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Hydrogen
Pathways to decarbonization

Key enabling role of hydrogen

The role of hydrogen in decarbonization

Hydrogen has received a great deal of attention in recent years for its potential to decarbonize the energy system—but despite the number of talks, events, and studies on the topic, production is still very low. This is beginning to shift as more green energy-focused bankable projects and attractive investment opportunities emerge—but much more work needs to be done.

Today, some 95 million tons of hydrogen are produced globally, virtually all of which is grey hydrogen. It's primarily used in refineries to upgrade fuels or in the chemical industry, through efforts like ammonia production.[1] Hydrogen is consequently currently mainly used as feedstock, not as energy.

To hit net-zero scenario by 2030, green hydrogen will need to account for two-thirds of the market with the remaining covered by blue hydrogen with robust carbon capture and storage (CCS) technology, Deloitte Center for Sustainable Progress' (DCSP) analysis shows.[2]

One way to do this is by dramatically increasing the energy applications of hydrogen, while also "greening" its use as feedstock[3]. Clean hydrogen can play a critical role in the decarbonization of the hard-to-abate sectors by acting as a fuel for high temperature processes and heavy-duty transport (due to its energy density-to-weight ratio of batteries), and to store electricity from variable renewables[4]. However, using hydrogen as energy only makes sense if the hydrogen has a higher value than the energy that was initially spent to produce it. This requires rapid and robust scaling of technologies such electrolyzers.

Meeting these ambitious targets will require rapidly accelerating the deployment of clean hydrogen across industries. This will involve focusing on five key success factors: demand, regulations, technology, assets and infrastructure, and collaboration. In this paper, we'll explore the role of hydrogen in decarbonization—and how its deployment may unfold.by 2050 (Figure 1).

The many colors of hydrogen

Despite hydrogen being the most abundant element in the universe[5], on earth it can rarely be found in pure form[6]. It is typically bound with oxygen to form water or with carbon to form different hydrocarbons like fossil fuels.[7] Therefore, hydrogen cannot be extracted (unlike oil or natural gas) but must be produced, expending energy. Let's start by clarifying the most important terminology around hydrogen production technologies as it is standard use in the industry.[8]

- **Grey hydrogen** is steam methane reforming of natural gas. This is today's dominant production technology. It is highly carbon intensive.
- **Blue hydrogen** is steam methane reforming in combination with carbon capture and storage technology. This reduces the carbon intensity of the hydrogen substantially but does not bring it to zero (due to failure to capture all emissions—both CO_2 and methane from natural gas). It is therefore also called low-carbon hydrogen.
- **Green hydrogen** is producing hydrogen from water via electrolysis using electricity generated by renewable energies (i.Ωe., solar photovoltaic (PV), wind, and hydropower). If the electricity is 100% renewable, green hydrogen is carbon free.
- **Turquoise hydrogen** (from pyrolysis of natural gas) or pink, sometimes also called red hydrogen (from nuclear), are technologically less advanced.

Clean hydrogen refers to green hydrogen as well as blue if it complies with stringent standards on methane emissions and CO_2 capture.

The hydrogen market outlook (demand and supply)

Fostering demand and supply in hard-to-abate sectors

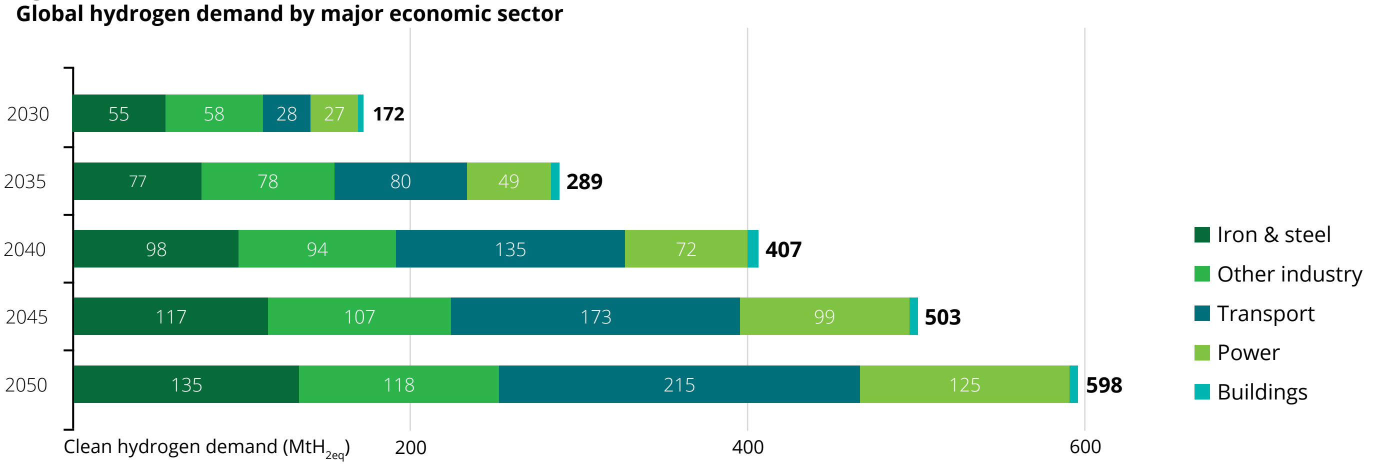
Clean hydrogen provides a crucial pathway to help decarbonize hard-to-abate sectors such as medium- and heavy-duty transportation, ammonia, steel, and energy. Unlike other forms of hydrogen, like grey and blue (which originate from natural gas), green hydrogen is produced from water via electrolysis using electricity generated by renewable sources. As a result, green hydrogen, when created by 100% renewable power sources, is carbon free. Green hydrogen can be used directly as pure hydrogen, or as feedstock to produce more suitable derivatives that are adapted to certain industrial applications and infrastructure, such as ammonia, methanol, or sustainable aviation fuels (SAF). Due to this versatility, it's an integral component to helping the world meet its Paris Climate Accord commitments and achieve net-zero by 2050. For this to happen, however, clean hydrogen market capacity must reach 170 million tons (MtH_{2eq}) by 2030 and grow to nearly 600 MtH_{2eq} by 2050 (Figure 1).

Leading up to 2030, market growth in this sector will be led by the greening of current demand (95 MtH_{2eq}). Specifically, companies that already use hydrogen for industrial purposes—most notably, for ammonia production—will be the first to embrace green hydrogen's potential as a versatile solution to decarbonization.

During these early stages, projects will likely depend on public support to break even, as illustrated by the first major schemes such as the European Union (EU) Fit-for-55 package[10] and Important Projects of Common European Interest (IPCEI) funding program,[11] the German H2Global mechanism[12] and Power-to-X (PtX) funds,[13] or the US Inflation Reduction Act.[14]

After demand for clean hydrogen grows in these sectors, it may become a more viable option for other industries—accelerating the net-zero transition. By 2050, industries such as iron, steel, chemicals, and cement—as well as aviation, shipping, and heavy road transport—are expected to account for 42% of total hydrogen demand, and 36% of clean hydrogen demand.[15,16] While demand will start in industrialized economies, the hydrogen economy also offers a major sustainable growth opportunity for developing countries. Overall, such a clean hydrogen transition could abate up to 85 $GtCO_{2eq}$ in cumulative emissions by 2050.

Figure 1
Global hydrogen demand by major economic sector



Source: Deloitte analysis based on (International Energy Agency (IEA), 2022c)[17]

Demand for green hydrogen is on the rise and is expected to continue to grow substantially over the coming decades. In fact, the green Hydrogen Market Outlook by the DCSP shows that the clean hydrogen market will reach US$640 billion in annual revenue in 2030, and grow to US$1.41 trillion in 2050.[9]

Table 1:
Demand per sector, where and when

	Sectors		Role of clean hydrogen	Timing 2030+	Timing 2040+	Timing Comments
Industry	Steel	H	**Reduction agent** for DRI or BF-BOF and for high temperatures	✓	✓	**Voluntary demand,** but long asset replacement times
Industry	Ammonia	H	Feedstock to **produce ammonia**	✓	✓	
Industry	Methanol	H	Feedstock to **produce methanol**	✓	✓	**Ease of asset replacement,** as H_2 is already used
Industry	Refining	H	Feedstock for **hydrocracking and hydrotreating**	✓	✓	
Industry	Other chemicals	M	Feedstock and / or fuel for **steam cracking**	–	–	Depending on **economics** (vs. e-cracking)
Industry	Cement	M	**Booster fuel** to increase calorific value	×	–	**Unfavorable short-term economics** (vs. biomass used)
Industry	Other Industry[1]	L	Most can be **directly electrifies / niche applications**	×	–	Depending on **economics**
Mobility	Road freight	H	Fuel in **heavy-duty long-haul** transport	✓	✓	**Voluntary demand** and **favorable economics**
Mobility	Shipping	H	Fuel in international shipping in the form of **H2, ammonia** or **methanol**	–	✓	Lack of **technology alignment and maturity**
Mobility	Aviation	H	**Direct use** or as **feedstock** to produce **Sustainable Aviation Fuel** (SAF)	✓	✓	**Regulatory pressure** (EU) and **no asset changes** needed
Mobility	Cars	L	**Electrification possible** and more economic	×	×	
Mobility	Trains	M	Fuel to **replace diesel engine trains** in long-haul transport	×	–	
Build	Residential	L	Heating alternative in case of **economic limitations of electrification** (e.g., high cost to electrify buildings with poor insulation)	×	–	Expected to **first start in areas where electrification is economic**
Build	Commercial	L		×	–	
Power[2]		M	Balance intermittency from renewables through **storage**	×	–	Required **when renewables reach high share in the mix**

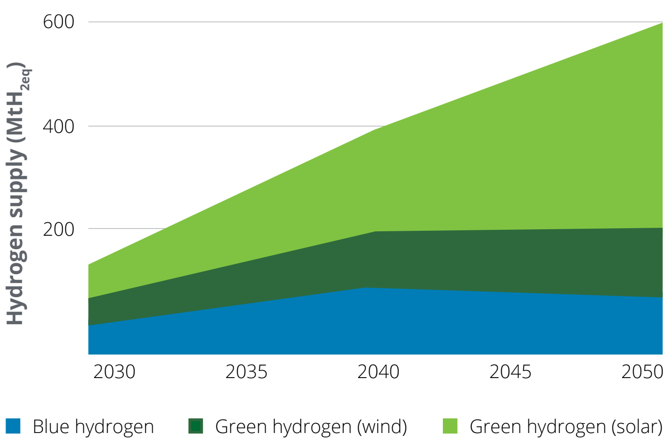
Source: DCSP analysis based on International Energy Agency (IEA), 2021[19]
Notes: 1 Incl. Non-ferrous metals, food, paper, pulp, glass, ceramics, wood, machinery, agriculture, textile and manufacturing;
2 Also in the form of ammonia;

Of course, demand is only one half of the equation—to meet it, there must also be sufficient supply. This will not only involve increasing the amount of clean hydrogen, but ensuring that clean hydrogen is financially advantageous to grey alternatives.

Green hydrogen will dominate the supply mix from the beginning and reach 85% of the market (above 500 MtH2eq) by 2050, becoming over time the most competitive clean hydrogen technology (Figure 2). Blue hydrogen will be a useful transition technology to build up demand or as a complementary solution to facilitate the emergence of the hydrogen economy, especially in regions that can leverage natural gas reserves such as the Middle East, North Africa, North America, and Australia, with production peaking in 2040 at almost 125 MtH_{2eq} (30% of supply). Blue hydrogen will be ultimately crowded out by rising competitiveness of green hydrogen and increasingly tight environmental constraints regarding unabated methane and CO_2 emissions.

This will be challenging. For many clean hydrogen solutions to emerge, a significant cost disadvantage to grey alternatives must be overcome. For example, if natural gas prices recover in the European Union in the coming years (as per International Energy Agency's EU natural gas price outlook in the latest world energy outlook scenarios),[18] and no additional regulatory incentives are created, green hydrogen adoption in ammonia production likely won't be cost competitive until 2030. Therefore, a set of success factors are needed to help promote and accelerate this development.

Figure 2:
Global clean hydrogen production evolution between 2030 and 2050 by technology type



Success factors for the hydrogen transformation

Five success factors

There are five factors that are needed to accelerate the deployment of clean hydrogen:

- **Demand**: The clean hydrogen industry will need to foster consolidated, voluntary demand which, in turn, will stimulate regulated demand. This could happen through new green value propositions and "book and claim" schemes.[20]
- **Regulations**: A new nomenclature of the Hydrogen Emission Intensity Index (HEII) will allow for the creation of simple, synchronized regulations across demand and supply, and ultimately accelerate the fast release of permits.
- **Technology**: A surge in research and development will accelerate the maturation of required technologies and fuels and allow for appropriate alignment, which, in turn, will ignite demand. To ensure there is appropriate supply, there must an increased focus on the scaling up of clean hydrogen supply chains.
- **Assets and infrastructure**: Asset reuse should be maximized with faster asset change cycles. More focus needs to be put on the infrastructure.
- **Collaboration**: New commercial and business models are needed, and a focus should be put on the acquisition of talent.

Hydrogen hubs

Hydrogen hubs are central to accelerating hydrogen development at scale and facilitating industry-wide transformations. Hubs can be defined as geographic areas with sufficient low-cost resources to produce clean hydrogen. They require a critical mass of clustered off-takers, favorable regulatory environment, and willingness to collaborate. This set-up can help drive down costs of the hydrogen value chain through economies of scale and reduced infrastructure needs.

Hubs reflect a new approach to ecosystem collaboration, requiring companies across sectors (even former competitors) to work together and sometimes share infrastructure. This leads to "co-opetition" amongst hub members that can accelerate innovation and scale mutual benefits.

Today, we see three forms of hydrogen hubs emerging:

- **Supply and demand hubs** are expected to play a big role in activating hydrogen deployment at local scale by creating supply chains and bringing down costs. These hubs will likely emerge in regions where sufficient local supply of clean hydrogen can be developed economically to meet demand of large local industrial customers. Density minimizes transportation complexity and costs (e.g., no need to ship over long distances) and maximizes economies of scale, and governments are willing to facilitate supply and demand development through transparent regulation, standards, and frameworks. Asset sharing, synergies, and willingness to collaborate across sectors will be a major factor.
- **Supply-led hubs** are likely to evolve in regions like the Middle East or US Gulf Coast where the scale of production capacity exceeds local demand and/or where the economics can compete in certain export markets with a higher willingness to pay due to lack of alternatives or overall dearth in supply. There is an important debate that is emerging around social license and the importance of using hydrogen to improve the social welfare of countries and prioritizing that versus exporting it. This is a valid argument that countries and governments are raising in their national plans.
- **Demand-led hubs** are geographies with a structural domestic supply shortage due to lack of renewables, natural gas, or CO_2 storage capacity. Examples here are Japan and South Korea which are switching from Liquid Natural Gas (LNG) dependence towards hydrogen, with some ability to produce locally at smaller scales. We see bi-lateral trades emerging first, with potential for some of these demand centers and offtakes to invest in supply as mentioned before.

Geographical and policy aspects

Emerging policy archetypes

To scale up the clean hydrogen economy and help ensure that green hydrogen plays a prominent role on the path to net-zero, decisive policy support is needed. To date, over 130 countries (83% of global carbon emissions) have announced national net-zero targets.[21] However, according to International Energy Agency (IEA), these global clean hydrogen projects would at best provide a collective production capacity of only 44 MtH_{2eq} by 2030[22]—a quarter of the amount needed.

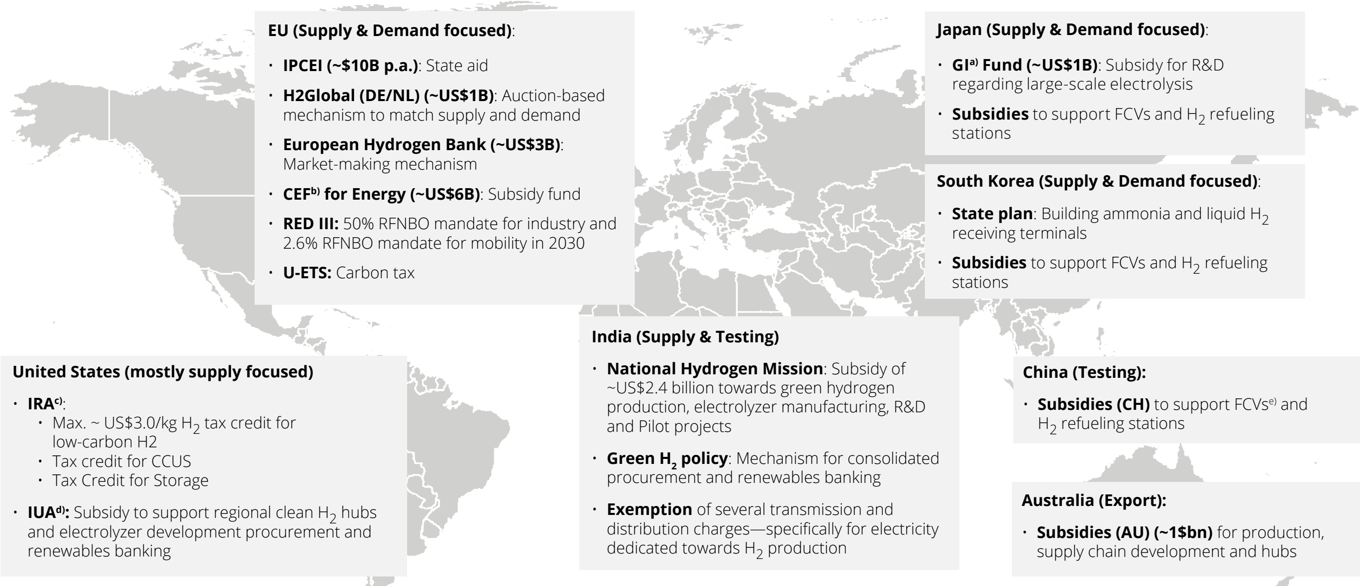
Active policy must be implemented now until at least the mid-2030s, when green hydrogen technologies will likely catch up with fossil-based alternatives in terms of costs. Currently, the production cost of grey hydrogen does not sufficiently reflect its impact on climate. Targeted policy support is therefore crucial to ensure today's early projects can compete on a level playing field and enter the market.

Right now, we're seeing such policies emerge in a variety of different forms:

- **Demand- and supply-side focus**: The EU is deploying demand-side mandates such as RED III and carbon pricing (EU-ETS) to make green hydrogen competitive with grey alternatives, as well as supply side subsidies (e.g., IPCEI) to ensure security of supply through local production.[23] Additional mechanisms are still being defined (e.g., Hydrogen Bank).[24]
- **Supply-side focus**: Through the Infrastructure and Investment Jobs Act (IIJA)[25] and Inflation Reduction Act (IRA),[26] the US will provide (tax) incentives for producers of low- carbon molecules, including hydrogen. This policy provides a tax credit of US$0.6 – 3 per kg for clean hydrogen, providing a significant push for producers to move post-Final Investment Decision and proceed with implementation. The scale and generous support of the IRA impacts global market dynamics, attracting (and shifting) investments from other regions. The IRA benefits can even make US green hydrogen export to the EU (including transport and cracking) competitive in comparison with EU locally produced green hydrogen. Other regions are therefore working to respond with new measures to maintain competitiveness.
- **Export-driven**: Australia is providing supply-side subsidies for blue and green hydrogen production and hub development. This includes approximately US$200 million/AU$300 million national[27] and US$335 million/ AU$500 million regional funds,[28] plus further local incentives, such as a 90% exemption from water costs for green hydrogen production which were announced by New South Wales with additional regional incentives (e.g., New South Wales announced up to 90% exemption of electricity cost for green hydrogen production).[29] While the focus started on stimulating export driven by the availability of low-cost (renewable) resources, focus on local demand is picking up, with some delays in the export projects.
- **Testing**: China is currently starting to grant demand-side subsidies to the mobility segment,[30] and India is exempting renewables for green hydrogen from transmission and distribution charges and drafting demand obligations for some sectors.[31] More clarity on their approaches is expected to emerge in the next years.

Active policy must be implemented now until at least the mid-2030s

Figure 3:
Overview on regulatory archetypes by region



Notes: List of regulatory instruments is not exhaustive, but only includes highlights: a) Connecting Europe Facility; b) Inflation Reduction Act; amount depends on total lifecycle CO_2 emissions; c) Fuel cell vehicles; d) Green innovation; and e) Contracts for Difference
Source: Deloitte analysis

How policy can drive lower-emission hydrogen technologies

As we wait for regulatory incentives to mature, policy support is necessary to drive investments and large-scale change. To make sure policies achieve the intended results, they should:

(1) Offer a business case. Use of targeted policy instruments such as mandatory green premiums, Carbon Contracts-for-Differences, tax credits, and offtake contracts may reduce the cost difference between clean and polluting technologies. Long-term offtake mechanisms, such as the German H2Global, can substantially mitigate project risks, bridge the gap between price and willingness to pay, and strengthen price stability.

(2) Lay the foundation for a climate-oriented market structuring. A robust and shared certification process for clean hydrogen can promote transparency while avoiding technological lock-ins. International cooperation is needed to implement national strategies that create a level playing field, strengthen synergies with development and climate objectives, and promote strong local content.

(3) Build long-term resilience. The award of public support (e.g., EU Global Gateway), and more broadly the establishment of energy relationships, should integrate diversification and inclusion targets to foster regional integration. Fair development implies that developing and emerging countries capture parts of the global value chain. More broadly, economic development based on political stability and human rights should be promoted.

Adopting a terminology that goes beyond a binary color classification can help to encourage investments and emission reduction. A possible approach to create immediate impacts and bridge the gap while long-term investments are being ramped up could be the adoption of the Hydrogen Emission Index (HEII).

The HEII takes into account both emission and economic considerations of different hydrogen production technologies. Depending on regional specifics, a more economically viable solution could be found that still provides a significant reduction in carbon intensity in the short term while shifting down the cost curve of cleaner solutions.

For example, developing electrolysis-based hydrogen production and initially blending both renewable and carbon-intensive electricity can increase the load factor of electrolyzers and operate at lower production cost while reducing emission intensity and addressing demand. Over time, while capacity is being built, assets and infrastructure will move down the cost curve (e.g., electrolyzers), which also reduces the production cost of hydrogen projects with a lower HEII.

This needs to be supplemented by policies that strongly encourage increased adoption of lower-emission technologies (i.e., moving to a lower acceptable HEII) within a clear timeframe. Industry leaders and governments need to come together to detail, refine, and align on such an approach, as well as develop assurance mechanisms.

The path forward

As the shift to a low-carbon global economy continues to gain momentum, the role of clean hydrogen is all but certain to grow.

To fully harness hydrogen's clean energy potential in hard-to-abate sectors—and ensure widespread, rapid adoption in time to reach the world's Paris Climate Accord commitments—innovators, regulators, policymakers, and industry leaders must work together by creating forward-thinking policies, technologies, and collaborative initiatives like hydrogen hubs.

Authors and contacts

This paper is part of a collection of insights on possible pathways to decarbonization for high-impact sectors. Each sector perspective offers a foundational starting point for leaders who would like to better understand the landscape across these critical sectors. For additional sector papers and links to in-depth reports, please visit Pathways to decarbonization on Deloitte.com.

At Deloitte, we're committed to illuminating new ways to power our world toward a sustainable future. To learn how we can help you identify your decarbonization pathway, ignite creative solutions, and leverage the power of green hydrogen to propel your organization into the future, contact us.

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