiO₂-based coating</td>
<td>Yale University</td>
<td>[381]</td>
</tr>
<tr>
<td>4. Solar photocatalysis (photoelectrochemical)</td>
<td>Production (breakthrough technology)</td>
<td>Bismuth vanadate (BiVO₄) photoelectrode for direct solar water splitting</td>
<td>University of Chicago, University of Wisconsin-Madison and Brookhaven National Laboratory; Tokyo University of Science and Northeast Normal University</td>
<td>[382, 383]</td>
</tr>
<tr>
<td>5. Photobiological hydrogen</td>
<td>Production (breakthrough technology)</td>
<td>Microalgal-based biohydrogen production via photosynthesis using droplet-based micro-reactors</td>
<td>University of Bristol and Harbin Institute of Technology</td>
<td>[384]</td>
</tr>
<tr>
<td>6. High-pressure electrolysis</td>
<td>Production (emerging technology)</td>
<td>High pressure (&gt; 50 bar), high-efficiency (95% efficiency at 42kwh/kg H₂) electrolysis (E-TAC, Electrochemical – Thermally Activated Chemical electrolysis) with a target of $1/kg green hydrogen production</td>
<td>H2Pro, Breakthrough Energy Ventures (BEV), Breakthrough Energy Ventures Europe (BEV-E) and IN Venture, Sumitomo Corporation CVC</td>
<td>[385]</td>
</tr>
<tr>
<td>7. Hydrogen boride nanosheets for storage</td>
<td>Storage (breakthrough technology)</td>
<td>Borophene-based lightweight, UV light-responsive, hydrogen carrier</td>
<td>Tokyo Institute of Technology, University of Tsukuba, University of Tokyo</td>
<td>[386]</td>
</tr>
</tbody>
</table>
Industrial decarbonization via hydrogen will require policy mechanisms that stimulate both hydrogen supply and demand and support development of the necessary supply chain infrastructure. While policy toolkits can be built upon existing efforts targeting renewable energy generation and use, as discussed throughout this section, hydrogen-targeted policy instruments are needed [390].

The breadth of hydrogen-related policies is presented in Table 11 with grouping under technology R&D, regulatory and fiscal incentives and public financing.

**Table 11. Overview of policy mechanisms relevant to the hydrogen sociotechnical system**

<table>
<thead>
<tr>
<th>Type</th>
<th>Focus</th>
<th>Description</th>
<th>Impact on hydrogen sociotechnical system</th>
<th>Examples</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Focus</td>
<td>Description</td>
<td>Impact on hydrogen sociotechnical system</td>
<td>Examples</td>
<td>Ref.</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------</td>
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</tr>
</tbody>
</table>
| Regulatory                  | CO₂ emissions standards and regulations    | Sectoral and technology specific measures to mitigate CO₂ emissions reductions | Development and adoption of low and zero-carbon hydrogen technologies across production, supply chain and use | - EU Revised Renewable Energy Directive (EU)2018/2001 (RED II)  
  - ICAO CORSIA                                                               | [407–412]                           |
| Other environmental standards and regulations | Voluntary or mandatory water use and water security measures | Adoption of electrolysis-based hydrogen                                    | - EU Directive (EU)2015/652: calculation of GHG intensity of fuels and efficiency factor of FC power trains  
  - EU Industrial emissions directive 2010/75/EU                                             | [417–421]                           |
| Electricity generation standards and regulations | Voluntary or mandatory decarbonization of energy mix | Stimulate development of low-carbon hydrogen from renewables                | - EU Revised Renewable Energy Directive (EU)2018/2001 (RED II)  
| Zoning, permitting and building codes | Management of physical installations for hydrogen | Support for development of production sites for hydrogen  
  Stimulation of demand for transmission and distribution of hydrogen  
<table>
<thead>
<tr>
<th>Type</th>
<th>Focus</th>
<th>Description</th>
<th>Examples</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Focus</td>
<td>Description</td>
<td>Impact on hydrogen sociotechnical system</td>
<td>Examples</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Fiscal incentives and public financing</td>
<td>Government procurement</td>
<td>Strategic public purchasing of goods and services</td>
<td>Stimulation of market demand for hydrogen</td>
<td>- California Renewable portfolio standard (RPS) Procurement Program</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Promotion of specific hydrogen production pathways or infrastructure options</td>
<td>- EU Directive on Electricity Production from Renewable Energy Sources</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- US Renewable Electricity Standard (RES)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- UK Renewables Obligation</td>
</tr>
<tr>
<td>Tendering/auctioning</td>
<td>Market-based instrument to support public investment</td>
<td>Stimulation of hydrogen production at lowest cost and to achieve specified socio-economic objectives</td>
<td>Introduction of price transparency in the development of hydrogen production projects</td>
<td>- India Ministry of New and Renewable Energy auction for green hydrogen planned in 2021</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- France ADEME (Agency for Ecological Transition) tenders for green hydrogen projects</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Scotland Ministry of Energy tender to European Marine Energy Centre (EMEC) for floating offshore wind and hydrogen supply chain in Scotland and France</td>
</tr>
<tr>
<td>Contracts for difference (CfD)</td>
<td>Price-guarantee instrument to prevent revenue volatility</td>
<td>Stabilization of revenues to de-risk new hydrogen project investment</td>
<td>Reduction of the need for production and demand forecasting for hydrogen business case development</td>
<td></td>
</tr>
<tr>
<td>Carbon pricing, carbon tax and Emissions trading schemes (ETS)</td>
<td>Quantification and monetary valuing of the social cost of carbon (or broader GHG) emissions</td>
<td>Improvement of the economic viability of hydrogen production pathways</td>
<td>Reduction of public costs for support of hydrogen projects</td>
<td>- US Executive Order 13990 and Technical Support Document on Social Cost of CO2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- EU Emissions Trading Scheme - Revised ETS directive (EU)2018/410</td>
</tr>
<tr>
<td>Energy subsidies</td>
<td>Government support for to lower energy prices</td>
<td>Reduction of energy, and therefore hydrogen, production costs</td>
<td></td>
<td>- German Renewable Energy Sources Act of 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Netherlands Stimulation of sustainable energy production and climate transition (SDE++)</td>
</tr>
<tr>
<td>Type</td>
<td>Focus</td>
<td>Description</td>
<td>Impact on hydrogen sociotechnical system</td>
<td>Examples</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Feed-in tariffs</td>
<td>Payment for energy production</td>
<td>Stimulation of private sector involvement in hydrogen production through stabilization of energy and hydrogen production revenues</td>
<td>- Ontario Feed-in Tariff Programme</td>
<td>- Denmark feed-in tariff premium program for renewable energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Renewable energy feed-in tariffs in Latin America countries</td>
<td></td>
</tr>
<tr>
<td>Tax rebates and subsidies</td>
<td>National and regional (e.g., state, province) tax incentives to help minimize the cost of project investments</td>
<td>Stimulation of private-sector involvement in developing hydrogen projects, e.g., in end-use and other energy applications</td>
<td>- Japan “ENE Farm” Residential Fuel Cell tax incentive</td>
<td>- US Emergency Economic Stabilization Act of 2008</td>
</tr>
<tr>
<td>Government-backed loans and sovereign guarantees</td>
<td>Government-issued guarantees against borrower default</td>
<td>Reduction of hydrogen project investment risk</td>
<td>- USDA - Rural Energy for America Program (REAP) Loan Guarantees (Federal)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- US DOE Improved Energy Technology Loans</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Title 17 Innovative Energy Loan Guarantee Program (Title 17) of the US Energy Policy Act of 2005</td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors

### 6.1 Policies on hydrogen technology R&D

Hydrogen R&D policies are necessary to support the maturation of new technologies and address scale-up hurdles, in order to reach commercial and industrial adoption. [475] The overarching goal of hydrogen R&D policies and the noted activities they support is to expedite the innovation cycle [392] and address technological “lock-ins” in the industry sector [476].

Dedicated allocation of funds to support R&D in academia and industry is part of national policies, and can be seen in examples such as the Australian CSIRO hydrogen roadmap, the European FCH 2 JU and Horizon Europe 2021-2027 programs, the various US agency-funded programs (DOE, DOT), and Japan’s METI hydrogen development program. In addition to research funding, these grants are also used to establish dedicated hydrogen research centers and programs in centers, such as EU Hydrogen Europe research centers, Germany’s Hydrogen Technology Center, Japan’s METI national universities and research centers, and the US DOE National Laboratories.

Public-private partnerships for the demonstration and scale-up of hydrogen technologies and projects are exemplified by the Australia ASME Hydrogen Energy Supply Chain (HESC), the 7th Energy Research Programme of the Federal Government of Germany, the EU H2ME, H2FUTURE and H2PORTS programs, the Japan Hydrogen Association, and the Sweden HYBRIT Project. Funding for these scale-up and demonstration-scale projects include the
European Clean Hydrogen Alliance (ECHA); the InvestEU Programme; the European Regional Development Fund; the Cohesion Fund; the Just Transition Mechanism (for carbon intensive regions); Connecting Europe Facility (CEF); and Connecting European Facility Transport (CEFT) [477].

6.2 Regulation and certification on hydrogen

In the hydrogen sociotechnical system context, current regulatory and certification frameworks exist covering the production, supply chain and industrial use elements. The relevant standards development organizations and the type of standards each body develops in relation to the hydrogen sociotechnical system is presented in Table 12.

<table>
<thead>
<tr>
<th>Organization</th>
<th>Type of Standard developed for hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGA American Gas Association</td>
<td>X</td>
</tr>
<tr>
<td>AIGA Asia Industrial Gases Association</td>
<td>X X X X</td>
</tr>
<tr>
<td>API American Petroleum Institute</td>
<td>X</td>
</tr>
<tr>
<td>ASME American Society of Mechanical Engineers</td>
<td>X</td>
</tr>
<tr>
<td>ASTM American Society for Testing and Materials</td>
<td>X</td>
</tr>
<tr>
<td>CEN European Committee for Standardization</td>
<td>X X X X X</td>
</tr>
<tr>
<td>CENELC European Committee for Electrotechnical Standardization</td>
<td>X X X X</td>
</tr>
<tr>
<td>CGA Compressed Gas Association</td>
<td>X X X X</td>
</tr>
<tr>
<td>CSA CSA Standards</td>
<td>X</td>
</tr>
<tr>
<td>DOT Department of Transportation</td>
<td>X</td>
</tr>
<tr>
<td>EIGA European Industrial Gases Association</td>
<td>X X X</td>
</tr>
<tr>
<td>FERC Federal Energy Regulatory Commission</td>
<td>X</td>
</tr>
<tr>
<td>GTI Gas Technology Institute</td>
<td>X</td>
</tr>
<tr>
<td>ICC International Code Council</td>
<td>X</td>
</tr>
<tr>
<td>IEC International Electrotechnical Commission</td>
<td>X X X X</td>
</tr>
<tr>
<td>IEEE Institute of Electrical and Electronics Engineers</td>
<td>X</td>
</tr>
<tr>
<td>IMO International Maritime Organization</td>
<td>X X</td>
</tr>
<tr>
<td>ISO International Organization for Standardization</td>
<td>X X X X X</td>
</tr>
<tr>
<td>NERC North American Electric Reliability Corporation</td>
<td>X</td>
</tr>
<tr>
<td>NFPA National Fire Protection Association</td>
<td>X X</td>
</tr>
<tr>
<td>NIST National Institute of Standards and Technology</td>
<td>X</td>
</tr>
<tr>
<td>SAE Society of Automotive Engineers</td>
<td>X X</td>
</tr>
<tr>
<td>UL Underwriters Laboratory</td>
<td>X X</td>
</tr>
<tr>
<td>SAC Standardization Administration of the People's Republic of China</td>
<td>X X X X X</td>
</tr>
</tbody>
</table>

Source: Authors

At the international level, standardization related to hydrogen systems is guided by the International Standardization Organization, which created in 1990 a technical committee dedicated to fuel cells (ISO/TC 197). The current scope of the ISO /TC 197 working group is
defined as the standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen. [478] Currently, seventeen published standards and a further fifteen under development cover most elements of the technical pathways for hydrogen production and use; these include: basic considerations for safety of hydrogen systems, hydrogen production via electrolysis (safety, performance and quality parameters), hydrogen separation and purification (safety), storage (safety and performance), distribution (safety and performance), and end use, with a large focus on transport sector applications, such as fuel cell vehicles, hydrogen refueling stations (safety, performance and quality parameters) [479]. Standards on hydrogen transmission (pipelines and tankers) and industrial use are not available, and globally recognized standards for these two elements come from industry association bodies (Compressed Gas Association, CGA; European Industrial Gases Association; EIGA).

Regarding the implementation of regulation, the degree to which countries have been able to translate policy ideals into action has been uneven, with many developing countries still in the earlier phases of policy development and lacking “into a heteronomous and coercive legislation”, as observed in Mexico and elsewhere in Latin America. [480] Nonetheless, existing regulatory, certification and standardization policy frameworks have been used [481] to inform the development of technical regulations on hydrogen use in new markets, despite a lack of national strategies or country-level policy frameworks (roadmaps, action plans). [482] Thus, whether a top-down (i.e., national policy-driven) or bottom-up (i.e., industry demand-driven) approach to standards-setting is observed, national and sub-national (i.e., regional) regulatory bodies should strive to adopt harmonized policy instruments, or risk being excluded from accessing international hydrogen markets.

The sections that follow further discuss the regulations and standards applicable to the hydrogen sociotechnical system as well as their current state of implementation.

6.2.1 CO2 emissions regulation

Existing policies that target industrial CO2 emissions reduction form the foundation of several National Strategies on hydrogen, and are also present both in international and regional (i.e., sub-national, such as in California) policy frameworks [483–506]. CO2 emissions obligations can stimulate end-user demand for hydrogen via an indirect, technology-neutral approach that does not favor any particular decarbonization options or technologies. As such, the existing financial disadvantages of low-carbon hydrogen production versus conventional fossil-based energy vectors, in particular natural gas, could be overcome if regulation of CO2 emissions were sufficiently strict. Such regulation imposed at various points in industrial value chains, including end products, could help overcome a lack of robust and well-defined fiscal and financial incentives for uptake of hydrogen for industrial decarbonization, even in regions like the EU that are leading in the development hydrogen policy frameworks [477]. It is important to note, however, that where low and zero-carbon hydrogen is not economically competitive relative to alternative decarbonization options, more direct measures will be needed to stimulate hydrogen adoption specifically.
6.2.2 Energy and environmental regulation

Because hydrogen is a platform for industrial decarbonization, all policy frameworks that stimulate hydrogen production play an important role in our industrial decarbonization considerations. Hence, we discuss here policies that do not directly apply to industrial use of hydrogen but rather support development of the broader hydrogen ecosystem. This ecosystem must be established in order to achieve the hydrogen production cost targets and supporting infrastructure deployment that will make industrial use of hydrogen broadly viable.

The adoption of hydrogen policies is commonly associated with policy mechanisms for renewable energy adoption, particularly as a form of long-duration energy storage to address solar and wind power intermittency [507]. Robust certification schemes for renewable energy are already adopted in the EU, as seen in the European Energy Certificate System (EECS) framework [508]. This harmonized scheme for the creation, maintenance, transfer, and cancellation of green electricity certificates was established to provide EU Member States with a platform to trade guarantees of origin (GO) certificates, which are discussed in the next section.

Regarding transportation fuels, technology requirements and lock-ins will require liquid fuels in the near future with hydrogen-derived fuels (e.g., ammonia, synfuels) likely to contribute, along with other energy carriers, in the longer term. In addition to regulatory and certification efforts, major fiscal and financial policies are need for hydrogen-based fuels, including R&D outlays for synthetic fuels and public infrastructure for synthetic fuels (e.g., adaptation and upgrading of existing pipelines for hydrogen, e-fuels, etc.). [509]

While the implications of energy regulations, in particular with regard to fossil fuel transition to renewables, are discussed in the literature related to hydrogen policies [14], the environmental implications of hydrogen adoption are usually part of policy discussions in other sectors, in particular in light- and heavy-duty transport, as seen in the European Directive 2014/94/EC on Alternative Fuel Infrastructure [510] or the Low Carbon Fuel Standard (LCFS) of the California Air Resources Board (CARB) in the US [511]

6.2.3 Certification schemes and Guarantees of Origin (GO)

Certification mechanisms that ensure traceability and accountability of low-carbon hydrogen production are essential to widespread adoption of hydrogen for decarbonization purposes. Guarantees of Origin (GO) schemes are already in use for renewable energy systems to account for lifecycle GHG emissions and enable geographically separated production and use. GOs should be designed to allow policy makers and end users to understand the impact of the relevant energy carrier, ensure consistency and compatibility with GHG emissions for other commodities, and allow comparison with other energy sources. [512] Existing and upcoming GO schemes for hydrogen are shown in Table 13, along with the main characteristics of each. The goal of these GOs, just like with the renewable energy-based ones, is to enable hydrogen markets to function. Figure 30 shows how both physical and virtual tracing of hydrogen can be used for GOs.
Table 13. Green hydrogen characterization initiatives worldwide [14]

<table>
<thead>
<tr>
<th>Body (Country)</th>
<th>Type</th>
<th>Main Policy Objective</th>
<th>Baseline GHG threshold</th>
<th>Qualification level</th>
<th>Qualifying processes</th>
<th>System boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFHYPC a (France)</td>
<td>GO scheme (working group proposal)</td>
<td>Renewable energy source</td>
<td>None</td>
<td>Must be 100% renewable</td>
<td>Any renewable pathway, including electrolysis powered by waste (with renewable electricity or)</td>
<td>Point of production</td>
</tr>
</tbody>
</table>

Figure 30: Chain of custody approaches for green hydrogen guarantees of origin [14]
<table>
<thead>
<tr>
<th>Body (Country)</th>
<th>Type</th>
<th>Main Policy Objective</th>
<th>Baseline GHG threshold</th>
<th>Qualification level</th>
<th>Qualifying processes</th>
<th>System boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BEIS</strong> b (UK)</td>
<td>Standard Consultation (abandoned)</td>
<td>Reduction of CO₂ emissions</td>
<td>Never determined</td>
<td>To be determined. A single threshold differentiated according to end use (e.g., transport)</td>
<td>Any (technology neutral)</td>
<td>Point of production</td>
</tr>
<tr>
<td>California Low Carbon Fuel Standard</td>
<td>Regulation (active)</td>
<td>Reduction of air quality and CO₂ emissions. Third of vehicle hydrogen produced from renewable energy.</td>
<td>WTW emissions from new gasoline vehicles</td>
<td>30% lower GHG and 50% lower NOₓ emissions (on WTW per mile basis) for fuel cell electric vehicles</td>
<td>Renewable electrolysis, catalytic cracking of SMR of biomethane or thermochemical conversion of biomass, including MSW.</td>
<td>Point of use</td>
</tr>
<tr>
<td><strong>CEN/CENELEC CLS JCT 6 WG1/WG2 (International)</strong></td>
<td>International Standard (in preparation)</td>
<td>Terminology, GO, interfaces, operational management, safety, training and education</td>
<td>Adopted from CertifHy</td>
<td>Adopted from CertifHy</td>
<td>Adopted from CertifHy</td>
<td>Adopted from CertifHy</td>
</tr>
<tr>
<td><strong>CERTIFHY (EU wide)</strong></td>
<td>GO scheme (testing)</td>
<td>Renewable energy source/GHG emissions</td>
<td>Hydrogen produced via SMR of natural gas</td>
<td>At least 60% lower than SMR c (this is ≤ 36.4 gCO₂e/MJ H₂ for the past 12 months)</td>
<td>Any renewable pathway meeting the threshold with 99.5% purity</td>
<td>Point of production</td>
</tr>
<tr>
<td><strong>TÜV SÜD (Germany)</strong></td>
<td>National Standard (active)</td>
<td>Reduction of CO₂ emissions</td>
<td>Hydrogen from SMR of natural gas</td>
<td>35–75% emissions reduction below baseline (83.8-89.7 gCO₂e/MJ), depending on production process, and time phase</td>
<td>Renewable electrolysis; biomethane SMR; pyro-reforming of glycerin</td>
<td>Point of use</td>
</tr>
</tbody>
</table>

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a L’Association Française pour l’Hydrogène et les Piles à Combustible.
b BEIS Green Hydrogen Standard was a consultation process that did not result in an official standard.
c The baseline carbon intensity considered by CertifHy for SMR is 91 gCO₂e/MJ H₂.
These certification schemes are needed from a technical perspective, as it is impossible to verify the embedded GHG emissions in hydrogen gas by analyzing the final product alone. [506] Without a mechanism to differentiate between conventional and low-carbon hydrogen products, producers of the latter are not able to obtain price premiums, limiting the market opportunities for such options. From a global market perspective, the lack of certification schemes hampers both domestic and international trade, and will hinder jurisdictions wishing to constrain the importation of high-embedded emissions products. [506]

Among the different certification schemes currently in use or under consideration, an important aspect to consider is the development of commonly agreed definitions and assessment scopes. This however is not presently the case, as the schemes identified have adopted varying definitions for what constitutes a “green” hydrogen production process. There is not a harmonized definition yet, which in turn makes international trade, and the inclusion of hydrogen in energy policies, more difficult [14,46,483,506,512–520].

In addition, the certification schemes also have placed process boundaries within the supply chain for emissions accounting purposes. [14] Without a clear determination of the boundaries of certification, achieving interoperability of hydrogen certification schemes and cross-market acceptance is not possible.

These certification schemes have also had a varying degree of discussion in the academic and grey literature [14,483,506,512,515,519–525]. As a result of our systematic review, the most discussed certification scheme among those shown in Table 13 is the EU CertifHy, which the one we’ve leveraged for our definition of low-carbon hydrogen. This certification is envisioned as a Guarantee of Origin (GO) scheme, where emissions associated with the feedstocks used and the specific hydrogen production pathways are the only ones within the certification boundaries (i.e., emissions associated with infrastructure, transmission, distribution, conversion into and regeneration from other energy vectors, and end use are not counted).

In order to fulfill its potential as an EU-wide GO, the current phase 3 of the CertifHy scheme seeks to become a harmonized GO scheme, while also aligning with the European Renewable Energy Directive II (EU RED II) [526]. CertifHy phase 3 will build a certification system for RED II-compliant renewable transport fuels (namely Renewable Fuels of Non-Biological Origin, RFNBOs). This work is being conducted in collaboration with stakeholders responsible for other GOs, such as TÜV SÜD, while other national-level bodies, such as AFHYPAC in France, are coordinating their certification scheme development efforts with CertifHy as well.

6.2.4 Safety, quality and other regulations

Another important aspect where regulatory frameworks on hydrogen are robust is in safety and quality control [430,527–532,431,533,432]. Due to existing use of fossil hydrogen, international and national standard development organizations (SDO) have comprehensive regulations and standards on existing hydrogen applications, with end-user safety, process quality assurance and other environmental impact controls being addressed. As new use cases for hydrogen emerge, these SDOs have quickly adopted and developed new regulations, and increasing efforts are seen to harmonize such documents across countries and regions.
6.2.5 Price controls

Price controls are relevant in the development of policies for hydrogen blending in natural gas pipelines, as network pricing for the end-product will have to take into consideration the blending ratios allowable in the distribution system, which can vary in tandem with renewable energy costs depending on the system in which the hydrogen is produced [433,534,535]. Stabilizing market prices at the entry point for hydrogen blending has the advantage of limiting the price volatility for end-users, as producers will be incentivized to introduce hydrogen (up to the blend allowances) only when renewable energy prices, in the case of renewable hydrogen, are supportive. Together with a renewable energy capacity forecasting, the allocation of excess renewable energy may follow two hydrogen compatible paths: network supply as hydrogen blended into natural gas or storage as hydrogen (geologic, vessel storage, LOHC or conversion into other intermediates).

6.3 Fiscal incentives and public financing

Fiscal incentives and public financing can catalyze the development of markets for new technologies that have yet to achieve market competitiveness with incumbent technologies. Fiscal incentives may relate to R&D in the form of measures such as tax credits and vouchers or may orient more toward technology deployment in the form of measures such as tax credits for production or investment or related tax-based measures. Public financing can also relate to both R&D and deployment in the form of venture capital, soft loans, direct investment, guarantees and public procurement [536–539]. As seen in Section 6.1, these incentives should align with R&D policies, as getting from research stage to market deployment is an identified bottleneck in the innovation system.

6.3.1 Fiscal policies to stimulate hydrogen production and demand

Hydrogen production and demand can be stimulated via direct support schemes (DSS), where the government mediates the hydrogen market price by establishing direct procurement systems (as an end-user) or mediates market access to producers via tendering or auctioning schemes (where price, performance, environmental and volume capacity can be requirements for participation).

In countries and regions focused on zero-carbon hydrogen, such as the EU, only renewable hydrogen would be eligible for DSS [477]. Allocation of such schemes will be made through competitive tenders, coordinated ‘within a transparent, efficient and competitive hydrogen and electricity market’, which provides price signals that reward electrolysers for services provided to the energy system, such as flexibility or reducing the burden of renewable incentives.

The other major focus point for fiscal incentives and public financing is industrial and commercial end-use. Support mechanisms are needed to integrate novel processes and use cases with existing industries and markets, as the status quo can represent economic barriers to wider adoption (e.g., lower existing costs and prices for competing, higher emissions technologies). A strong push for these technologies could be envisaged if the full costs of fossil solutions would be priced in via appropriate policy measures. [509]
6.3.2 Energy subsidies and feed-in tariffs

The Production Tax Credit (PTC) is a preferential tax treatment that was included in the US Energy Policy Act of 1992 [540]. PTC, where relevant, provides an inflation-adjusted tax credit on every kilowatt-hour of electricity generated by the qualified energy sources for a limited time period. In a study on policy effectiveness in British Columbia, [541] found that PTC for low-carbon hydrogen production is up to 24 times more effective than other incentives, such as capital subsidies (grants) and utility incentives for electrolytic hydrogen. In addition, production subsidies and electricity incentives were found to be more effective in GHG emissions reduction than capital subsidies, bans on SMR-production or adoption of higher carbon tax rates.

6.3.3 Carbon pricing

Carbon pricing is considered a key stimulus for broad adoption of low-carbon technologies [453–464]. It influences energy use and investment decisions and, designed well, can encourage significant emission reductions. It can also be used to raise revenue to support complimentary policies or technologies [453]. By incorporating the true social cost of carbon emissions, this mechanism is seen as quantifiable tool to create a level-playing field between fossil-based and renewable energy-based technologies.

The United States has published in 2021 updated guidance (Executive Order E.O. 13990) to ensure that the “social cost of greenhouse gases” (SC-GHG) estimates used by the U.S. Government (USG) “reflect the best available science and the recommendations of the National Academies (2017) and work towards approaches that take account of climate risk, environmental justice, and intergenerational equity” [452]. Interim figures estimate this cost at 51 US dollars (2020, $/tCO2) per ton of CO2, using the reference model and discount rates (3%) [451]. This figure is the basis for establishing environmentally-related policies in the United States but is not an explicit carbon price that the government will impose.

While carbon pricing fulfills a need to embed the externalities of energy and industrial systems, two main mechanisms are pursued: a direct carbon tax on emissions, and a cap-and-trade program (such as EU’s ETS). A comparison between these two approaches is shown in Figure 31.
As shown in Figure 32, carbon pricing schemes are growing globally but generally lower than required to support broad adoption of hydrogen. As shown Figure 33, if hydrogen could be produced by 2050 at 1 USD/kg, carbon prices in excess of 51 US dollars per ton of CO₂ would be needed to economically justify broad industrial adoption.
Figure 32: Carbon pricing initiatives implemented, scheduled for implementation and under consideration (ETS and carbon tax). Note: Carbon pricing initiatives are considered “scheduled for implementation” once they have been formally adopted through legislation and have an official, planned start date. Carbon pricing initiatives are considered “under consideration” if the government has announced its intention to work towards the implementation of a carbon pricing initiative and this has been formally confirmed by official government sources. The carbon pricing initiatives have been classified in ETSs and carbon taxes according to how they operate technically. ETS not only refers to cap-and-trade systems, but also baseline-and-credit systems as seen in British Columbia and baseline-and-offset systems as seen in Australia. The authors recognize that other classifications are possible. [454]
Even where carbon pricing is adopted, a key concern for industrial use of hydrogen is “leakage,” or the relocation of emitting industrial activities to locations with less stringent or absent carbon pricing [475]. There exist several approaches to limit leakage. Border tax adjustments can therefore apply an import tariff calibrated to reflect embodied emissions in imported goods and to rebate taxes on goods for export, or a fee can be placed on the consumption of goods based on embedded carbon [475].

6.3.4 Government-backed loans and sovereign guarantees

Sovereign guarantees and government-backed loans are fiscal mechanisms that have long been used in renewable energy financing [474,542], and may provide another path for supporting private sector investment in hydrogen projects. In the US, the Innovative Energy Loan Guarantee Program (Title 17) of the US Energy Policy Act of 2005 is a legal framework applicable to hydrogen projects in the energy and transport sectors, while other federal agencies have also provided similar mechanisms for loan guarantees (e.g., USDA, Rural Energy for America Program, REAP, Loan Guarantees; US DOE, Improved Energy Technology Loans).

These loan guarantees aim to shift the risk burden on new technology projects from potential investors to national governments, in particular in nations where institutional risk is associated with the country itself (e.g., low credit rating by international risk assessing firms and credit rating agencies; political instability; uncertainty surrounding fiscal and environmental policies; economic instability and restricted or unstable currency flows), as observed mainly in developing countries. This negative risk perception may require sovereign guarantors to cover for obligations both from the primary payment defaults and from risks deemed under government control, such as contractual deviations, tax treatment alterations and monetary policy changes that impact currency value and conversion. State-owned enterprises (SOE) often finance projects under sovereign guarantees, and SOEs have been major drivers in renewable energy projects in emerging and developing countries [543]. Given their prominent role on the development and adoption of new energy initiatives, government backing of investments in projects supporting the transition to a hydrogen economy and wider adoption in industrial systems may be necessary. Ideally, such efforts are planned along national priorities aligned along a central, unified implementation strategy.
7. Barriers to hydrogen adoption in industry

The general barriers identified for industrial adoption of low-carbon hydrogen and the impacts of these barriers are presented in Table 14, grouped by barrier type and technology pathway.

Table 14. Comparison of main barriers and gaps across hydrogen producing pathways

<table>
<thead>
<tr>
<th>Technological pathway</th>
<th>Barrier</th>
<th>Type</th>
<th>Impact on adoption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen from renewables</td>
<td>“Green hydrogen” is still not consistently well-defined in regulatory and policy frameworks</td>
<td>Policy</td>
<td>Uncertainty associated with which production pathways and certification schemes are considered low or zero-carbon might restrict hydrogen investment and adoption, particularly when renewable electricity is sourced from the power grid rather than a captive source</td>
</tr>
<tr>
<td></td>
<td>Tariffs remain for electricity consumed for hydrogen production</td>
<td>Policy</td>
<td>Hydrogen produced from renewable electricity may remain costly compared to hydrogen produced via alternative mechanisms</td>
</tr>
<tr>
<td></td>
<td>The cost of hydrogen production via electrolysis is still higher than existing fossil hydrogen pathways</td>
<td>Financial</td>
<td>Hydrogen from electrolysis may not achieve high levels of deployment</td>
</tr>
<tr>
<td></td>
<td>Emerging technologies (e.g., high-temperature electrolysis) are still low TRL</td>
<td>Technology</td>
<td>Hydrogen from electrolysis may not achieve high levels of deployment</td>
</tr>
<tr>
<td>Hydrogen from fossil fuels &amp; carbon capture</td>
<td>Geologic carbon storage potential is geographically specific</td>
<td>Technology/Policy</td>
<td>Hydrogen production coupled with carbon capture may not achieve high levels of deployment</td>
</tr>
<tr>
<td></td>
<td>CCS applications are expensive to develop and operate</td>
<td>Financial</td>
<td>Hydrogen production coupled with carbon capture may not achieve high levels of deployment</td>
</tr>
<tr>
<td></td>
<td>Upstream emissions associated with fossil energy are not properly considered</td>
<td>Technology/Policy</td>
<td>Leakages and emissions associated with natural gas extraction and transport limit the adoption of hydrogen from fossil fuels as a low-carbon option</td>
</tr>
<tr>
<td></td>
<td>Circular economy and upcycling of CO₂</td>
<td>Technology/Market</td>
<td>Insufficient destination and use opportunities for</td>
</tr>
<tr>
<td>Technological pathway</td>
<td>Barrier</td>
<td>Type</td>
<td>Impact on adoption</td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------</td>
<td>--------------------</td>
<td>-------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>emissions is still in development</td>
<td></td>
<td>CO₂ restricts the potential for hydrogen production coupled with carbon capture</td>
</tr>
<tr>
<td>Hydrogen from nuclear energy</td>
<td>Production of nuclear energy-derived hydrogen is not considered in most National Strategies</td>
<td>Policy/Market</td>
<td>Low-carbon hydrogen from nuclear energy not widely adopted as a source of low-carbon hydrogen</td>
</tr>
<tr>
<td></td>
<td>Tariffs remain for electricity consumed for hydrogen production</td>
<td>Policy</td>
<td>Hydrogen produced from clean electricity may remain costly compared to hydrogen produced via alternative mechanisms</td>
</tr>
<tr>
<td></td>
<td>Nuclear waste and safety perception has negative impacts on end-user adoption</td>
<td>Market</td>
<td>Low-carbon hydrogen from nuclear energy use is prevented from being considered on the basis of social acceptance (or lack thereof)</td>
</tr>
<tr>
<td></td>
<td>High-temperature, thermochemical water splitting hydrogen production is still low TRL</td>
<td>Technology</td>
<td>Direct thermochemical water splitting (using nuclear or even concentrated solar) technology maturity may not be reached, limiting the broadest possible adoption of low-carbon hydrogen</td>
</tr>
<tr>
<td>Turquoise hydrogen</td>
<td>Methane pyrolysis production is still mid TRL</td>
<td>Technology</td>
<td>Technology maturity may not be reached in time for contribution to aggressive hydrogen adoption targets</td>
</tr>
<tr>
<td></td>
<td>Circular economy and upcycling of solid carbon product is still in development</td>
<td>Technology/Market</td>
<td>Insufficient destination and use allocation of solid carbon products at very large scale restricts the potential for turquoise hydrogen</td>
</tr>
<tr>
<td>Common among all pathways</td>
<td>Certification schemes (emissions reductions, guarantees of origin) are still in development</td>
<td>Policy</td>
<td>International trade of hydrogen is hindered</td>
</tr>
<tr>
<td></td>
<td>Internationally agreed framework for pricing carbon emissions not in place</td>
<td>Policy</td>
<td>Hydrogen use remains economically unattractive across multiple use cases</td>
</tr>
<tr>
<td></td>
<td>Regulatory framework for international transmission of hydrogen (maritime, pipelines) still not harmonized</td>
<td>Policy</td>
<td>International trade on hydrogen is hindered</td>
</tr>
</tbody>
</table>
Sectoral barriers for industry adoption of hydrogen produced from renewable energy are presented in Figure 34, based on analysis of the EU hydrogen landscape and existing conditions in Member States. As shown in the figure, the production, transmission and distribution of renewable power and related hydrogen production is considered a main challenge to hydrogen adoption in all industries. This illustrates why many countries consider hydrogen produced from fossil fuels along with CCS as a transition approach to zero-carbon hydrogen adoption.
In addition to the availability of renewable power, four major challenges that encompass multiple barriers must be addressed to enable the transition to a hydrogen economy are discussed in further detail below.

7.1 National and international frameworks for hydrogen use

The absence of comprehensive, national and international policy and regulatory frameworks for hydrogen adoption in industrial systems is the first major challenge identified in the development of the hydrogen sociotechnical system. Policies, standards and regulations typically follow from plans articulated in strategies and roadmaps [545,546]. Despite the
recent positive signals seen in the increasing interest exhibited by national and regional
governments in the promotion of hydrogen as a clean energy vector, policy support in the
form of roadmaps, action and strategic plans is still not fully implemented on a global level.
By the beginning of 2021, thirteen countries had made National Strategies for hydrogen
available, with another eleven countries having National Strategies in preparation. Within the
EU, six countries have National Strategies available, three are in preparation and the other
eighteen are part of the EU supranational hydrogen strategy only [547]. In addition, eleven
other countries support hydrogen adoption via R&D initiatives and/or non-hydrogen specific
energy and climate policies. These countries are shown in Figure 35 and reflect a rapid
increase in institutional support for hydrogen at the governmental level, as only three of the
countries (Japan, South Korea, and France) had published National Strategies by early 2019,
with Australia publishing its National Strategy in November 2019. All other publications
occurred from 2020 onwards. Given the dynamic pace of change, online resources are
available that track the current status of hydrogen strategies [548].

From a policy-making perspective, National Strategies can be preceded by earlier initiatives,
segmenting the path towards these frameworks into related steps: direct support for R&D
activities, preparation of a vision document and definition of a roadmap [512]. These efforts
can be guided by existing legal frameworks or conversely help inform the introduction or
reformation of laws and regulations. Engagement with stakeholders in industry and end-use
markets is necessary at each step, which can take the form of open consultations or public-private partnerships.

Despite the vast majority of National Strategies being published from 2020, they are characterized by varying levels of detail, both between countries and within focus topics in each document (i.e., the National Strategies vary from comprehensive to narrow topics, and from detailed metrics and specifications to more generally defined goals). Effective national and international frameworks must include both clear goals with quantifiable targets and the proposed mechanisms (fiscal and economic, policy, technological) to achieve them.

The World Energy Council has summarized the main goals of several published hydrogen strategies [549] and, as show in Table 15, the common elements are emissions reductions and integration of renewables. Support for national technology development and economic growth are also prominent considerations while plans for hydrogen export are limited to just a few countries that have abundant solar or natural gas resources relative to projected national demand for hydrogen.

Table 15. Main goals of current hydrogen strategies per country. Adapted from: [549]

<table>
<thead>
<tr>
<th>Strategic goals</th>
<th>EU</th>
<th>Germany</th>
<th>Netherlands</th>
<th>France</th>
<th>Spain</th>
<th>Italy</th>
<th>UK</th>
<th>Norway</th>
<th>Switzerland</th>
<th>Ukraine</th>
<th>Russia</th>
<th>Japan</th>
<th>South Korea</th>
<th>China</th>
<th>Australia</th>
<th>US</th>
<th>Morocco</th>
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</thead>
<tbody>
<tr>
<td>Reduce emissions</td>
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<tr>
<td>Diversify energy supply</td>
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<tr>
<td>Foster economic growth</td>
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<tr>
<td>Support national technology</td>
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<td>development</td>
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<tr>
<td>Integration of renewables</td>
<td>●</td>
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<tr>
<td>Develop hydrogen for export</td>
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</table>

● main goal; ○ less relevant; - not addressed; a: current hydrogen strategies in the US refer to state- and city-level initiatives, in particular in California; b: import and export as a hydrogen “transit hub” considered; c: indirect hydrogen export via natural gas export with local CCS

Regarding industrial use of hydrogen, this is prominent in the strategies of EU countries, the UK, Russia and Australia but missing from the strategies of Asian countries (Table 16). As discussed throughout this paper, the chemicals, iron and steel and refining industrials are primary targets for low-carbon hydrogen since these are the sectors that already are using significant quantities of hydrogen or have a clear path toward technologies that use low or zero-carbon hydrogen (i.e., iron and steel).
Table 16. Main target sectors of current hydrogen strategies per country. Adapted from: [549]

<table>
<thead>
<tr>
<th>Hydrogen use sectors</th>
<th>Country or region</th>
<th>EU</th>
<th>Germany</th>
<th>Netherlands</th>
<th>France</th>
<th>Spain</th>
<th>Italy</th>
<th>UK</th>
<th>Norway</th>
<th>Switzerland</th>
<th>Ukraine</th>
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<th>South Korea</th>
<th>China</th>
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<th>Morocco</th>
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<tbody>
<tr>
<td>Industry</td>
<td>● ● ● ● ○ ○ ● ● - - ● ○ - - ● ○ ● ●</td>
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<tr>
<td>Iron and steel</td>
<td>● ● - ● - - ● - - - ○ ○ - - ● - -</td>
<td>● ● ● ○ ● ○ - ● - - ● ○ ○ - - ● - -</td>
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<tr>
<td>Oil and gas refining</td>
<td>● ● ○ ● ○ - ● - - - ● ○ ● - - ○ ○ -</td>
<td>● ● ● ○ ● ○ - ● - - ● ○ ○ - - ● - -</td>
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<td>Chemicals</td>
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<td>● ● ● ○ ● ○ - ● - - ● ○ ○ - - ● - -</td>
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<td>Others b</td>
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</tbody>
</table>

- main goal; ○ less relevant; - not addressed; a: current hydrogen strategies in the US refer to state- and city-level initiatives, in particular in California; b: others include glass and ceramics, cement industry, mining, process heat generation.

As can be seen in Figure 36, the timelines for these strategies, and their impacts on key industry sectors, start in 2020 but do not reflect the establishment of hydrogen markets until 2050. By 2050 it is envisioned that countries in Asia, such as South Korea and Japan, will have fully established hydrogen societies that are supplied, at least partly, by major hydrogen exporting countries, such as Australia.

Figure 36. Development of hydrogen market in three major phases (based on examples from selected countries). [549]

7.2 Technology development and hydrogen pathway adoption

A second barrier to hydrogen adoption is the lack of consensus on the technology pathways that should be pursued as part of a global low-carbon energy transition. Regional, national and international governments and policy-making bodies have announced a wide range of
production capacity goals, with varying perspectives on adoption of different hydrogen producing pathways. The main perspectives can be separated into three groups, namely: a) enabling the hydrogen economy will require the adoption a technology neutral approach; b) only renewable hydrogen production pathways should be pursued and fossil hydrogen, even with CCUS, is not part of the solution; and c) renewable hydrogen production should be favored, but the use of fossil-based, low-carbon hydrogen as a bridge technology must not be ignored. In addition, these perspectives can also be separated based on the energy source envisioned for hydrogen production, this time into four groups: a) only renewable sources; b) favors renewable sources, with fossil energy phase-out period; c) both fossil and renewable sources are used; and d) nuclear energy is used as a low-carbon energy source (in addition to the other two sources).

A comparison of these perspectives based on the existing policies from a technology adoption perspective is presented in Table 17. The use of fossil-dependent pathways for hydrogen production must be coupled with CCS technologies, under the blue hydrogen pathway, in order to achieve energy decarbonization goals. Unlike renewable hydrogen, certifying carbon abatement from fossil sources is a more complex endeavor, as both emissions associated with upstream processes and leakages, as well as actual carbon sequestration of carbon gases must be correctly inventoried. In addition, international certification schemes, such as CertifHy [550], have minimum abatement requirements in comparison with conventional processes.

The Australian National Strategy adopts a technology-neutral stance on hydrogen production, referring to “clean hydrogen” (which includes both renewable hydrogen and fossil hydrogen coupled with CCS) [551,552].

Given the need for further R&D support (Section 6.1) to bring low-TRL technologies to market (Section 5.4), and the policy gaps that exist for broad hydrogen adoption (Table 14), fragmented views on how hydrogen markets should develop could very well derail plans for widespread adoption.

---

Table 17. Comparison of hydrogen production pathways across the National Strategies and relevant policy documents. Adapted from: [549]

<table>
<thead>
<tr>
<th>Country or region</th>
<th>EU</th>
<th>Germany</th>
<th>Netherlands</th>
<th>France</th>
<th>Spain</th>
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<tbody>
<tr>
<td><strong>Main hydrogen sources</strong></td>
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<td>Renewable</td>
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<tr>
<td>Fossil with CCS</td>
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<td>Methane pyrolysis</td>
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<td>Fossil</td>
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<td><strong>Towards 2050</strong></td>
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<tr>
<td>Renewable</td>
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<td>Fossil with CCS</td>
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<td>Methane pyrolysis</td>
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</tbody>
</table>

● pathway option considered; - pathway option not considered; a: current hydrogen strategies in the US refer to state- and city-level initiatives, in particular in California; b: no data available
7.3 International trade

Presuming that large-scale production and use of hydrogen, be it green, blue or any other color, connecting suppliers and consumers at the global level via the most cost-effective means of transmission, distribution and shipping will be a great challenge (Section 5.2). The final cost of hydrogen from any international trade will depend on the cost of hydrogen production as well as the cost of transporting hydrogen, potentially in one of several relevant vectors that include liquid organic hydrogen carriers (LOHCs), ammonia or any of the fuels that can be created from a power-to-fuels (PtL) approach (Figure 37).

As shown in Figure 38, such considerations are particularly relevant from expected hydrogen demand centers in Asia, Europe and North America.
As shown in Figure 39, the final cost of hydrogen using these different approaches can vary considerably and hence the future of hydrogen import and export relationships will be tied very closely to advances in reducing the cost of long-distance hydrogen transport. The drawbacks of the transport vectors are distinct, with ammonia being readily shipped but costly in conditioning for export and conditioning to gaseous hydrogen after export, LOHCs being costly to ship as well as condition to gaseous hydrogen after export and liquid hydrogen being expensive to condition for export and to ship.
7.4 The geopolitics of hydrogen

In light of the expected international trade of hydrogen and its potential role in decarbonization, geopolitics, or power competition over access to strategic locations and natural resources [554], is an important consideration and potential barrier to hydrogen adoption if not sufficiently considered and proactively managed.

While the literature on the geopolitical implications of a transition to renewable energy systems has increased in the past decade and proven helpful in developing an understanding how the transition to low-carbon technologies might affect energy geopolitics, [519,555–563], the role renewable hydrogen could play and how it could affect these nascent dynamics remains widely unexplored [562]. According to Vakulchuk et al. [555], the literature on the geopolitics of renewable energy transitions focuses mainly on topics related to electricity, such as critical materials for clean power technologies and batteries and cybersecurity of electricity systems. In this literature, little focus is placed on the role of hydrogen as an energy vector and only since 2020 has the notion of hydrogen geopolitics become more prominent in the literature [519,562,563].

In defining the geopolitical implications of the transition to renewable energy at large, the relevant questions for renewables can be summarized and extended to hydrogen as presented in Table 18 (from [519,555–563]).
Table 18. Comparison of geopolitical ramifications of existing fossil, renewable energy transition and hydrogen adoption

<table>
<thead>
<tr>
<th>Existing fossil energy paradigm</th>
<th>Open issues for the renewable energy paradigm</th>
<th>Open issues for the hydrogen economy paradigm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy security is uneven across nations and presents national security implications</td>
<td>Will a renewable energy-based society be more secure given that energy production can be localized?</td>
<td>Will the adoption of large-scale hydrogen systems improve energy security given that energy production can be localized, stored and used across multiple sectors?</td>
</tr>
<tr>
<td>Fossil energy resources can be used as foreign policy instruments</td>
<td>What elements of renewable energy systems are used as foreign policy instruments when the materials and technologies that produce renewable energy may have greater relevance than the energy sources themselves?</td>
<td>Will hydrogen provide new opportunities for use of renewable and fossil energy as foreign policy instrument, particularly when international trade is involved?</td>
</tr>
<tr>
<td>Fossil energy-based foreign policy instruments can be used to create military advantage</td>
<td>Which renewable energy-based foreign policy instruments (if any) can be used to gain military advantage, particularly given the important role cybersecurity of the electricity grid?</td>
<td>Can hydrogen-based foreign policy instruments (if any) can be used to gain military advantage, and to what extent are the instruments related to fossil fuels and electricity for hydrogen production as opposed to hydrogen trade?</td>
</tr>
<tr>
<td>Existing fossil energy-producing countries possess geopolitical cache and strong positions in international affairs</td>
<td>Which countries will have primacy in international affairs in renewable energy when electricity is the dominant energy vector?</td>
<td>Will hydrogen production leaders strengthen their positions in world affairs or will hydrogen trade use lack such international relevance?</td>
</tr>
<tr>
<td>Geopolitical tensions have been negatively impacted by fossil energy producing countries</td>
<td>What are the potential geopolitical tensions and risks associated with a renewable energy paradigm when critical materials, electricity and cybersecurity gain prominence?</td>
<td>Will the adoption of large-scale hydrogen systems improve international security and peace my mitigating the importance of any single energy source or vector?</td>
</tr>
<tr>
<td>The emergence of new fossil energy producers (e.g., newfound fields, novel fossil energy sources such as shale or deep-sea) has shifted the energy dynamics among countries during the past century</td>
<td>Will a new set of major energy players emerge in a renewable energy paradigm?</td>
<td>How will new and emerging renewable energy and fossil energy producing countries engage in a hydrogen transition?</td>
</tr>
<tr>
<td>Fossil energy is largely expected to lose prominence over time due to associated emissions and environmental impacts</td>
<td>Will renewable energy become the dominant source of energy due to associated avoidance of emissions and environmental impacts?</td>
<td>Will low-carbon hydrogen systems that perhaps leverage carbon capture, storage and utilization, provide a bridge opportunity for continued fossil energy production or will renewable hydrogen serve as a compliment to a primarily renewables-based energy system?</td>
</tr>
<tr>
<td>Development of fossil energy sources led to the economic development of petrostates</td>
<td>Which countries are expected to benefit most from a renewable energy transition and what will</td>
<td>How can hydrogen support the continued economic success of current petrostates and bring</td>
</tr>
</tbody>
</table>
Industrial decarbonization via hydrogen

Existing fossil energy paradigm | Open issues for the renewable energy paradigm | Open issues for the hydrogen economy paradigm
--- | --- | ---
be the scale of economic benefit? | economic opportunity to new energy players?

International supply chains present security risks and defensive strategy concerns
Will electricity from renewable and/or trade in core renewable energy technologies, such as solar panels and batteries, create supply chain security risks?
If hydrogen is traded via land and maritime routes, will it incur a unique set of supply chain risks?

Source: Authors

As seen in Table 18, the open questions related to the geopolitics of hydrogen generally overlap with the questions associated with a renewable energy transition, as might be expected given that hydrogen is an energy vector rather than a fundamentally new source of energy. Notably, hydrogen production pathways include fossil energy sources coupled with CCS technologies and so one key differentiating question stands-out for hydrogen: will low-carbon, fossil fuel-derived hydrogen systems provide a bridge, or even extended, opportunity for continued fossil energy production?

A renewable energy transition will contrast with the existing fossil energy paradigm as existing international relations and materials and goods flows shift over time [564]. As alluded to in Table 18, the focus of geopolitical issues will change from a primacy of where these energy sources are found to where the technology development centers and sources of critical materials are located. In other words, the increased abundance of renewable energy sources and their more equitable distribution around the globe (albeit still asymmetric) will decrease the relative importance of where resources are found and shift toward where the technology to explore these resources is developed and manufactured [519,562,563]. A comparison between fossil and renewable energy considerations is presented in Table 19 and summarizes the main points of discussion in the literature [519,555–563].

Table 19. Comparison of fossil fuels and renewables according to the literature. Adapted from [555]

<table>
<thead>
<tr>
<th>Main issues</th>
<th>Fossil fuels</th>
<th>Renewable energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource scarcity</td>
<td>Very significant</td>
<td>Perhaps significant (for critical materials used in renewable energy technologies)</td>
</tr>
<tr>
<td>Importance of location</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Control over resources</td>
<td>Centralized</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Geopolitical power</td>
<td>Asymmetric</td>
<td>Less asymmetric</td>
</tr>
<tr>
<td>International competition</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>International interdependence</td>
<td>High</td>
<td>Low if renewables domestic/high if imported</td>
</tr>
<tr>
<td>Security of supply</td>
<td>Highly important</td>
<td>Moderately important</td>
</tr>
<tr>
<td>Geopolitical tensions</td>
<td>Frequent</td>
<td>Opinions vary greatly</td>
</tr>
<tr>
<td>Conflict type</td>
<td>Large-scale and violent</td>
<td>Small-scale and non-violent</td>
</tr>
<tr>
<td>Critical materials</td>
<td>Unimportant</td>
<td>Important</td>
</tr>
<tr>
<td>Cybersecurity</td>
<td>Unimportant</td>
<td>Important</td>
</tr>
<tr>
<td>Key market aspects</td>
<td>Demand and supply, exports and imports</td>
<td>Storage, intermittency, infrastructure management</td>
</tr>
</tbody>
</table>
When considering hydrogen, the low-carbon, renewable energy perspective on geopolitics remains given that clean electricity is the primary low-cost means of decarbonization and is the basis of zero-carbon hydrogen production.

However, a key difference between the broader renewable energy transition and hydrogen adoption at large scale is the expected role of current major fossil energy exporting countries, in particular Russia and the Middle Eastern Gulf States. Existing relationships between energy exporting countries, their competitors and markets (EU—Russia; EU—Maghreb; Russia—post-Soviet neighbors; Saudi Arabia—US; Saudi Arabia—Iran; Gulf—China; China—Russia, as well as Gulf—EU and Gulf—East Asia) [558] provide a template for where hydrogen international trade may be most relevant (Section 7.3). Given its prominence in the development of the hydrogen economy, the EU is poised to be a significant import market, and the ongoing energy transition will impact their current energy exporting partners unevenly, as seen in Table 20. Outside these corridors, Australia—East Asia is also a prominent supply chain route.

<table>
<thead>
<tr>
<th>Least and most exposed to EU energy transition [565]</th>
<th>Geopolitical winners [566]</th>
<th>Geopolitical losers [566]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saudi Arabia (least exposed)</td>
<td>Uruguay</td>
<td>Brunei</td>
</tr>
<tr>
<td>Qatar</td>
<td>Namibia</td>
<td>Qatar</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>Kenya</td>
<td>Bahrain</td>
</tr>
<tr>
<td>Egypt</td>
<td>Mali</td>
<td>Kuwait</td>
</tr>
<tr>
<td>Libya</td>
<td>Sweden</td>
<td>Timor-Leste</td>
</tr>
<tr>
<td>Russia</td>
<td>Finland</td>
<td>Trinidad &amp; Tobago</td>
</tr>
<tr>
<td>Algeria (most exposed)</td>
<td>France</td>
<td>Bhutan</td>
</tr>
<tr>
<td></td>
<td>Nicaragua</td>
<td>Slovakia</td>
</tr>
<tr>
<td></td>
<td>Honduras</td>
<td>Belize</td>
</tr>
<tr>
<td></td>
<td>India</td>
<td>Georgia</td>
</tr>
<tr>
<td></td>
<td>Jordan</td>
<td>Bangladesh</td>
</tr>
<tr>
<td></td>
<td>Mongolia</td>
<td>Gabon</td>
</tr>
<tr>
<td></td>
<td>Sri-Lanka</td>
<td>Samoa</td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>Puerto Rico</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Algeria</td>
<td></td>
</tr>
</tbody>
</table>

Whether countries will adopt particular roles in a hydrogen economy transition is likely to depend on existing resources and infrastructure, as summarized in Figure 40. In this assessment, the propensity of individual countries and regions around the world to adopt hydrogen production strategies can be categorized in five groups. [567] This assessment does not indicate whether particular production pathways are favored (e.g., green versus blue hydrogen), but indicates the expected local capacity to contribute to the international hydrogen market. Nonetheless, analysis of the groupings leads to the following considerations [562]:

- Group 1 countries and regions are likely to lead the global markets in renewable and low-hydrogen hydrogen production capacity, with an exporting role being likely pursued, as seen already in selected national strategies (Section 7)
- Group 2 countries will favor low-carbon hydrogen production capacity, with exporting roles being contingent on the development of suitable transmission and distribution supply chains and capacity to meet local demand. Should geologic storage capacity be present for CCS applications (e.g., Saudi Arabia, China), blue hydrogen production (or related vectors for hydrogen transport and utilization, such as ammonia) can take a prominent share of the hydrogen production portfolio. Achieving significant green hydrogen production capacity will require the adoption of large desalination infrastructure or the technological maturity of direct seawater and other saltwater electrolysis systems.

- Group 3 countries will favor renewable hydrogen production capacity, which may be insufficient to meet local demand. These countries will adopt a hydrogen importer role, potentially pursuing international supply agreements with Group 1 countries. These countries and regions are likely already net energy importers under the current fossil energy paradigm.

- Group 4 countries will not favor any particular role, as local production capacity and internal market demands will inform whether renewable and low-carbon hydrogen exports are possible or hydrogen imports are needed. Supply and demand opportunities in nearby countries have a larger impact on which role these countries adopt, as regional supply chain corridors being the likely scope of their international trade capacity.

- Group 5 countries will lag the development of the hydrogen economy, as local market demand is insufficient to stimulate hydrogen production capacity, export opportunities are limited due to geographical limitations and higher costs versus other supply chain routes, or both simultaneously. Alternatively, where demand exists, lacking infrastructure prevents the development of hydrogen production systems at scale. As such, the countries will not have prominent roles in the hydrogen economy international markets, with localized efforts and smaller scale developments being the norm.
Another geopolitical ramification of hydrogen economy adoption that is unique when compared to the renewable energy transition is the security and defensive strategy implications of long-distance transmission and distribution supply chains. These hydrogen-specific ramifications more closely resemble oil and gas implications from the current fossil energy paradigm. Strategic bottlenecks in the current oil and gas transmission, such as the Strait of Hormuz and the Suez Canal, could remain highly relevant also in a low carbon economy, if renewable hydrogen produced in the Middle East were to be exported. [562] Likewise, existing natural gas pipelines into Europe (e.g., from North Africa across the Mediterranean and from Russia across the Eastern European countries) are equally applicable: whether hydrogen is blended into the natural gas network or dedicated hydrogen pipelines are used, the risks and threats are the same from a geopolitical perspective. Novel transmission and supply chain routes, such as those connecting Oceania with Southeast Asia and East Asia countries, or North America to East Asia, may also be exposed to threats and create new risks. In the latter case, increased animosities between the US and China governments may lead to impacts on maritime corridors across the Pacific [568], while in the former increased tensions concerning territorial disputes in the South China Sea could have consequences on trade through these waters [569,570].
8. Future hydrogen research agendas

This review of the literature associated with the hydrogen sociotechnical system has identified opportunities for further research into the use of hydrogen as a fuel for industrial decarbonization. In the following sub-sections, the technology, policy and market barriers to industrial adoption of low-carbon are summarized along with the potential policy measures to explore these barriers. Although a significant and growing body of literature covers these topics, we see a significant opportunity for further elaboration of context-specific policy interventions. We further consider emerging and unifying topics for research, particularly the impact of COVID-19 on hydrogen market development, hydrogen as a cross-cutting solution to decarbonization and the opportunities for hydrogen to play a role in energy transitions outside of developed economies.

8.1 Policy measures to address barriers in the hydrogen sociotechnical system

Given the significant number of barriers that exist to industrial adoption of low-carbon hydrogen, there are many policy interventions that be explored. The following set of interventions should be explored within a given context of hydrogen use to ensure that the costs and benefits are tailored to need. Research to be conducted will be particularly impactful when accounting for a full systems perspective that extends across national borders.

*New or more fully developed standards and regulations:* regulatory and standardization instruments are perhaps the key means of driving rapid hydrogen utilization. Although direct mandates and certification of low-carbon hydrogen are clear examples of such policy measures, other less obvious measures exist as well. For example, although the international transmission of hydrogen via shipping is being trialed using liquid nitrogen carriers, the governing regulation for maritime transport of bulk liquified gases (International Maritime Organization – IMO – “IGC Code”) does not directly apply to hydrogen. In this particular case, a bilateral agreement between Australia (producer) and Japan (consumer) regulates the safety standards of this transport, reflecting the national policy goals of both countries [571]. Expansion of the IMO IGC Code to regulate hydrogen maritime transmission is under development, and may enable other cross-border maritime supply chains to be established.

Hydrogen production regulatory gaps are mostly in the definition of eligible hydrogen production pathways under low-carbon and zero-carbon perspectives, as the types of feedstocks and energy sources relevant to each category are not consistently defined. Guarantees of Origin (GOs) with tamper-free transparency, such as a block-chain ledger might provide, are needed to enable robust local regulatory support for hydrogen production, such as supply tariffs. Such localized GOs need to be followed by an international GO system that enables robust hydrogen trade. Supply chain regulatory gaps are notably in the transmission (maritime shipping, dedicated hydrogen pipelines and blend ratios in natural gas pipelines), storage (geologic storage), and conversion (safety, performance, and quality of hydrogen storage and transport vectors). Carbon border adjustments will also be needed as supply chains mature to create a level playing field for all hydrogen producers wishing to locally as well as internationally.
Research, Development and Demonstration (RD&D) support: emerging technologies are currently being investigated across all hydrogen pathways. In particular, high-temperature and direct seawater electrolysis (i.e., green hydrogen), CCUS (i.e., blue hydrogen) and methane pyrolysis (i.e., turquoise hydrogen) are key technology platforms that have received ongoing attention and support from industry and academia. Respectively, these research efforts aim to limit feedstock needs in terms of freshwater, provide a destination for storage or utilization of carbon emissions, and provide another pathway for hydrogen production that does not lead to carbon dioxide emissions, producing solid carbon instead (which has different use applications). Perhaps more pressing than R&D for hydrogen production, however, is R&D for low-cost hydrogen storage and transport. Movement of hydrogen long distances is currently hindered by the high energy and economic costs of liquefaction for liquid hydrogen, production and cracking of ammonia and dehydrogenation of liquid organic carriers. Pipeline transport can also be challenging from the materials and compression perspectives. As shown in Figure 41, the hydrogen supply chain has multiple opportunities for R&D interventions.

In light of such challenges, a large number of bilateral partnerships have evolved between countries to explore the further development of hydrogen supply chains. As shown in Figure 42, Japan and Korea have been particularly active in exploring hydrogen trade with both existing energy trade partners (e.g., Saudi Arabia) as well as newcomers. Such efforts need to be expanded and accelerated.
Non-regulatory market demand stimulation: hydrogen use already established in heavy industries, emerging renewable energy transitions and the need to decarbonize the industrial sector are collectively expected to increase hydrogen demand significantly in coming years.
However, continued development of robust fiscal policies and financial incentive mechanisms (Section 6.3.1) is necessary to support and stimulate hydrogen markets. While regulations can mandate the use of hydrogen, financial incentives are important for making hydrogen adoption economically viable at large scale. Further, financial instruments need to support the operational cost of hydrogen supply and use in addition to just the capital costs of related equipment. Alignment of multiple sectors via the establishment of industrial clusters is also seen as a viable path for the development of hydrogen demand, particularly when the challenges of long-distance hydrogen transport and CO₂ storage can be mitigated through such clusters.

**Supply chain development:** achieving hydrogen production capacity to meet industrial demand must be pursued under economically favorable conditions. As both renewable energy sources and CO₂ storage capacity vary around the world, reaching production cost parity with existing grey hydrogen production or alternative production routes may only be possible in select locations. Thus, long-distance supply chains and their associated costs are key issues that require detailed understanding of make versus import tradeoffs. Optimizing the supply source of hydrogen depends critically on not just the cost of production, but also the cost of transforming hydrogen to a transportable vector and converting it back to hydrogen if necessary. If hydrogen produced from fossil fuels is considered, one needs to consider whether conversion to hydrogen should take place before or after shipping of the source fuel. Would, for instance, it be better to ship “green” LNG from Qatar to Europe and then produce “blue” hydrogen on site or rather ship “green” hydrogen from Saudi Arabia for direct use? If hydrogen is not the required end product for industrial use, perhaps shipping green or blue ammonia is most cost effective? Could long-distance power transmission lines be built to enable renewable energy to be produced in optimal locations (e.g., Australia) with the production of green hydrogen at distant locations with lesser renewable energy resources (e.g., Singapore)? The answer to such questions requires close analysis of the environmental and economic costs of each option.

**Pipeline infrastructure transition:** today’s 3 million kilometers of gas-transmission pipelines were designed to transport natural gas but would need to contribute to the mass adoption of hydrogen given that less than 5 thousand kilometers of dedicated hydrogen pipelines exist globally today. Therefore, thorough assessments are needed to assess their suitability to accommodate hydrogen. Elevated hydrogen concentrations can weaken certain grades of steel used in transmission pipelines (a condition called embrittlement) and damage compressors and valves. Polyethylene-distribution pipelines generally have a high tolerance for hydrogen blending and could potentially accept 100% hydrogen, although a massive buildout of new pipelines to accommodate hydrogen would come at a significant cost. Introducing hydrogen into gas distribution networks requires consideration of constraints associated with the tolerance of downstream appliances, vehicles and connected equipment.

**Lead market development:** the transition to hydrogen-based technologies will require first movers and technology pioneers to demonstrate the feasibility of technology platforms at progressively larger scales and hence catalyze large-scale demand for hydrogen [571]. For instance, the cost of introducing hydrogen use in maritime shipping could be reduced by selecting a small number of large vessels that are limited to point-to-point routes between highly developed ports with the available infrastructure (e.g., Rotterdam and Tokyo) or within a small geographic area (e.g., North Sea). Hence, hydrogen vectors like ammonia
should be considered as further opportunities for catalyzing large-scale hydrogen production [223].

**Overhaul and streamline regulation compliance:** existing regulatory frameworks are either insufficiently developed for widescale renewable hydrogen production and use, or exist in a patchwork-like state where different government levels have legislation and regulation covering specific cases. Harmonization must occur on multiple fronts, such as: technical standards, emissions and environmental criteria, building and zoning permitting, safety and quality parameters, pricing and taxation. In addition, regulatory administrative barriers must be minimized, *e.g.*, via the establishment of single authorities with centralized competences (*i.e.*, “one-stop shop”), where entrants in the hydrogen market are able to obtain all the necessary permits at once. This process can also be supported by reforms in regulatory bodies and agencies, with the goal of aligning incentives between the industry sector and government, and reducing overlaps among closely related sectors, such as energy, transport. Efforts to systematically address the development of harmonized legal and administrative processes and the removal of regulatory barriers in the hydrogen sector are best exemplified by the Hydrogen Europe HyLAW project and its legal database [572].

### 8.2 Hydrogen in a post-COVID-19 world

A key emerging topic of study for all aspects of the global economy is the long-term impacts of the COVID-19 pandemic. While the negative impacts of reliance on fossil-based energy sources in human health are well-established [573–579], the COVID-19 pandemic reinforced the importance of proactively addressing issues with significant global impacts, such as climate change [580–584].

The economic impact of the COVID-19 pandemic was a significant global GDP contraction in 2020 and an uncertain recovery trajectory for several years to follow [585]. Governments have thus enacted fiscal recovery packages to counteract these impacts, and policymakers have aimed to address both climate mitigation efforts and post-pandemic recovery. As discussed by Sovacool *et al.* [583], it is important that policy actions to address these issues simultaneously are carefully crafted to avoid “bloated stimulus packages, misaligned incentives, the embedding of unsustainable practices, and acute and troubling consequences for vulnerable groups”.

Following on this consideration, COVID-19 recovery packages have allocated funds to hydrogen technologies and industrial adoption. As shown in Figure 43, USD $18.5 billion has been allocated to hydrogen infrastructure with Germany and France leading the way. Some other examples of these efforts include Norway, where hydrogen is the focus in a 3.6-billion-kroner (USD $510.5 million) clean stimulus package, while state-owned Equinor aims to be a player in hydrogen at home and abroad [586].
The EU green recovery strategy is backed by the EU’s COVID-19 stimulus package, which earmarked at least 30% of its €1.8-trillion ($2.7-trillion) total for climate action over the next seven years [588]. In addition to promoting hydrogen industrial systems, stimulus spending allocation to R&D activities towards industrial sustainability is another major component of a green recovery plan. As shown in Figure 44, USD$29 billion has been committed to “green” R&D as part of stimulus packages, with USD$5.5 billion focused on industry [587]. South Korean leads this investment, which is consistent with the country’s focus on “Innovation in the Green Industry” as part of its Green New Deal COVID-19 stimulus efforts [589] and aligns with other efforts by the country to establish its hydrogen economy [502], renewable energy R&D [590], and industry decarbonization [591]. Perhaps surprisingly, however, South Korea’s national hydrogen strategy does not put emphasis on industrial uses of hydrogen.
Figure 45 elaborates further countries with hydrogen development funds. Clearly the breadth of commitment creates an interesting opportunity for future studies on how hydrogen as a fuel for industrial decarbonization unfolds internationally.

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Has a plan</th>
<th>Funds committed*</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Union</td>
<td>✔️</td>
<td>Backed by COVID-19 stimulus package that earmarked at least €547.2 billion ($630.3 billion) for climate action</td>
</tr>
<tr>
<td>South Korea</td>
<td>✔️</td>
<td>Included in clean stimulus plan worth W114-trillion ($128.6-billion)</td>
</tr>
<tr>
<td>Germany</td>
<td>✔️</td>
<td>€9 billion ($13.7 billion)</td>
</tr>
<tr>
<td>France</td>
<td>✔️</td>
<td>€7.2 billion ($10.0 billion)</td>
</tr>
<tr>
<td>Portugal</td>
<td>✔️</td>
<td>€7 billion ($10.6 billion)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>✔️</td>
<td>Highlighted in £350-million ($602.2-million) clean stimulus package and Scotland’s £62-million ($106.7-million) energy recovery fund</td>
</tr>
<tr>
<td>Norway</td>
<td>✔️</td>
<td>Included in clean stimulus plan worth 3.6 billion kroner ($520.5 million)</td>
</tr>
<tr>
<td>Australia</td>
<td>✔️</td>
<td>A$300 million ($273.2 million)</td>
</tr>
<tr>
<td>Denmark</td>
<td>✔️</td>
<td>€100 million ($151.7 million)</td>
</tr>
<tr>
<td>Netherlands</td>
<td>✔️</td>
<td>€35 million ($53.1 million)</td>
</tr>
<tr>
<td>Spain</td>
<td><strong>DRAFT</strong></td>
<td>€25 million ($37.9 million)</td>
</tr>
<tr>
<td>Lithuania</td>
<td>✔️</td>
<td>€22 million ($33.4 million)</td>
</tr>
<tr>
<td>New Zealand</td>
<td>✔️</td>
<td>NZ$20 million ($17.2 million)</td>
</tr>
<tr>
<td>Canada</td>
<td><strong>DRAFT</strong></td>
<td>?</td>
</tr>
</tbody>
</table>

Figure 45: Hydrogen funding and planning status of major countries and regions. * Italics indicate that funds are part of a COVID-19 stimulus and recovery package that also covers other funding areas [592]

8.3 Hydrogen as coupled to other sociotechnical systems

Because hydrogen is an energy vector capable of converting into and being converted from other relevant vectors, such as electricity, ammonia, methanol and synfuels, it is perhaps the most prominent of all energy vector solutions for industrial decarbonization where direct electrification is not feasible. As seen in Figure 46, in addition to its potential use as a feedstock for industry applications, it is a key component of low-carbon energy transition across a breadth of sociotechnical systems. Simultaneous decarbonization of multiple end-uses is particularly relevant in the context of industrial clusters [593–595], where infrastructure investment and market demand both aid in the de-risking of hydrogen production and use. This offers a great opportunity for further study of hydrogen as a low-
Industrial decarbonization via hydrogen  

Carbon energy vector for not just sector coupling, but also coupling of entire sociotechnical systems.

In addition to hydrogen adoption, other related interventions will need to play a key role in the decarbonization of the discussed industrial and transport sectors given the differential availability of hydrogen interventions over different time horizons (Table 21). The selected interventions are classified using the extended Technology Readiness Level (TRL) scale developed by IEA [10,596], and grouped as: near-term (TRLs 9-11, for early-adoption and mature technologies), medium-term (TRLs 5-8, for large prototypes and demonstrators), and long-term (TRLs 1-4, for conceptual, lab-scale and small prototypes). Understanding the potential of these other interventions provides a context for where and when hydrogen use is the preferred approach across industries and activities.
Table 21. Interventions in the hard-to-decarbonize sectors (industry and non-industry) to reduce emissions. Hydrogen and hydrogen-derived solutions are highlighted bold

<table>
<thead>
<tr>
<th>Sector</th>
<th>Near term</th>
<th>Medium term</th>
<th>Long term</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (industry)</td>
<td>- CCUS (via mineralization)</td>
<td>- CCUS (via calcium looping, chemical absorption, oxy-fueling, silica adsorption, direct separation, partial chemical absorption)</td>
<td>- CCS (membrane separation)</td>
<td>[323–325,597–600]</td>
</tr>
<tr>
<td></td>
<td>- New formulations (use of calcined clay, alkali binders)</td>
<td>- New cement production pathways (advanced grinding)</td>
<td>- New cement process operations (electrolyzer decarbonation prior to clinker production)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Re-use and waste upcycling (unhydrated cement recycling)</td>
<td>- New formulations (calcium silicates)</td>
<td>- Renewable and low-carbon hydrogen for high-temperature processes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Renewable energy (concentrated solar) replacement of fossil fuels</td>
<td>- Direct electrification</td>
<td></td>
</tr>
<tr>
<td>Iron and Steel (industry)</td>
<td>- CCUS (chemical adsorption), - Natural gas-based direct reduction</td>
<td>- CCUS (physical adsorption), - Biomass-derived carbon (i.e., biocharcoal) for steel production</td>
<td>- Direct iron electrolysis (high-temperature molten oxide, low-temperature alkaline electrolysis)</td>
<td>[302,318,320,405,448,601–612]</td>
</tr>
<tr>
<td></td>
<td>- Increase in scrap metal recycling (EAF pathway)</td>
<td>- New process operations (smelling reduction, hydrogen-enrichment of process gases, additive manufacturing)</td>
<td>- New process operations (plasma smelting reduction)</td>
<td></td>
</tr>
<tr>
<td>Chemicals (industry)</td>
<td>- CCUS (physical absorption, chemical absorption),</td>
<td>- CCUS (physical adsorption), - Biomass use (lignin fraction use, gasification)</td>
<td>- Novel production pathways (steam cracking electrification)</td>
<td>[613–630]</td>
</tr>
<tr>
<td></td>
<td>- Improved process and waste recycling (pyrolysis, thermal decontamination, chemical depolymerization)</td>
<td>- Renewable hydrogen production and use</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Renewable energy and materials replacement of fossil fuels (fermentation)</td>
<td>- Novel chemicals process operations (hydrothermal upgrading)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Improved process and waste recycling (solvent dissolution, solvent depolymerization)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport (non-industry)</td>
<td>- Hydrogen carriers (ammonia, maritime)</td>
<td>- Solid oxide fuel cells (maritime)</td>
<td>- Hydrogen carriers (hydrogen and synthetic fuels for aviation)</td>
<td>[330,331,366,436,534,631–641]</td>
</tr>
<tr>
<td></td>
<td>- Fuel cell electric vehicles (FCEV) (road, light- and heavy-duty)</td>
<td>- Novel battery technologies (solid state Li-metal; road)</td>
<td>- Engines for on-board use of liquid organic hydrogen carriers (maritime)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Battery technologies (Li-ion)</td>
<td>- Improved engines (aviation)</td>
<td>- Direct hydrogen fuel use (maritime)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Grid powering when docked or parked (maritime and aviation)</td>
<td>- Molten carbonate fuel cell (road)</td>
<td>- Novel battery technologies (Li-sulfur, Li-air, multivalent ions)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Biofuels (all)</td>
<td>- Hydrogen fuel cell (maritime)</td>
<td>- Novel aircraft design (aviation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Hydrogen vehicles (road)</td>
<td>- Fast charging (road)</td>
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<td></td>
<td>- Methanol fuel (rail, road)</td>
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<td></td>
<td>- Magnetic levitation (rail)</td>
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●: sector is discussed in this reference; -: sector is not discussion focus of this reference. Source: Authors

### 8.4 Cross-cutting solutions for hydrogen to decarbonize industry

We have discussed in detail the extent to which hydrogen is poised to contribute to the decarbonization of multiple industrial activities. However, developing hydrogen that is low or
zero-carbon, taking into account all hydrogen supply chain elements, requires integrative cross-cutting solutions, including hydrogen itself.

Material and design improvements along with resource efficiency are the first cross-cutting solutions identified for the hydrogen sociotechnical system. Enabling low-TRL hydrogen production processes to achieve maturity has been associated with breakthroughs in materials science (e.g., development of novel catalysts, membranes, reactor design configurations and reaction media), while in high-TRL, mature processes, material and design improvements are associated with more cost-effective project implementations (as process efficiency yields are improved due to better operating conditions afforded by the improved materials), as seen in Section 5.1 (and summarized in Figure 20). Advances to enable robust hydrogen distribution, storage, and dispensing infrastructure will require continued improvements of the physical infrastructure associated with these activities (Section 5.2). Both from economic and safety perspectives, a multi-materials approach to the development of this infrastructure is needed, whether the transmission occurs under compressed and liquified states or via other intermediates. Finally, the same developments for stationary hydrogen storage during the supply chain development can be further integrated into end-use applications (Section 5.3), as both hydrogen fueling stations and mobile and remote applications can also benefit from these solutions [642].

As for resource efficiency specifically, two main trends were identified: for existing infrastructure, from a waste minimization and resource reuse perspective, co-opting and repurposing the existing fossil gas infrastructure whenever feasible appears as a solution across the sociotechnical system. For new infrastructure development, from a waste recycling and resource demand reduction perspective, circular processes targeting the upcycling of all materials toward zero waste systems are particularly relevant. As seen in Section 5 and discussed in Sections 7 and 8.1, both sets of solutions can expedite the adoption of hydrogen technologies during a phase-out of carbon-intensive vectors currently in use, reducing the potential economic and environmental impacts of such replacement initiatives.

Waste energy recovery and utilization also consistently appears as a solution in multiple elements of the hydrogen sociotechnical system. While energy losses are expected across the sociotechnical system elements, solutions and technology options that enable the recovery and re-use of such energy streams can indirectly improve the energy efficiency. At the overall hydrogen sociotechnical level, recovery of energy losses associated with hydrogen conversion into and regeneration from other intermediates is paramount to enable their use for storage and transmission applications [148,182,201,643–654].

Energy efficiency and renewable and low-carbon energy use is another cross-cutting solution identified. All elements and sub-elements of the sociotechnical system can benefit from increased overall energy performance, and additional renewable and low-carbon energy use can aid in the reduction of energy-related indirect emissions. At the overall hydrogen sociotechnical level, improved energy efficiency is important to enable energy storage applications (i.e., power-to-hydrogen-to-power) [655–665].

The fourth cross-cutting solution, CCUS, also impacts multiple elements and sub-elements identified in the hydrogen sociotechnical system. Various CO₂ and hydrogen value chains exist and may be suitable for the decarbonization of large portions of hard-to-decarbonize
As a cross-cutting solution, any improvements on the carbon intensity of hydrogen interventions via CCUS is directly applicable to the industrial use of hydrogen. From a hydrogen sociotechnical perspective, all energy uses within all elements that can be coupled with CCUS represent a path for direct decarbonization, and thus represent an additional opportunity for blue hydrogen and blue hydrogen-derived intermediates [674–676].

Lastly, the final cross-cutting solution identified is the use of hydrogen itself in the decarbonization of its sociotechnical system. The strong coupling between hydrogen and renewable and low-carbon energy sources incentivizes the use of hydrogen as an energy vector whenever possible, across its sociotechnical elements. Thus, a unique feature in the form of a positive feedback loop exists within this system, where wider hydrogen adoption enables the greater production of low and zero-carbon hydrogen through decarbonization of power, heating and fuels used through the hydrogen supply chain [677–691].

Figure 47 shows these five cross-cutting solutions – material and design improvements, resource efficiency; waste energy recovery and utilization; energy efficiency, renewable and low-carbon energy sources; CCUS; and hydrogen – graphically, in the context of the hydrogen sociotechnical system technological elements. In parallel to the policy measures discussed in Section 8.1, the cross-cutting solutions presented here showcase the priority areas and technology options to be pursued. We note that hydrogen is only shown where it is a direct solution so as to avoid double counting with renewable and low-carbon energy sources.
8.5 The role of hydrogen in the circular carbon economy (CCE)

Another topic for further exploration cross-cutting nature of hydrogen across multiple sociotechnical systems in the circular carbon economy (CCE) framework [692]. The CCE framework builds on the principles of circular economy but with specific application to managing carbon emissions through reducing the carbon that must be managed, reusing carbon as an input to create feedstocks and fuels, recycling carbon through the natural carbon cycle and removing excess carbon via storage [693]. As show in Figure 48, hydrogen can play a prominent role in the CCE.
Although green hydrogen is seen by many as the key form of hydrogen for sustainability, perhaps future research agendas will capture the potentially prominent CCE role of blue hydrogen and other shades that leverage fossil fuels with carbon capture [495]. The IEEJ Outlook 2021 [695] provides an in-depth assessment of the role that blue hydrogen could play in a CCE that achieves significant long-term CO2 emissions reductions globally without a significant change in fossil fuels’ share of global energy consumption.

Consideration of hydrogen’s role in the CCE also serves to reinforce the importance of assessing hydrogen adoption from a complex systems perspective. While much of the reviewed literature discusses hydrogen adoption generally or with focus on specific applications, little detail is available as to exactly how energy systems would be able to evolve to accommodate the most ambitious levels of hydrogen adoption espoused in the grey literature. Hence, further work is needed to begin tackling this very challenging issue related to specific system transformations that will need to take place if indeed hydrogen is going to be as prominent by 2050 as many national roadmaps and industry reports suggest.

8.6 The role of hydrogen in energy transitions of developing economies

While the current drive to achieve net-zero emissions by many countries has hastened the adoption of hydrogen [6,11], perspectives on the actual role and potential for hydrogen vary significantly between countries. As seen in Figure 49, developed countries (also referred to as advanced or high income countries) and developing countries (also referred to as emerging and developing or low and middle-income countries) generally diverge in their perceptions of hydrogen’s potential impact within their own energy systems. Countries that consider hydrogen impactful and therefore have developed or are developing hydrogen strategies tend to be developed countries.
Both developed countries with extensive heavy industry infrastructure and energy exporting countries have recognized the potential role of hydrogen in achieving net-zero emissions goals [697–700], with most of the literature identified in our meta-review focusing on markets, policies, regulations and institutional dynamics in developed economies. However, literature on net-zero emissions and industrial decarbonization pathways for Africa [701–707], Latin America [708–712] and Southeast Asia [501,713–715] show a focus on other interventions (energy justice, electricity infrastructure development) and energy vectors (bioenergy and direct electrification) as their focus priorities. Thus, rather than taking an active role in the transition to a global hydrogen economy, developing countries seem to be somewhat sidelined. Future research agendas should consider the extent to which developing countries may benefit from low-carbon hydrogen production and use.

In cases where hydrogen is considered in the developing country context, consideration of institutional capacity to fully benefit from opportunities is insufficient. As exemplified by the case in Argentina, despite having pioneered efforts both on technological and legal fronts in the Latin America region, the country still does not have a National Strategy in place. While Argentina clearly has an opportunity for hydrogen from renewable energy using water electrolysis as exemplified by its flagship Hychico project (in operation since 2008) [716], needed legislation for hydrogen is missing. Despite Argentina’s Promotion of Hydrogen Law of 2006 (Argentine Congress Law 26.123, 2006) [717,718], which tasked the Argentine
Government with the creation of a National Fund for hydrogen promotion (“FONHIDRO”) as well as a national program for hydrogen development (“Programa Nacional de Desarrollo del Hidrógeno”), neither has developed.

9. Conclusion

Although ambitions for hydrogen have grown significantly in recent years, hydrogen use on a global scale is still limited and overwhelmingly dependent on fossil energy sources. Decarbonization of the industry sector presents two connected opportunities for hydrogen use: low-carbon and renewable hydrogen to replace current uses of hydrogen derived from fossil fuels, and low-carbon and renewable hydrogen for new decarbonization applications. The potential use of hydrogen outside of industry, for instance in transportation and power and heating applications, also highlights the importance of considering opportunities and challenges for the hydrogen value chain as it relates to decarbonization opportunities across a broad range of sociotechnical systems.

Innovation on the hydrogen sociotechnical system is expected to address challenges with all elements, and expected low-carbon interventions are summarized in Figure 50.

![Image: Figure 50: Summary of interventions, benefits, barriers and policies for decarbonization of the hydrogen sociotechnical system. Source: Authors]
Enabling market demand for hydrogen will require strong efforts on standards and regulations that support economies in their net-zero ambitions and transitions. While a price on carbon that does not leak across borders would be a particularly important catalyst, financial incentives and support are also important in stimulating the uptake of hydrogen and supporting the establishment of hydrogen-focused industrial clusters.

From the geopolitical perspective, a global hydrogen economy would alter the roles that countries play in global energy markets. Unlike the current fossil energy paradigm of resource-based power concentration, the hydrogen sociotechnical system broadens the potential for widespread renewable energy adoption (albeit unevenly distributed) and places a greater importance on the geopolitical ramifications of broad electricity adoption with significant importance placed on the competition to develop related technologies, such as electrolyzers. As noted, however, the rise of a circular carbon economy may create more opportunities for low-carbon, but non-renewable, hydrogen produced from fossil fuels with carbon capture. One can expect a struggle in coming years between countries strongly oriented toward green hydrogen adoption (e.g., EU countries) and those hoping to benefit from export of hydrogen (or derivatives) of other colors, particularly blue (e.g., Saudi Arabia, Russia).

Thus, roles in a global hydrogen market extend beyond producers and consumers to include:

- **Hydrogen technology leaders**: countries that invest in hydrogen R&D and are technology exporters. The multiple potential pathways for hydrogen production provide opportunities for technology providers to address needs not only in different production and use systems, but also in the transmission and distribution of hydrogen and its derivatives. China and Germany are examples.

- **Hydrogen supply chain leaders**: countries that can take advantage of local market conditions and low-carbon energy resources to provide hydrogen to external markets using long-distance supply chains. This role differs from the traditional energy producer role (i.e., fossil energy exporter) in that a hydrogen supply chain leader must provide the most cost-effective way to supply hydrogen for tailored end uses. This could include the transmission, and possibly distribution, of:
  - Hydrogen via a vector like ammonia;
  - A low-carbon fossil energy source, like LNG, for conversion to hydrogen at or near the point of use;
  - Renewable electricity for production of hydrogen at or near the point of use.

  Australia and Saudi Arabia are examples.

- **Hydrogen conversion leaders**: countries that have other intrinsic capabilities, such as suitable geologic formations for CO₂ storage or infrastructure for hydrogen conversion into other vectors (e.g., ammonia, methanol, synfuels), that enables their role as intermediaries in hydrogen markets. Such countries may work between producers and consumers by receiving low-carbon hydrocarbon fuels and producing low-carbon hydrogen with CCS for export to end users, or enabling the transmission and distribution of hydrogen via other vectors. The latter path is further strengthened...
when an existing demand for direct use of an intermediate hydrogen derivative (e.g., ammonia in maritime transport) is strong. The Netherlands and the UK are examples.

The hydrogen sociotechnical system is intrinsically linked with the overall energy transition and the efforts to decarbonize the energy, transport and industry sectors. While some struggle to see the clear case for hydrogen being widely adopted purely on economic grounds, the use of hydrogen for industrial decarbonization does provide a growing number of valid use cases. Moving forward, however, the most ambitious targets for hydrogen utilization will require additional study of the entire hydrogen sociotechnical system, ranging from R&D to market stimulation, and with further consideration of potential geopolitical ramifications.

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