HYDROGEN DEMAND HUBS REPORT

Unlocking potential: Scaling demand through hydrogen hubs

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H2Global Stiftung

Federal Ministry
of Education
and Research

Glossary

Term	Definition
ARCH2	Appalachian Hydrogen Hub, United States
ARCHES	California Hydrogen Hub, United States
ATR	Autothermal reforming
ATT	Annual Tonnage Tax, Singapore
Bio-methanol	Methanol made from biomass through biological or thermochemical processes. It has a closed carbon cycle and is used in fuels and chemicals.
Bunkering	The process of supplying fuel to ships, typically involving the transfer of fuel oil from storage tanks to a vessel's fuel tanks.
CAPEX	Capital expenditure, i.e., funds used by a company to acquire, upgrade, and maintain physical assets.
CCfD	Carbon-contract-for-difference
CCUS	Carbon capture, utilization and storage
Certification	The process of providing a formal attestation that a product, service, or system meets specific standards or requirements.
CfD	Contract-for-difference: subsidy model in which both positive and negative deviations from a fixed reference price are paid out to the contractual partner.
CO2e	Carbon dioxide equivalent, a measure used to compare the emissions from various greenhouse gases based upon their global warming potential.
DAC	Direct air capture
Derivatives	Various products that can be synthesized from hydrogen through chemical processes, e.g., ammonia, methanol, synthetic fuels.
DOE	Department of Energy, United States
DRI	Direct reduction of iron
E-fuels	Synthetic fuels produced by the conversion of electrical energy into chemical energy, often produced using renewable energy sources.
EHB	European Hydrogen Bank
E-methanol	Methanol produced by combining renewable hydrogen and captured CO2. It is CO2-neutral and used in fuels and chemicals.
Energy carrier	A substance or system that contains energy which can be converted to useful work. For example, hydrogen, which can carry/store energy until it is converted into other forms, such as electricity.
eNG	Electric natural gas
EOI	Expression of interest
ESG standards	Environmental, social and governance standards
EU	European Union
FID	Final investment decision: a decision by the board of directors that officially sanctions and allows for the commitment of funds to a project or investment.

Term	Definition
GHG	Greenhouse gas
GSP	Green Ship Program, Singapore
HH2H	Heartland Hydrogen Hub, United States
HSA	Hydrogen Sale Agreement
HyVelocity H2Hub	Gulf Coast Hydrogen Hub, United States
IEA	International Energy Agency
IH2A	India Hydrogen Alliance
IRA	Inflation Reduction Act
IRF	Initial Registration Fee, Singapore
LNG	Liquified natural gas
MACH2	Mid-Atlantic Hydrogen Hub, United States
MACHH2	Midwest Hydrogen Hub, United States
MPA	Maritime and Port Authority of Singapore
Mtpa	Million tons per annum
NZE	Net-zero emissions
OCED	Office of Clean Energy Demonstrations, United States
OPEX	Operating expenditure, i.e., the ongoing costs for running a product, business, or system.
PNWH2	Pacific Northwest Hydrogen Hub, United States
PPA	Power purchase agreement
PtX	Power-to-X
Pyrolysis	A chemical process where organic materials decompose at high temperatures in the absence of oxygen, producing gases, liquids, and solid residues.
Reallabor (plural form is Reallabore)	A German term meaning "living lab" or "real-world laboratory" where innovations are tested in real-life conditions with collaboration between researchers, businesses, and citizens.
Sector coupling	The integration of energy-consuming sectors with the power-producing sector to increase the share of renewable energy, optimize energy use, and reduce greenhouse gas (GHG) emissions.
SMR	Steam methane reforming
SNG	Synthetic natural gas
TEU	Twenty-foot equivalent unit
Value chain	The full range of activities required to bring a product or service from conception, through different phases of production, delivery to final consumers, and final disposal after use.
WtP	Willingness to pay

Foreword

H2Global is committed to addressing the challenge of climate change with its unique double-auction mechanism, international stakeholder engagement, and research on the clean hydrogen economy. In 2024, the H2Global Pilot Auction delivered first results in the form of a renewable ammonia offtake agreement worth EUR 300 million for a project delivering renewable ammonia from Egypt to Europe, due to start in 2027. Four new H2Global tenders totaling EUR 4.43 bn, committed and/or earmarked by Germany, the Netherlands, Canada and Australia, are to be launched in the coming months.

H2Global's mission extends beyond auctions to identifying and alleviating market development barriers for clean fuels. As part of this endeavor, H2Global is building the H2Global Knowledge Hub, which is financially supported by a research grant issued by the German Federal Ministry for Education and Research. With the Knowledge Hub's support, H2Global engages its current 72 private sector supporters to produce valuable insights into market creation for clean hydrogen and its derivatives. The result is a series of reports in 2024 addressing three key challenges: the clean hydrogen infrastructure investment gap, the lack of clean hydrogen demand commitments, and the need to optimize auction designs.

Having a consistent, guaranteed source of revenue is essential for projects in the nascent clean hydrogen industry to become bankable and to enable at-scale manufacturing. End users and consumers have, however, built an expectation of falling prices for clean hydrogen and its derivatives and are consequently reluctant to enter into long-term contracts. Besides such price development expectations, relative prices compared to the use of fossil fuels, certainty of supply and other issues, foster the reluctance of offtakers. Hydrogen demand hubs present an opportunity to coordinate and thus unlock the necessary level of demand needed to accelerate market creation, while facilitating a level playing field, and avoiding industry relocation and carbon leakage. To understand the contribution hydrogen demand hubs can make, this report takes a use-case-oriented approach that allows for tailored measures to enhance the formation of such hubs.

Unlocking demand for clean hydrogen and its derivatives will require significant investments in infrastructure to enable physical deliveries. The specific challenges for financing midstream infrastructure are discussed in depth in H2Global's first report in 2024, "Bridging the gap: Mobilizing Investments in hydrogen infrastructure". Increased offtake commitment is also a pre-requisite to ensure effective and efficient support allocation through auctions, such as H2Global's double-auction mechanism and the European Hydrogen Bank's auctions, which are discussed in H2Global's third report: "Keep it simple: Aligning auction objectives for success".

With the 2024 reports, H2Global is working towards becoming a center of excellence in clean fuels' market creation, reinforcing its role as a green market maker and its commitment to protecting the climate and the environment.

"We applaud H2Global's clear message in this report on the importance of demand-side incentives to help closing the cost gap between clean hydrogen and high-polluting counterfactuals. CfD schemes, quotas and mandates are key to accelerate demand creation and foster the development of clean hydrogen hubs."

Ivana Jemelkova
CEO
Hydrogen Council

Executive Summary

Hydrogen hubs: the key to overcoming bottlenecks and unlocking demand

As global efforts to transition toward a sustainable, low-carbon economy accelerate, clean hydrogen has emerged as an essential pillar for decarbonization strategies. This report examines the role of hydrogen hubs as pivotal enablers of demand within the hydrogen economy, exploring their potential to bridge existing gaps and alleviate critical bottlenecks that impede market growth. By anchoring clean hydrogen production and distribution within these hubs, industries can synergize efforts across sectors, promote shared infrastructure, and drive down costs through economies of scale. This approach creates a self-reinforcing ecosystem where hydrogen can be produced, stored, and consumed efficiently, advancing both environmental and energy resilience goals.

Hydrogen hubs are uniquely positioned to address the multifaceted challenges inherent in scaling hydrogen as a clean energy carrier. In particular, they can foster collaboration across industries within concentrated geographic areas, serving as localized markets that can reduce infrastructure bottlenecks and optimize resources, thereby increasing offtaker demand.

In this report, two types of demand-driven hubs are described: self-sufficient hubs and import-dependent hubs. Each type is designed around industrial clusters, which have the following differentiated uses and transformation needs:

1. **Self-sufficient hubs**: These hubs typically involve industries that already use hydrogen or its derivatives, such as the chemical and refinery industry and the fertilizer industry. These industries generally produce and consume hydrogen themselves, allowing for local hydrogen production with minimal reliance on external sources. The main focus of self-sufficient hubs is cost-efficient transformation, either through carbon capture for existing hydrogen production processes or by using locally produced renewable hydrogen.

2. **Import-dependent hubs**: These hubs are more suited for industries like steelmaking and those requiring process heat, which have been relying on conventional fossil fuels. These hubs require extensive infrastructure to connect to domestic or international hydrogen markets, emphasizing the need for long-distance pipelines, import terminals, and large-scale storage facilities. These hubs aim to secure a stable supply of hydrogen from external sources to meet local industrial demand.

In contrast to isolated initiatives, hubs allow stakeholders to address a full range of offtaker challenges. H2Global has grouped these challenges, and recommendations, as listed in Table 1.

In developing this report, the H2Global Foundation analyzed diverse regional contexts, drawing insights from case studies in countries including the US, Germany, India, and Singapore. The US Hydrogen Hubs program emerged as a market leader, as it is currently the only operational program that centers on hubs as a solution for meeting demand and supply needs.

IMAGE CREDIT: AVIGATORPHOTOGRAPHER / ISTOCKPHOTO

Table 1: Offtaker challenges and recommendations

	Key recommendations	
Challenge	**Self-sufficient hubs**	**Import-dependent hubs**
Cost-of-difference	— Support capital expenditure (CAPEX) for carbon capture, usage and storage (CCUS) assets and local renewable hydrogen production. — Support operational expenditure (OPEX) for operational costs of CCUS and sourcing sustainable energy.	— Support CAPEX for reconfiguring industrial assets to consume clean hydrogen. — Support OPEX for procuring clean hydrogen as a fossil fuel replacement.
Infrastructure access	— Invest in short-distance pipelines to connect production and consumption within the hub.	— Provide CAPEX for mid- and long-distance pipelines and terminals to facilitate hydrogen imports.
Supply security	— Monitor local production and incentivize increased capacity to meet demand.	— Develop infrastructure to connect the hub with domestic or international hydrogen production sources.
Value-chain coordination	— Create matchmaking platforms for within-hub supply chains.	— Support collective procurement through auctions and international cooperation with exporting countries.
Flexibility needs	— Implement fallback options to allow companies flexibility during fluctuating hydrogen availability.	
Research & development needs	— Support experimental regulation (e.g., reallabor/living-lab models) to foster new business models and innovative hydrogen solutions.	
Ease of doing business	— Establish one-stop shops for permitting and administrative procedures within the hub to streamline setup for new projects.	

Each region faces distinct barriers yet shares the common goal of advancing clean hydrogen as a competitive energy alternative. The findings highlight the importance of tailored approaches—whether through government support, policy incentives, or public-private partnerships—that enable these hubs to act as engines of economic growth and environmental sustainability. With an emphasis on adaptability, the report outlines strategic recommendations that can be customized to meet regional and industrial needs, reinforcing the foundational role of hydrogen hubs in the broader energy transition.

Recommendations for hydrogen demand hubs and offtakers

The feedback from the surveys and research that are elaborated upon in this report indicates that effective support for hydrogen demand hubs should be tailored to address the distinct challenges associated with the dominant transformation strategies of each industry type.

For **self-sufficient hubs**, the focus should be on supporting self-production strategies and within-hub supply chains, which involves financial support for investments in local production infrastructure, operational incentives for self-consumption, and short-distance pipelines to link production and consumption within the hub.

Import-dependent hubs, on the other hand, require a different approach, emphasizing mid- and long-distance infrastructure like pipelines, import terminals, and large-scale storage facilities. These hubs benefit from investments in asset reconfiguration to enable hydrogen use within existing industrial processes and from infrastructure that connects the hub to external hydrogen production sites.

This report outlines strategic recommendations that can be customized to meet regional and industrial needs, reinforcing the foundational role of hydrogen hubs in the broader energy transition.

Developing hydrogen demand hubs is a complex but valuable endeavor. This analysis offers a roadmap for policymakers across the hydrogen ecosystem, with relevant findings also for industry leaders and investors seeking to build resilient, scalable hydrogen hubs that can evolve to overcome emerging bottlenecks.

IMAGE CREDIT: ONUMA INTHAPONG / ISTOCKPHOTO

The clean hydrogen demand bottleneck

Clean hydrogen and its derivatives[1] are a key pillar of the efforts to decarbonize the global economy.

Sectors like heavy industry and long-haul transport are hard to electrify. In such cases, clean hydrogen and its derivatives can play a significant role thanks to their high energy density and their ability to generate high temperatures, to be used directly in chemical processes like direct reduction of iron (DRI) and, very critically, to be produced using a variety of sources. As renewable energy sources like solar power or wind power are intermittent, hydrogen can also perform a seasonal storage function in the power sector to bridge phases with high power generation at low demand and those with lower power generation at high demand. Such diversity of use cases provides valuable flexibility to potential market participants, but may induce a need for focus in market development.

Overall, the global demand for clean hydrogen to meet global emission-reduction goals has been estimated to reach 65 million tons per annum (Mtpa) by 2030.[2] Despite these ambitious estimates, demand for clean hydrogen is at present small and uncertain: only 1.7 Mtpa of clean hydrogen production planned by 2030 has secured offtake through binding contracts—corresponding to 1.4% of the announced capacities.[3]

Having a consistent, guaranteed source of revenue is essential for clean hydrogen projects to become bankable and to enable at-scale production of clean hydrogen and its derivatives.[4] This revenue comes from demand-side projects, which in turn trickle certainty up the value chain, allowing it to flourish. Clean hydrogen economies of scale are expected to see costs fall by 50 percent by 2050 compared to 2020.[5] Consequently, end users and consumers who are interested in reaping the benefits of falling prices are reluctant to enter long-term contracts early on, and this negatively affects first movers on the supply side, infrastructure developers, and, ultimately, the financing of hydrogen production projects. At the same time, short-term developments may increase the cost of clean hydrogen temporarily. This had been expected for 2024, as the cost of capital was projected to increase momentarily and electrolyzer manufacturers envisaged bottlenecks until production capacities increased.[6] Thus, coordinated action is required to unlock the level of committed demand needed to accelerate market creation for clean hydrogen and its derivatives while ensuring there is a level playing field, and avoiding industry relocation and carbon leakage.[7] Such coordination can be organized either through integrated large-scale projects that cover the entire value chain, or through demand-pull measures, which are at present insufficient.[8]

Having a consistent, guaranteed source of revenue is essential for clean hydrogen projects to become bankable and to enable at-scale production of clean hydrogen and its derivatives.

Yet, there is not just one plug that needs to be pulled to clear the bottleneck. Hydrogen demand presents a heterogeneous challenge. This demand may come from different sectors, some of which are already using unabated fossil fuel-based hydrogen, while others plan to introduce it as a feedstock for industrial processes or vehicles. Such different use cases on the demand side face different bottlenecks, despite sharing some challenges. To properly analyze clean hydrogen demand, it is useful to distinguish two general cases:

- **Substitution cases**, where users already consume hydrogen in their conventional business model and need incentives to switch to clean hydrogen.
- **Introduction cases**, where potential users currently use other sources of energy or feedstocks, such as natural gas or coal, and need to introduce hydrogen from scratch.

Both cases may include examples from the industry and transport sectors, and there is a conceptual grey area when it comes to natural gas, synthetic natural gas (SNG) and e-fuels. These cases, however, help to structure analyses aiming to discern the key challenges and needs of companies interested in using hydrogen in their decarbonization efforts. Moreover, there are differences regarding the extent of investment and redesign needed to accomplish the transition. Depending on the use case, the scale of demand varies significantly: major steel plants vs. a large supermarket chain's fleet of forklifts, for example. Challenges for offtakers may also vary depending on their geographic location and exposure to international competition, which is discussed in more depth in the next section.

The reasons why demand for clean hydrogen is still lagging are complex. On a basic level, potential offtakers suffer from lack of confidence in being able to secure sufficient volumes of clean hydrogen reliably and at a price that they can afford and pass on to consumers, which is in line with the chicken-and-egg problem that clean fuels face. Governments have taken different approaches to addressing the lack of financial investment decisions for offtake projects and corresponding contractual commitment with suppliers. Most countries focus on instruments that allocate support to individual companies or consortia as offtakers defined by sector, not by the location of production sites in hubs.

Industries, however, tend to form clusters, i.e., geographical agglomerations of companies from the same or similar sectors which are structured by a common socio-economic ecosystem. Industrial clustering implies that one could expect local concentrations of substitution or introduction cases of clean hydrogen. This report argues that this allows for the development of two distinct hydrogen demand hub types—self-sufficient and import-dependent hubs—building on locally dominant substitution and introduction cases, respectively. In practice, there might be a mix of offtakers in each hub, but the cluster effect suggests a local concentration of particular use cases. The concept is elaborated on in Section 3.

Box 1: Hub terminology

There is no consistent definition of hydrogen hubs. The frequently used terms for regional bundling of offtakers (hub, valley, cluster) are ambiguous, both conceptually and in terms of real-world naming. In the context of the hubs selected in the US Hydrogen Hub program, for example, hubs are understood as an agglomeration of companies that may spread over several US states and comprise both hydrogen supply and demand with a high degree of self-sufficiency.[9] In Europe, a similar concept developed by the Clean Hydrogen Partnership uses the term hydrogen valley.[10] Meanwhile, major European ports, like Hamburg or Rotterdam, and some ports in the Global South, understand trade as a constitutive element of a hub which serves as an import or export terminal.[11] Geographically, these hubs are naturally defined as dense locations in harbors. The latter corresponds with a common understanding of industrial clusters in the academic debate.[12] Countries looking to export clean hydrogen derivatives may also talk of hydrogen hubs, but the emphasis of these is on producing clean hydrogen (derivatives) for external markets with only limited anchor demand. This report thus uses the terms valley, hub and cluster interchangeably.

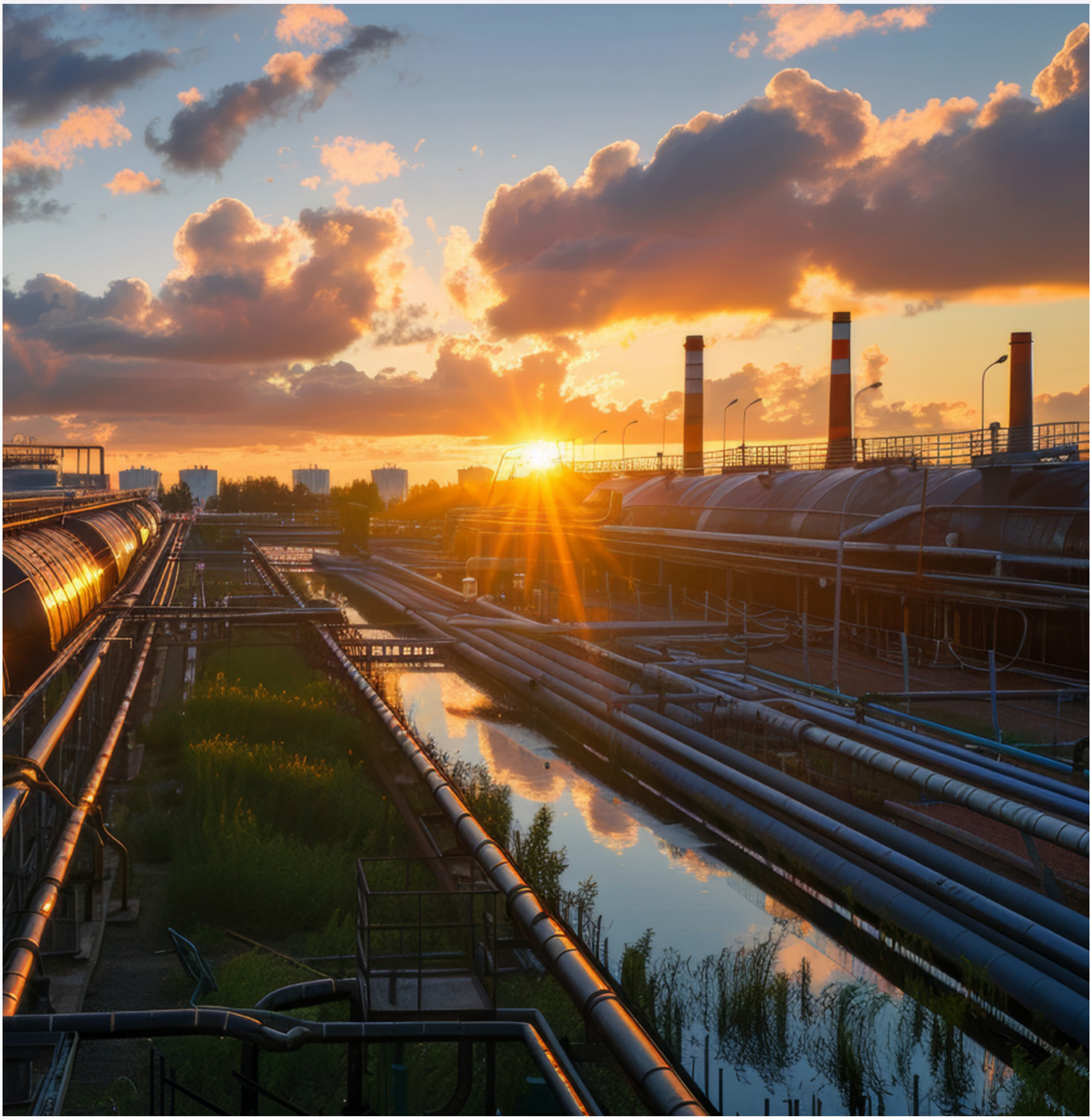


IMAGE CREDIT: KAMONRAT / ADOBE STOCK

In general, hydrogen hubs have been identified as a key demand support tool by multiple governments around the world, including 36 countries active in the Mission Innovation Hydrogen Platform[13], although this does not necessarily translate to comprehensive support mechanisms. Conceptually, hubs imply a focus on geographic clustering with sectoral diversification, i.e., the opposite of support programs that typically focus on specific sectors or types of companies. Hubs provide an opportunity to bundle offtake, thus increasing offtake security where companies are not willing to commit to long-term contracts.[14] The coordination of hubs may pose practical challenges. Integrated hubs that include both production and offtake facilitate learning by doing, infrastructure build-out, and the emergence of hydrogen ecosystems that include research facilities, engineering companies, and industrial and other users. They also have the potential to create new well-paying jobs, including for those potentially impacted by the phase out of fossil fuels.[15] Integrated hubs' success depends, however, on the effective handling of financial friction and unintended consequences of knowledge spillovers and/or emissions associated with fuel-based hydrogen production.[16]

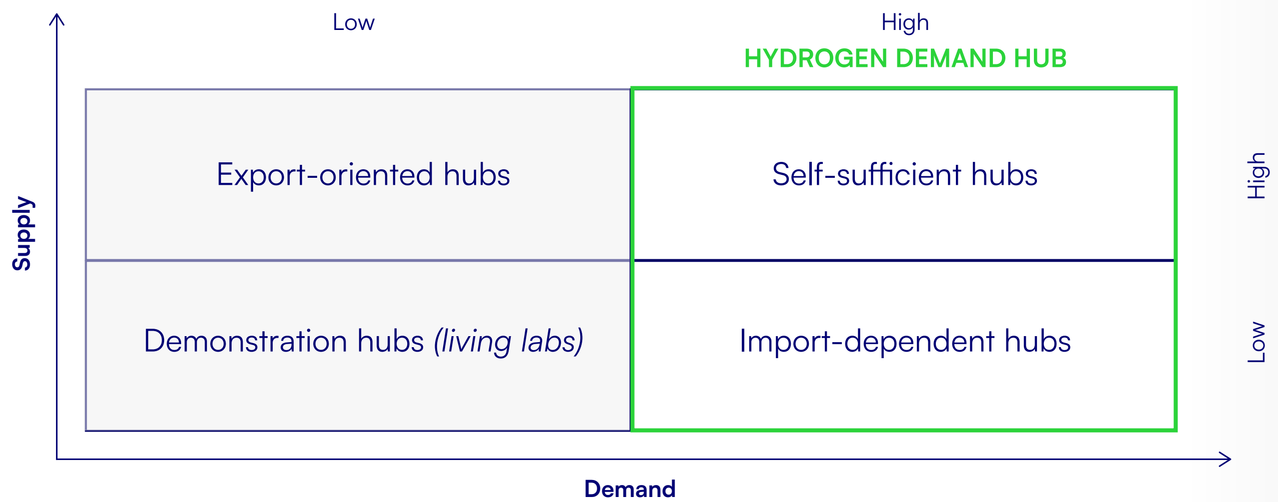
The approach with the most comprehensive aspiration for hydrogen demand based on hydrogen hubs to date is the US Hydrogen Hubs program. It was established by the Bipartisan Infrastructure Law, which channeled USD 1 billion worth of support through the Hydrogen Demand Initiative. In total, the US Hydrogen Hubs will receive support worth USD 8 billion.[17] Through this program, seven hubs have been selected to negotiate a support agreement with the Department of Energy (DOE). They are conceptually designed as regions in which the amount of produced hydrogen is met by equal demand from various sectors, and are expected to leverage the benefits of geographical proximity, including a reduced need for infrastructure build-out and easier delivery.

Hubs have also been discussed for purposes beyond demand support (see Figure 1). Some countries are looking to hubs as a means to build new industries and infrastructure, create jobs, and develop a hydrogen export sector. In Australia and Brazil, for example, hubs assume the form of special economic zones, in which exports are promoted alongside domestic offtake as an anchor to clean hydrogen production[18] Countries like Germany use hubs as "living labs" *(reallabore),* focused on demonstrating and assessing, in close cooperation with research institutions, the viability of sector coupling and of hydrogen applications at industrial scale.[19] In some places, most notably in major ports, hydrogen hubs are associated with trade hubs, and thus a focal point in the value chain for exports and imports. Ports are often important locations of industrial production and general transport nodes, thereby combining layers of different types of offtake. Their role as trade nodes alone, however, does not qualify them as focal points for a demand-driven analysis (see Box 2).

Hydrogen hubs can offer an opportunity to aggregate demand, to anchor hydrogen supply, and to develop the socio-economic ecosystem and infrastructure needed for the clean hydrogen sector to flourish.

In a nutshell, hydrogen hubs can offer an opportunity to aggregate demand, to anchor hydrogen supply, and to develop the socio-economic ecosystem and infrastructure needed for the clean hydrogen sector to flourish.

Figure 1: Typology of hydrogen hubs



Box 2: The relation of trade hubs and hydrogen hubs

The term "trade hub" was part of economic discussions and analyses long before hydrogen hubs became a concept in the energy transition. Trade hubs are typically marked by large flows of goods and people that pass through these locations, which are often, although not exclusively, ports. Such locations assume the position of nodes in trade networks and consequently often involve the co-location of important transport infrastructure, such as airports, major train stations, and harbor facilities. These transport modes in turn require large volumes of fuel. In a world where fossil fuels and feedstocks need to be transported from natural deposits to consumption sites, these trade hubs often also boast the infrastructure necessary for importing and exporting these fuels, namely terminals, storage facilities, and access to pipelines. As a result of easy access to fuel and feedstock supplies, industries often cluster in these locations.

In the transition from fossil fuels and feedstocks to clean fuels, these locations may develop the infrastructure needed to cater to diverse downstream offtakers using different derivatives. Local industries could profit from using imported derivatives directly, without costly reconversion.[20] Trade hubs can be hydrogen (demand) hubs, as local industries and transport—such as aviation and shipping—may choose solutions based on clean hydrogen (derivatives) for their transition to carbon neutral operations. However, trade infrastructure per se does not represent offtake and may play only a middle position in the value chain. In other words, a trade hub with significant clean hydrogen (derivatives) infrastructure may exist for the purpose of exports or imports without significant hydrogen demand on site.

IMAGE CREDIT: BERGAMONT / ISTOCKPHOTO

This report aims to understand the role that hubs can play in the development of the demand side of the clean hydrogen economy and how they can be supported. Not all hubs are created equal, as some more clearly aim at supporting either supply, trade, or demand build-up. In the pursuit of solutions for the demand side, this report consequently focuses on hubs that concentrate on demand (hydrogen demand hubs). The next section discusses different use cases for hydrogen and the challenges and needs that the respective offtakers face. Based on this assessment, the third section identifies the contribution that clean hydrogen hubs can make to solve these challenges, and it develops two distinct concepts of hydrogen hubs that can be constructed around these use cases and transformation pathways. The fourth section identifies overarching and specific hub-type recommendations for policymakers and practitioners to enhance the establishment of hydrogen hubs.

IMAGE CREDIT: SIMONSKAFAR / ISTOCKPHOTO

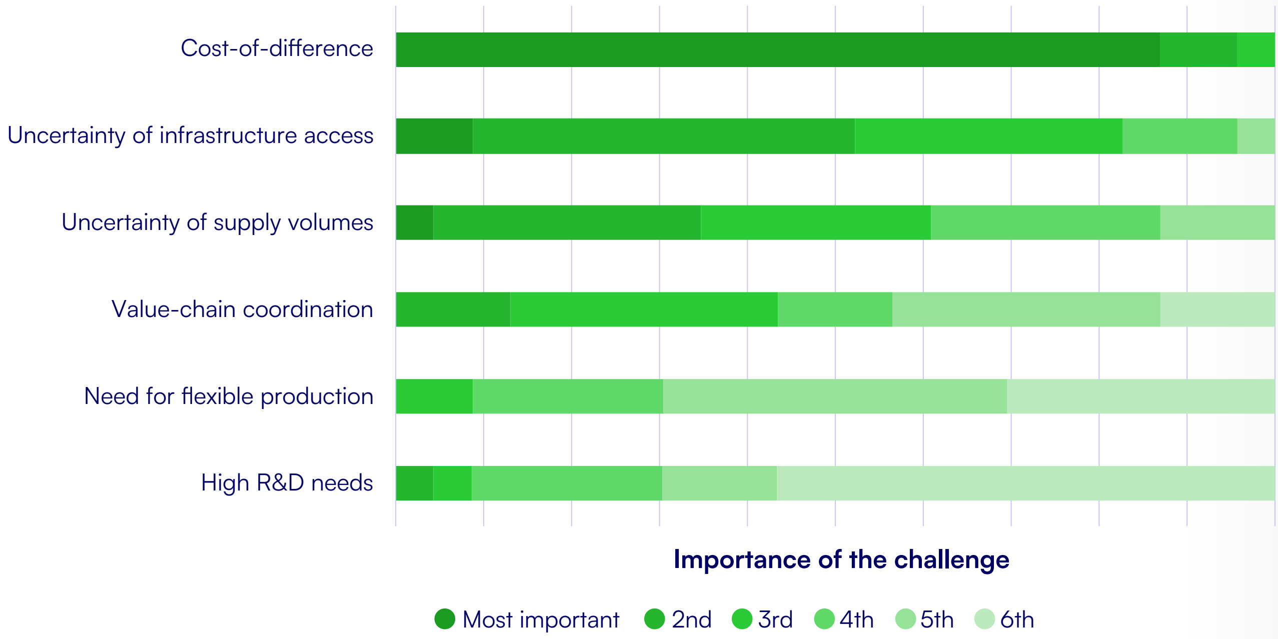
2

Causes of bottlenecks: challenges and needs of different offtakers

Potential users of clean hydrogen face challenges associated with the nascent state of the market, from an unclear and evolving regulatory environment to complex permitting ("red tape").

A survey of H2Global Foundation donors highlighted six key challenges clean hydrogen (derivatives) offtakers are facing: cost-of-difference, infrastructure access, certainty of supply volumes, value-chain coordination, a need for flexible production, and high research and development needs. Amongst these, the gap between the production cost and the willingness to pay (WtP)—the so-called cost-of-difference—emerged as the top challenge, having 87% of the respondents' votes (see Figure 2). While these challenges are of relevance for all types of offtakers, the way in which each challenge affects individual offtakers may differ.

Figure 2: Common challenges of offtakers of clean hydrogen (derivatives)



Source: H2Global Foundation, 2024
N=23 H2Global Foundation donors (48% internationally operating companies; 35% companies with European focus; 13% companies with East Asian focus; 4% companies with North American focus)

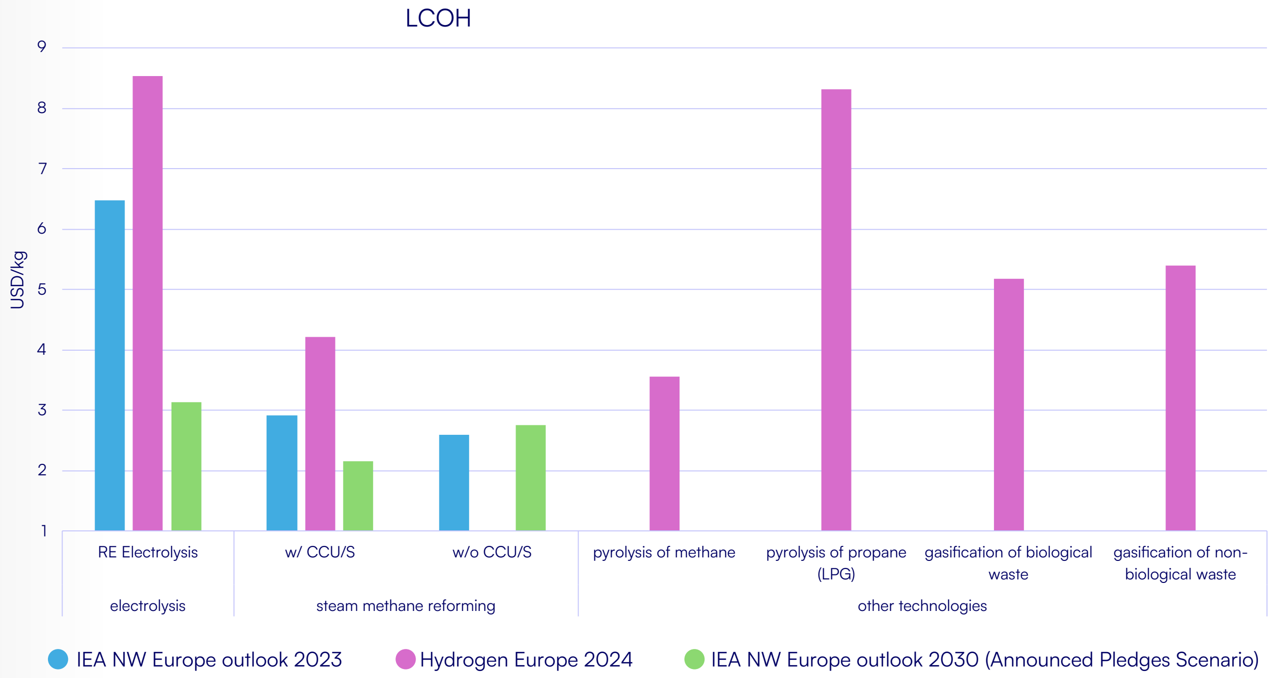
Cost-of-difference

Cost differences between clean and unabated fossil fuels are the most salient challenge for most market participants when considering a transition to clean fuels. One important driver for this cost gap is the additional cost associated with the clean fuels production process, regardless of whether hydrogen is produced using steam methane reforming, electrolysis, pyrolysis, or other production technologies (see Figure 3). These cost differences are primarily driven by the varying prices for natural gas, electricity, and biomass, which are the main cost determinants of the three main production pathways for clean hydrogen. Other drivers include the cost of building new infrastructure (like terminals, pipelines, and reconversion facilities) and the suboptimal size of production assets as they do not allow for flexible production.

On the clean hydrogen production side, each production pathway entails additional energy needs or losses when compared to the direct use of electricity or to the conventional production technologies for hydrogen.[21] Thus, a premium will be included in the price of hydrogen to cover these additional energy needs and losses, as long as the hydrogen is not sourced from naturally occurring deposits.[22] In the case of steam methane reforming (SMR) or autothermal reforming (ATR), combined with carbon capture technologies, production costs include not just the SMR or ATR process costs, but also the operation of the carbon capture facilities and additional measures to minimize greenhouse gas (GHG) emissions along the natural gas production value chain. In the case of renewable hydrogen, production costs include, inter alia, the operational cost of electrolyzers, grid fees and/or the cost of renewable energy production, water processing (desalination in some instances), and transformation losses. Business cases for clean hydrogen thus need to reflect

Besides having to deal with the inherent costs of production of clean hydrogen and its derivatives, offtakers need to mitigate the costs associated with the reconfiguration of their own industrial or transport-related assets.

Figure 3: Levelized cost of hydrogen production in Europe by technology in 2023, 2024 and the Net Zero Emissions (NZE) by 2050 scenario in 2030



Source: International Energy Agency (2023), Hydrogen Europe (2024); the value of electrolysis for the hydrogen Europe 2024 report represents an average of low- and high-temperature technologies

how such additional costs generate a relative disadvantage compared with the cost of production of unabated fossil fuel-based hydrogen.

Besides having to deal with the inherent costs of production of clean hydrogen and its derivatives, offtakers need to mitigate the costs associated with the reconfiguration of their own industrial or transport-related assets. This may include, for example, the retrofitting or replacement of furnaces, valves or temporary on-site storage capacities to accommodate the technical requirements of hydrogen (derivatives) or the replacement of vehicles. Furthermore, since the initial number of users is limited, first movers in the clean hydrogen economy are often asked to absorb a disproportionate share of infrastructure costs and to deal with delivery bottlenecks while the infrastructure is under construction or in the process of being repurposed. This infrastructure is at the same time critical to enable the use of clean hydrogen and its derivatives, especially in import-dependent locations. For consumers that cannot rely on their own production of clean hydrogen (derivatives) for self-consumption, these costs become a key challenge that needs to be mitigated, particularly if supply is not available from sites in close proximity. Simultaneously, an adequate scaling of the infrastructure is a prerequisite to provide sufficient security of supply.

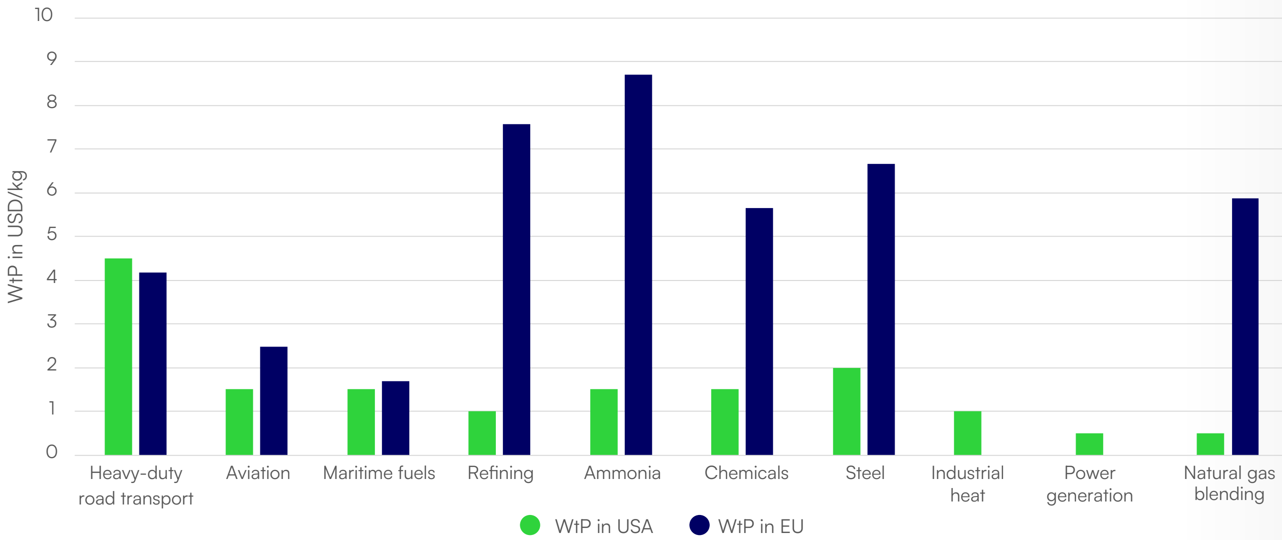
The other side of the equation is the price offtakers are willing to pay for clean hydrogen. WtP varies across industries depending on the reference price of the fossil fuel industry, the availability of alternative decarbonization technologies, transformation pressure derived from carbon pricing (where applicable) and other regulatory measures, exposure to

An adequate scaling of the infrastructure is a prerequisite to provide sufficient security of supply.

international competition, and the relevance of first-mover advantages. WtP varies regionally (see Figure 4). At this nascent market development stage, WtP is not derived from firm market data, but from surveys and estimates.

According to the results of an industry survey and estimates by the US DOE, based on fossil fuel reference prices (see Figure 5), offtakers' average WtP for clean hydrogen in the US ranges from 1.0-1.5 USD/kg in the ammonia sector,

Figure 4: WtP in the US and EU in comparison

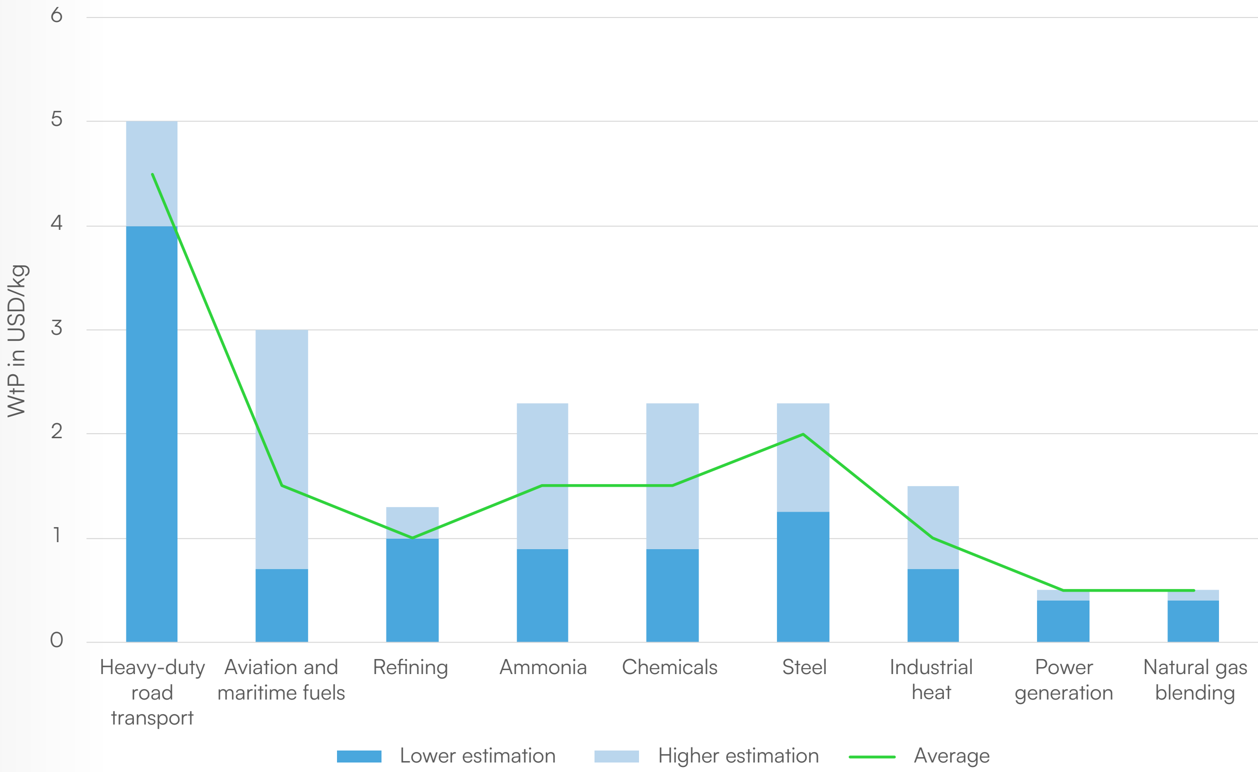


Note: EU (European Union) data is based on the estimates that suppliers provided in the European Hydrogen Bank (EHB) Hydrogen Pilot Tender (2024). US data is based on Pathways to Commercial Liftoff: Clean Hydrogen, US Department of Energy (DOE) (2023)

chemicals and refining—three sectors that are exposed to international competition and existing uses for conventionally produced hydrogen. Steelmakers—traditionally not major users of hydrogen—are expected to be willing to pay 2.0 USD/kg in particular for direct reduction of iron (DRI). The WtP of companies in need of industrial process heat is significantly lower, at 0.7-1.5 USD/kg.[23] The relatively low WtP for ammonia, chemicals, refining, steel, and industrial heat is to a large extent due to smaller profit margins in these sectors and the existence of alternative decarbonization options like carbon capture or direct electrification—although it is not yet clear which options will turn out to be more competitively viable.[24] Heavy duty road transport has a higher WtP of around 4.5 USD/kg[25] compared to an average 1-2 USD/kg in aviation and shipping.[26] As highlighted in the DOE's Pathways to Commercial Liftoff report, the

IMAGE CREDIT: LIM WEIXIANG - ZEITGEIST PHOTOS / ISTOCKPHOTO

Figure 5: Offtakers' willingness to pay for clean hydrogen in the USA



Source: based on Pathways to Commercial Liftoff: Clean Hydrogen, US DOE (2023)

transportation sector's relatively high WtP could be a result of higher marginal abatement costs and reliance on volatile diesel prices. Hydrogen fuel cells offer significant advantages to heavy-duty vehicles, such as fast refueling and minimal downtime compared to battery-based vehicles. Additionally, in some regions, regulatory incentives like the Low Carbon Fuel Standard (LCFS) boost hydrogen's attractiveness in transport.

In Europe, the EHB Pilot Auction had suppliers estimate the price they expected to achieve on the market for their renewable hydrogen products, reporting an aggregated industrial WtP of 6.2 USD /kg and 8.6 USD/kg for mobility.[27] This is a very different approach to that of the US DOE, revealing how vastly WtP estimations can differ.

The current cost modeling for clean hydrogen and the above considerations for WtP result in a price gap between unabated fossil fuels and clean fuels of up to 8 USD/kg, depending on the combination of technology and fuel prices. This price gap is eventually expected to fall to 1.3 USD/kg in the future.[28] The price gap between unabated fossil fuels-based hydrogen and clean hydrogen plays an important role, particularly in commodities like steel, jet fuel, and basic chemicals, i.e., in many of the industries that consider clean hydrogen and its derivatives as part of their solution to achieving climate neutral production in a competitive context where a green premium cannot easily be offset to customers.[29] Reasons for this lack of price elasticity include: the advanced standardization of commodities, which produces a global reference price, and carbon pricing schemes that affect international competition.[30] Offtakers' WtP is thus generally based on the driver of operational costs of the dominant conventional technologies (i.e., fossil fuels), including carbon pricing costs (when applicable). For offtakers, it is thus imperative to develop the clean hydrogen economy in a cost-efficient way that reduces the cost-of-difference.

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IMAGE CREDIT: MA LI / ISTOCKPHOTO

Access to infrastructure

The second most crucial challenge for offtakers is access to infrastructure. Depending on whether one needs to transport pure hydrogen or derivatives, and whether derivatives need to be reconverted, different infrastructure and storage facilities are required. For the transport of pure hydrogen via pipelines, this includes the availability of pipelines themselves, as well as compressors, valves, and international gas network interconnectors. Shipping of liquid hydrogen requires cooling the gas to -253°C (resulting in corresponding energy losses) while dissolving hydrogen in liquid organic hydrogen carriers (LOHC) comes at the cost of transport volumes and energy losses during the dehydrogenation process. Furthermore, both modes of transport require specific infrastructure for liquefaction and regasification, or (de-)hydrogenation, that are not yet widely available.

Transport of clean hydrogen in the form of ammonia, methanol, or synthetic methane uses technologies that have been used at industrial scale for decades, but that may entail additional reconversion losses if the final product to be consumed is clean hydrogen.[31] Different use cases need different infrastructure that must be in place and sufficiently scaled up to enable initial, and future, larger deliveries.

The absence of pipelines, reconversion units, terminals or ships for the respective hydrogen or derivative molecules presents a barrier for value-chain establishment.

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Uncertainty of volumes, value-chain coordination and need for flexible production

The third most important challenge that offtakers highlighted (i.e., uncertainty on supply volumes), as well as the fourth (i.e., value-chain coordination) and fifth (i.e. the need for flexible production), are interrelated and hard to solve in the nascent hydrogen economy. In the absence of a liquid market for clean hydrogen and a fully developed infrastructure, business cases relying on deliveries of hydrogen risk their production processes being interrupted. This challenge is pronounced for supply using CCUS, due to remaining uncertainties regarding certification and regulation, and for electrolysis-based production, due to remaining technical challenges regarding the lifetime and performance stability of electrolyzers.

In this context, offtakers need to secure purchase agreements and hedge the risk of technical deficiencies. Hedging includes contractual arrangements (like fees for delivery failure or delay), portfolio approaches to mobilize alternative sources when needed, and flexible production facilities at the offtake site that can flexibly adjust to volatile deliveries. Long-term purchasing agreements can be used as a part of this strategy. Purchase agreements with renewable powered electrolysis producers may entail some residual risk of volatility due to intermittent production. Large-volume (underground) hydrogen storage is crucial to address such volatility for offtakers that, for technical or economic reasons, can only make limited use of flexible production. As renewable hydrogen is projected to contribute the bulk of clean hydrogen supply in the future,[32] this should be regarded as a common challenge, although individual business cases may be able to avoid this issue by deploying alternative technologies or storage.

Research and development needs

Many clean hydrogen applications are still not fully developed for at-scale deployment, requiring significant investments in research and development, which poses a challenge to offtakers. Although industries, such as the chemical and fertilizer industries, have been handling hydrogen for decades, sectors such as steel, glass, ceramics, paper and mobility are new to using this energy carrier. In the steel sector, DRI is in principle hydrogen-ready and already available and implemented at scale in economies that have cheap access to natural gas. Adjusting to the different characteristics of hydrogen compared to natural gas, however, requires reinvestment in steel-making facilities. Steelmakers that currently use conventional blast furnaces based on coking coal that decide to transition to DRI must make significantly higher investments in new facilities, as well as go through extensive learning processes. Other industries require even more significant investment in research and development to introduce new industrial processes and develop new engines and new refueling infrastructure (mobility), etc. Even companies that are used to hydrogen applications already may still need to adopt carbon capture technologies and/or find new ways to integrate clean hydrogen technologies into complex production processes.[33]

Many clean hydrogen applications are still not fully developed for at-scale deployment, requiring significant investments in research and development, which poses a challenge to offtakers.

Ease of doing business

Besides the six major challenges assessed through the aforementioned survey, discussions in the H2Global working group highlighted as salient the ease of doing business. Most of the potential use for clean hydrogen is situated in both developed and emerging countries.[34] In many of these jurisdictions, the complexity of administrative processes, and correspondingly slow speed of permitting, generates costs for both administrative bodies and companies (so-called "red tape"). Additionally, many new climate-friendly solutions require adjustments of existing regulations, or new regulations, to become viable. This pertains, inter alia, to environmental, social and governance (ESG) standards, including emissions accounting, safety regulations, water access, and taxation of clean fuels.[35] In the absence of adequate regulation, companies find themselves in a situation of legal uncertainty that requires extensive exchanges with local institutions to find solutions that work. As such procedures are time intensive, they can delay the realization of projects.

Ease of doing business also encompasses access, in large numbers, to a well-trained staff and easy access to finance. The former requires long-term investment in skills and education. Establishing specialized education institutions, like universities and training centers, at or near industrial clusters has the potential to create and leverage synergies in this regard.[36] Ease of access to finance broadly includes a strong and stable regulatory framework, including a unified legal framework for secured transactions, priority payments to secured creditors in cases of default or liquidation, free arrangements for collateral between the involved parties, a collateral registry, and access to information on the creditworthiness of borrowers.[37]

Use case-specific challenges

Besides these shared challenges, the circumstances of certain industries create a set of specific challenges. In some instances, the industry in question already uses hydrogen or its derivatives, in others they must introduce such uses in their processes. Depending on the sector and competitive context, industries also display a varying willingness to pay for the cost-of-difference.

Industries that already use hydrogen include refinery, chemical and fertilizer plants, and other industries where hydrogen is used as a process gas. Refineries, for example, use hydrogen mostly to process crude oil or to synthesize liquid hydrocarbons through the Fischer-Tropsch process.[38] In these use cases, hydrogen is mostly used as a feedstock and reacts with other molecules to form more complex products. To date, the hydrogen used in these processes is mostly provided through the unabated steam reformation of fossil fuels, often based on self-production and self-consumption of hydrogen (captive procurement). Industries that regularly use hydrogen are often regarded as low-hanging fruits for clean hydrogen adoption as this would allow for a comparatively easy substitution of unabated fossil fuels.[39] For one, industry participants are already equipped with the necessary technology and personnel to handle hydrogen and its derivatives that are processed in the production facilities. They may, however, need to transition to a sustainable feedstock for CO or CO2 depending on the chosen transformation path (compare the methanol route example in Figure 6). The relevant benchmark for the WtP in such industries is the cost of today's unabated production prices, typically based on the price of the (mostly fossil) feedstock. This implies a price of 1-3 USD/kg for clean hydrogen.[40]

For some industries, the potential to transition from unabated fossil fuels to hydrogen is significant but hard to accomplish since the technologies that would allow for its use are not widely available. A case in point is steel

For some industries, the potential to transition from unabated fossil fuels to hydrogen is significant but hard to accomplish since the technologies that would allow for its use are not widely available.

production, which is currently dominated by conventional blast furnaces that use coking coal to reduce iron ore to pure iron. DRI is still seen as a more expensive alternative and is mostly used in countries that enjoy low prices for natural gas, such as Mexico and the US.[41] In DRI units, both natural gas and hydrogen can be used to replace coking coal as a reducing agent. The reduction process produces sponge iron that must be re-smelted afterwards, which can be achieved through hydrogen or electric furnaces.[42]

Figure 6: Schematic representation of the methanol route

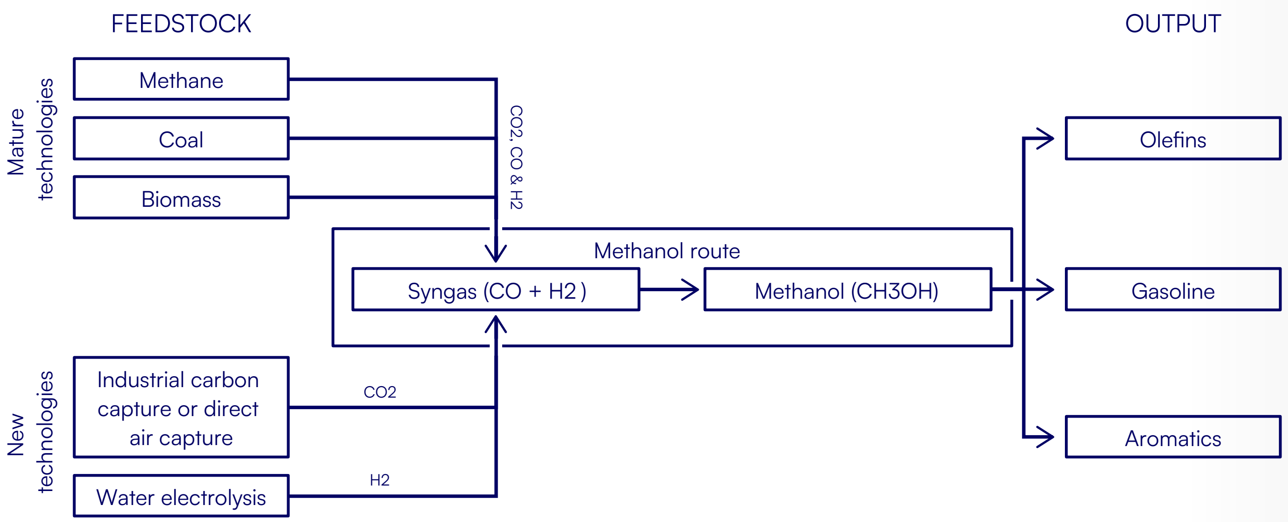


IMAGE CREDIT: DEDMITYAY / ADOBE STOCK

The use of clean hydrogen or its derivatives is completely new for some industries. This includes industries such as glass and ceramics that rely on high temperature process heat that currently use natural gas and other fossil fuels to fire blast furnaces. The sinter and smelting processes of these industries cannot be electrified with currently available technologies and they may therefore resort to using hydrogen, particularly if alternative processes are deemed uneconomical.[43] Securing continuous hydrogen supply at similar levels will be critical for these industries, since industrial smelting processes typically require a continuous supply of fuel due to the machines being designed to run non-stop.[44] The relevant benchmark for the WtP for clean hydrogen in these industries is the cost of unabated fossil fuels, which is currently around 1-2.7 USD/kg.[45]

Public debates about hydrogen solutions in the transport sector largely agree that clean hydrogen and its derivatives will mostly contribute to the defossilization of heavy-duty and long-distance transport, such as shipping and aviation that rely on high energy density of their fuels.[46] Where possible, solutions that allow for direct electrification (notably in the transport sector) are preferable from an energy system's perspective, as they avoid the losses associated with the conversion of clean energy to molecules and back. Compared to industrial applications, transport uses of clean hydrogen face a particular challenge: they require decentralized refueling stations. This challenge is exacerbated in road-borne transport, but also applies to aviation and shipping. Nevertheless, some locations represent important nodes where multiple modes of transport meet, including international airports and major seaports. The estimates for the WtP in the transport sector are higher than for other industries with a range of 4-8 USD/kg in the US[47] and up to 9 USD/kg in the EU.[48]

IMAGE CREDIT: MA YICHAO/STOCKSY, ADOBE STOCK

3

Clearing the bottlenecks: hydrogen demand hubs as a solution

Market introduction of new technologies such as those using clean hydrogen (derivatives) in the context of the energy transition is not new.

Policymakers therefore have had experience in addressing some of the challenges new energy solutions face, including cost differentials, infrastructure challenges, supply chain development needs, supply security and flexibility requirements, as well as research and development needs. Supporting the transformation of a few—but large—offtakers, like steel mills in a small country, represents a much larger task, however, than facilitating gradual changes such as the incremental replacement of heavy-duty cargo fleets. The following examples spell out some of the instruments policymakers have used to navigate the challenges clean hydrogen-based technologies face, without claiming completeness.

When dealing with cost differentials, comparing the costs of hydrogen-based production with fossil fuel-based production is of the essence. Possibly the most direct way to support demand creation for clean hydrogen is the adoption of a "sustained, elevated carbon price that raises costs" of unabated fossil fuels-based hydrogen.[49] Carbon prices, however, have yet to be adopted on a global scale. Those that exist have proven to be either volatile or too low.[50] The flipside of this coin is the reduction of fossil-fuel subsidies, which has yet to materialize systematically in any jurisdiction, largely due to potential side-effects on social justice and/or industrial competitiveness.

Looking beyond carbon pricing and the elimination of fossil fuel subsidies, policymakers have looked to reduce the costs that offtakers face when using clean hydrogen. The European Commission, for example, has introduced the Important Projects of Common European Interest (IPCEIs) on hydrogen. The first IPCEI, called "IPCEI Hy2Tech", was approved in July 2022 to develop innovative technologies for the hydrogen value chain to decarbonize industrial processes and the transport sector, with a focus on end users. In September 2022, the Commission approved "IPCEI Hy2Use", which complements IPCEI Hy2Tech. It supports the construction of hydrogen-related infrastructure and the development of innovative and more sustainable technologies for the integration of hydrogen into the industrial sector. The European Commission awarded EUR 5.2 billion to 35 clean hydrogen demand projects, triggering an expected EUR 7 billion of private investments.[51] These projects are of varying sizes, with one project by Thyssenkrupp Steel, for example, receiving EUR 2 billion in state aid over ten years.[52] EU member states have also set up additional capital expenditure (CAPEX) support schemes. Germany devised a scheme, *Klimaschutzverträge* (or Carbon-Contracts-for-Difference (CCfDs)) that covers both CAPEX and operational expenditure (OPEX) and to which hydrogen offtake projects may apply.[53]

IMAGE CREDIT: ALPHA / ADOBE STOCK

Investment support has also been provided to facilitate infrastructure build-up for clean hydrogen. The EU's "IPCEI Hy2Infra" supports the development of electrolysers, hydrogen transmission and distribution pipelines, large-scale hydrogen storage facilities, and handling terminals. At a national level, various governments have developed support mechanisms to facilitate investment into the infrastructure needed for clean hydrogen. Canada, for example, has launched a CAD 500 million Charging and Hydrogen Refuelling Infrastructure Initiative to help remove barriers to the adoption of zero-emission vehicles.[54] Both the Netherlands and Germany have advanced planning for a hydrogen core grid to foster hydrogen infrastructure access. The German government has put in place a mechanism using amortization accounts that enables intertemporal compensation for infrastructure operators that need to build initially oversized—or underused—infrastructure.[55] More information on dedicated infrastructure support mechanisms can be found in H2Global's report, "Bridging the gap: Mobilizing investments in hydrogen infrastructure".

The European Commission awarded EUR 5.2 billion to 35 clean hydrogen demand projects, triggering an expected EUR 7 billion of private investments

Policymakers have also tried to tackle incomplete value chains due to lack of demand commitment. Japan, for example, has sought to build clean hydrogen demand by setting ambitious mobility targets (especially regarding fuel cell use, hydrogen trains, and shipping) and providing robust funding for research and development, as well as demonstration facilities in industries. Additionally, the government has set a target for a combined one percent share in the energy mix for hydrogen and ammonia power plants.[56] In total, the Japanese government has allocated JPY 15 trillion (approx. EUR 90 billion) to support the hydrogen value chain.[57] This includes funds to compensate the cost-of-difference of hydrogen and ammonia to fossil fuels for 15 years, as well as the cost of short- and mid-range infrastructure in and around major cities.[58]

Apart from the instruments detailed above, countries around the world finance research and development programs targeting, inter alia, hydrogen technologies. Many have also developed measures to encourage supply security of clean hydrogen (derivatives), including tax incentives (e.g., in the American Inflation Reduction Act), CAPEX support, and auctions. Supply support measures are outside the scope of this report, but readers can find more information on auctions in H2Global's report, "Keep it simple: Aligning auction objectives for success".

Hydrogen hubs as an integrated response to multiple challenges

The above instruments represent isolated, yet broad-reaching approaches policymakers have developed to address the challenges of nascent clean hydrogen markets. Industries, however, tend to form geographic clusters per sector, clustering similar challenges, which can be addressed in some instances more effectively through integrated and focused approaches.[59]

Geographic industrial clusters or hubs facilitate demand aggregation that provides a high level of certainty to suppliers, reduces midstream infrastructure requirements, and maximizes learning effects.[60] Focusing infrastructure development in the hubs reduces the risk of stranded asset development for infrastructure providers. Aggregation not only reduces risk for offtakers but also enables economies of scale that can contribute to bringing down the overall cost of the transformation process.[61] Hubs end up working as a demand anchor, improving the bankability of all projects related to the hub.[62] But hubs are not without their own challenges. Coordination can be particularly difficult, since they are comprised of many independent actors with varying interests that need to be aligned, including for joint action regarding third parties.[63]

Hydrogen demand hubs can be distinguished by the extent of the hydrogen value chain that they cover (see Figure 7):

— Hubs can be **self-sufficient**, meaning that the hub produces most of the consumed clean hydrogen (derivatives) itself, or

— Hubs can **depend on imports** from other regions (domestic or international production).

Self-sufficient hubs

Self-sufficient hubs produce most of the hydrogen (derivatives) they consume, and their participants have experience in producing and handling these molecules. This hub type is found primarily in locations that feature industries already using conventional hydrogen (derivatives) and producing hydrogen for their own consumption and/or have production and offtakers in relative proximity (co-location). The challenge here is to find cost-efficient ways to substitute conventional hydrogen sources with clean hydrogen for the anchor industries—refinery, chemical and fertilizer plants—featured in the hubs.

There are three business models for switching from conventional to clean hydrogen. First, a company keeps its steam methane reformation units and adds carbon capture units to extract and safely store excess CO and CO2, where this is legally and technically possible. Second, a company replaces its existing steam reformation processes

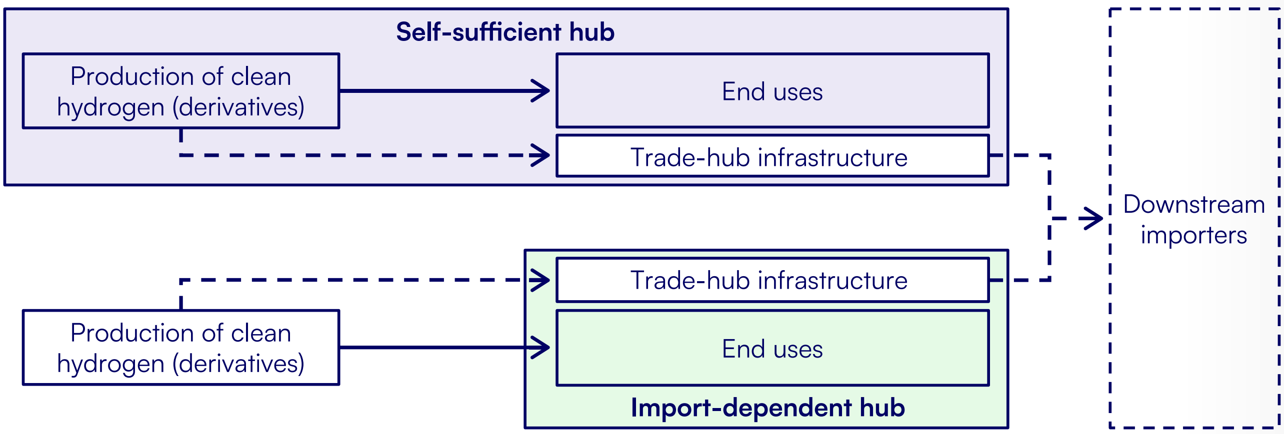
Self-sufficient hubs produce most of the hydrogen (derivatives) they consume, and their participants have experience in producing and handling these molecules.

with electrolysis-based hydrogen production technologies powered by clean energy, and source the required CO or CO2 from biomass, from industrial partners that capture and trade their CO2, or from direct air capture (DAC). Finally, a company chooses to fully outsource its hydrogen and CO and CO2 sources by switching to a merchant model, whereby it no longer produces the hydrogen it consumes.[64] This last business model implies a pivot to an import-dependent hub type if the new hydrogen supply is located outside the hub.

Among the three transition pathways, adding carbon capture units to existing production facilities presents the lowest barrier. The companies choosing this path for transformation maintain their feedstocks and contractual supply frameworks for natural gas, but they must address long-term supply risks for fossil fuels. To fully align this transition pathway with climate objectives, the electricity needed to power the CCUS assets must come from clean energy sources, feature a high capture rate (>95%), and use natural gas with very low upstream methane emissions. Excess carbon emissions that are not absorbed within the hub must also be transported to external carbon sinks. From a carbon emissions perspective, upstream gas methane emissions must also be considered because, when unchecked, they can negatively affect the overall carbon intensity of the hydrogen being produced. In regions with increasingly strict regulation and oversight of gas leakage and accounting for carbon emissions, this business model consequently entails regulatory and pricing risks. However, this transition pathway also allows for more controlled production patterns, and does not require the level of production flexibility needed to deal with intermittent renewable power sources. For an extensive overview of the transition overview, see Figure 8.

Companies operating in self-sufficient hubs may opt to produce hydrogen for their own consumption, using electrolysis. This comes with additional investments in electrolyzer capacities, grid connections, and water treatment and/or desalination units. It also requires the adoption of measures to deal with the volatility of the renewable energy used to produce renewable hydrogen: adoption of flexible production processes or use of excess power to overproduce renewable hydrogen in combination

Figure 7: Value-chain coverage of hydrogen demand hubs



with storage, mass balancing, or additional hydrogen purchases through a portfolio approach.[65] Additionally, carbon feedstocks must be secured—ideally within the hub— through collaboration with nearby industries sequestering CO_2 such as cement or lime production sites. All these additional requirements suggest higher transition costs are involved in switching to electrolysis-based technologies when compared to the CCUS-based approach, particularly if increasing carbon pricing for residual emissions in CCUS are not contemplated.

Companies that add CCUS and companies that adopt electrolysis-based hydrogen production must engage in local coordination and rely on short-distance infrastructure within the hub to succeed.

The transformative investments outlined above that are needed in self-sufficient hubs would benefit from CAPEX and OPEX support measures designed to address key cost drivers and infrastructure needs. Companies embracing CCUS to transition, for example, could benefit from CAPEX support for the build-out of CCUS facilities, and from OPEX support covering the additional power needed to run CCUS assets. Companies willing to switch to electrolysis-based hydrogen-producing technologies could benefit from CAPEX support for the build-out of renewable energy capacity, electrolyzers, water facilities, and short-distance infrastructure. They could also benefit from OPEX support covering the cost of carbon feedstocks.

Leveraging existing expertise on producing hydrogen for own consumption—captive procurement —means that self-sufficient hubs may develop faster than import-dependent hubs. Close proximity of supply and demand also allows for reduced infrastructure needs and thus infrastructure development costs. The involvement of the full value chain within self-sufficient hubs allows for improved coordination, fosters research and development of integrated solutions, and enhances control of the timelines regarding project development.

Figure 8: Business models of power-to-x (PtX) production, based on Frankfurt School of Finance and Management, Planet Power Finance, and Perspectives Climate Group (2023) with added carbon flows

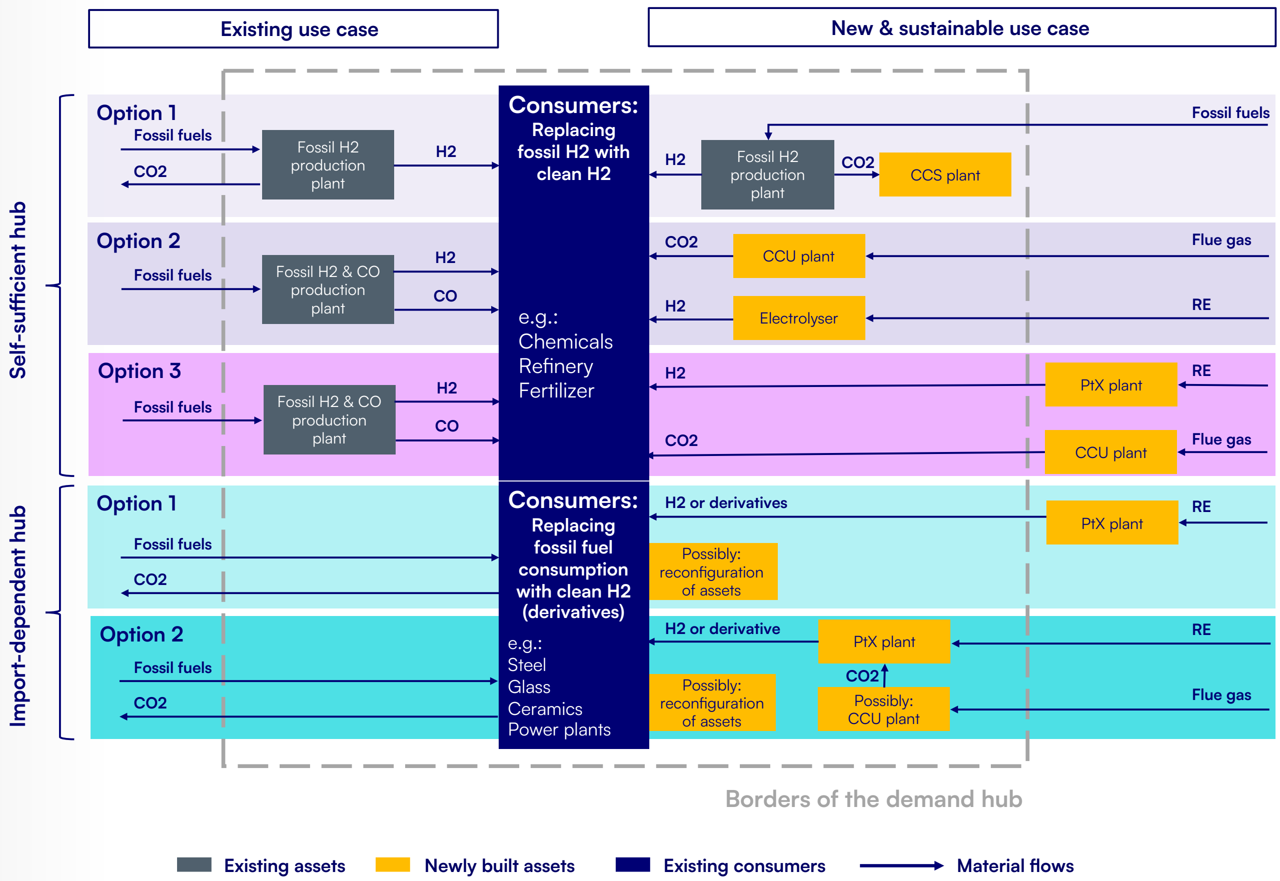


IMAGE CREDIT: MEDIA SROCK / ADOBE STOCK

Import-dependent hubs

Import-dependent hubs import most of the hydrogen (derivatives) they consume, and their participants have experience in trading these molecules. This hub type principally consists of locations with limited local ability to supply clean hydrogen (derivatives) at the required scale for local demand. A good example thereof are traditional industrial clusters in the hinterland that are reliant on unabated fossil fuels and are currently seeking to redesign their production processes to achieve carbon-neutral production.[66] The challenge here is to find cost-efficient ways to replace existing processes with new processes that use clean hydrogen (derivatives), while ensuring clean hydrogen supply through imports.

Industries that introduce clean hydrogen (derivatives) for the first time encounter different cost drivers and must deal with limited existing experience working with these molecules. For some industries (such as steelmaking, non-ferrous metals processing, glass, and ceramics) the main challenges faced are securing sufficient supplies of clean hydrogen and mobilizing CAPEX for reconfiguring their industrial production assets so they can handle a different input molecule. Reconfiguration may include minor exchanges of valves or major replacements of blast furnaces or turbines. If the conventional production facilities have reached the end of their life cycle and need replacement, reinvestment costs will be lower. Nevertheless, a major investment is necessary in midstream infrastructure delivering clean hydrogen (derivatives) supplies to the import-dependent hubs. Alternatively, companies may endeavor to avoid depending solely on imports and produce clean hydrogen themselves to ensure or contribute sufficient supplies, moving their business model in the direction of self-sufficient hubs.

Other companies may opt for hydrogen derivatives like synthetic natural gas (SNG, sometimes referred to as eNG to highlight the use of electrolytically produced hydrogen). SNG has the advantage that it limits the need for reinvestment in industrial plants. The synthesis of SNG from clean hydrogen and carbon sources is, however, energy intensive and may include additional operating costs, leading to a shift of internal CAPEX to future OPEX.

Solutions based on SNG rely on soundly monitored and certified open or closed loops for the carbon emissions that continue to be produced when SNG is consumed. The long-term viability of this strategy relies on a continuation of existing methane infrastructure as SNG would be blended in existing gas grids and use liquified natural gas (LNG) export, transport and import infrastructure.[67] A strategy relying on SNG thus entails an infrastructure risk and may only provide a temporary solution for offtakers if policymakers decide to decommission natural gas grids.[68] Regardless of which transformation pathway is finally selected, the relevant reference for OPEX remains the fossil fuel conventionally used by the industry.

Import-dependent hubs import most of the hydrogen (derivatives) they consume, and their participants have experience in trading these molecules.

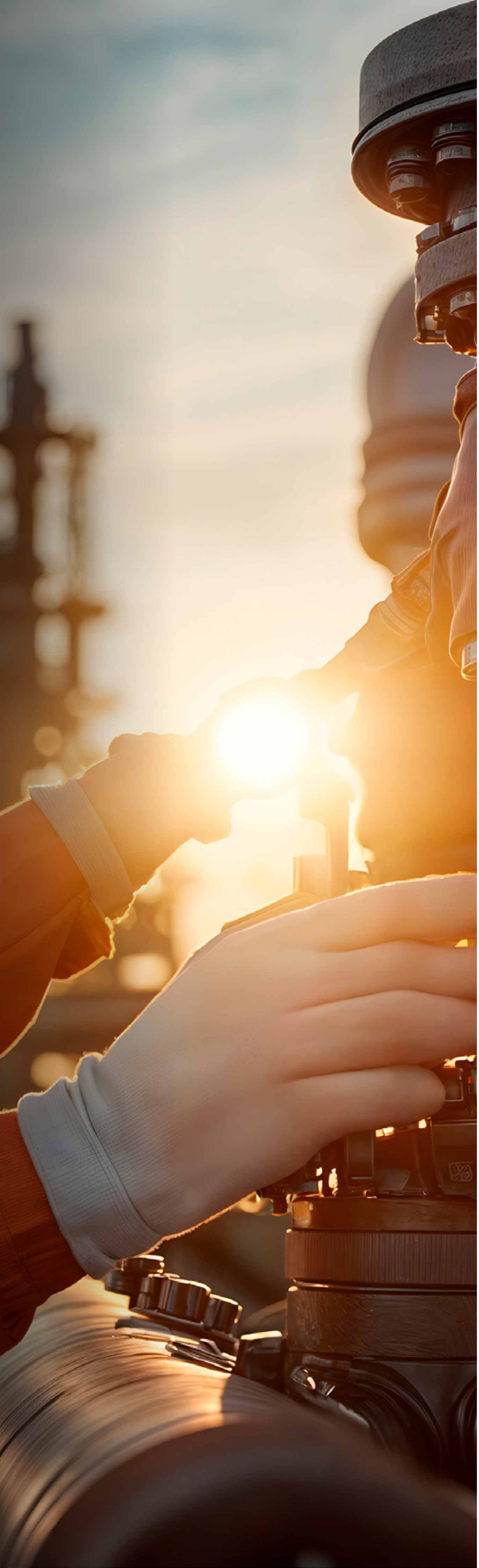
The above-detailed transformative investments needed in import-dependent hubs would benefit from CAPEX and OPEX support measures designed to address the key cost drivers and infrastructure needs. CAPEX support for the reconfiguration of industrial plants in the hub and for the mid- and long-distance infrastructure required to ensure reliable and sufficient deliveries of clean hydrogen (derivatives) from outside the hub would be critical. On the OPEX side, support to help bridge the green premium would be essential for companies to retain international competitiveness.

Import-dependent hubs help focus infrastructure development. Infrastructure can now be concentrated on the corridor from production sites to the import-dependent hub, requiring only limited local distribution networks. This hub type also aggregates demand, allowing for some economies of scale for suppliers, bringing down overall cost-of-difference. This is particularly true when industries in the hub engage in a form of joint procurement—provided the necessary anti-trust measures are in place. Procurement from different locations also reduces the need for flexible production, as supplies will be from different, potentially complementary sources. Compared to self-sufficient hubs, the effects on cost-of-difference and supply security are more indirect and require more coordination with upstream stakeholders.

Table 2: Hub-specific challenges

Challenge	Self-sufficient hubs	Import-dependent hubs
Cost-of-difference	— Significant CAPEX for (a) CCUS assets or (b) electrolysis-based production assets. — Increased OPEX for (a) electricity to run CCUS assets or (b) electricity to run electrolysis and purchasing carbon feedstock (where necessary).	— Significant CAPEX for large industrial assets to process clean hydrogen (derivatives). — Increased OPEX for clean fuel and feedstock supply.
Infrastructure access	— Building relatively short-distance infrastructure to connect companies in the hub.	— Retrofitting or building midstream pipelines to import terminals for hubs in the hinterland, and for terminals and storage facilities if the hub is in a coastal location.
Security of supply volumes	— Ensuring availability of matching supply and demand volumes within the hub.	— Ensuring access to infrastructure to participate in clean hydrogen markets.
Value-chain coordination	— Connecting supply and demand within the hub and synchronizing the timelines of both sides of the supply chain.	— Connecting demand in the hub to external supply sites and synchronizing the build-up in different locations (including internationally). — Overcoming legal restrictions for collective procurement as a hub.
Flexible production	— Coping with volatile supply from production based on renewable energy (where applicable) while storage buffer is not yet available.	
Research & development needs	— Scaling relatively new technologies. — Experimenting with new business models based on clean fuels and feedstocks.	
Ease of doing business	— Complex regulation derived from different authorities with varying requirements.	

IMAGE CREDIT: STUDIO-FI / ADOBE STOCK

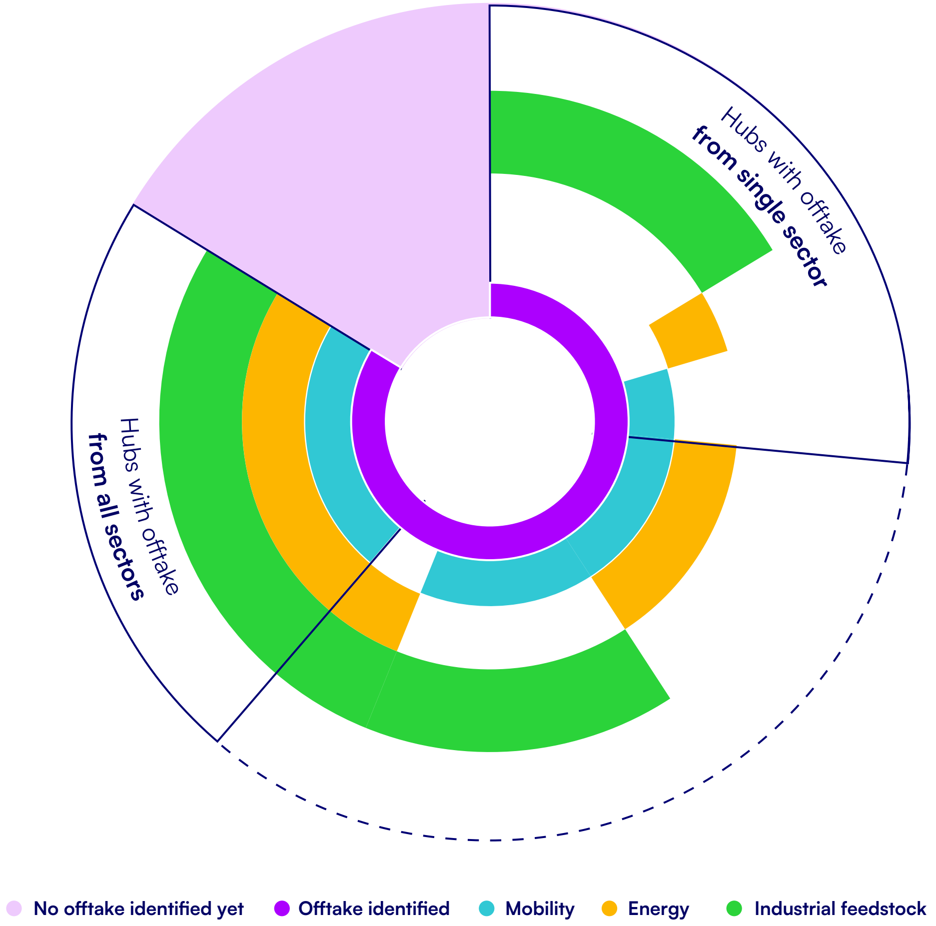


4

Case studies

Clean hydrogen hubs have been discussed for some time. The Clean Hydrogen Partnership currently lists 98 clean hydrogen hubs from around the world in their database (see Figure 9), of which 82 have stated a focus on offtake. The main targeted offtake sectors are mobility (67 hubs), power generation (45 hubs), and industrial use (48 hubs). Twenty-two hubs are seeking to promote offtake in all three sectors. At present, only six clean hydrogen hubs are operational and eleven are under construction.[69]

Figure 9: Potential offtake in ninety-eight hydrogen hubs



Source: Own depiction based on data from Clean Hydrogen Partnership (2024)

Given the early development stage of most hubs and the challenges identified in section 3 for self-sufficient and import-dependent hubs, it is relevant to assess strategies and programs designed to build and support hydrogen demand hubs. Most support programs centered on hubs have so far focused primarily on production and export of clean hydrogen (derivatives), but there are a few exceptions. Most demand-support programs do not comprehensively address the full set of demand-related challenges. A case in point is support schemes that combine multiple different programs, targeting some of the demand challenges, including the demonstration hubs in Germany, the export-oriented hubs with anchor demand in India, and the trade hubs in Rotterdam and Singapore. The US Hydrogen Hub program stands out as an exception, with the most comprehensive demand-support aspirations to date.

The next section of the report zooms in on the US Hydrogen Hub program, and this is followed by snapshots of approaches adopted in Germany, India and Singapore. These shorter case studies provide only a brief overview of these approaches, due to limited availability of precise information on individual hubs. Nevertheless, they provide information which can be used when formulating comprehensive hydrogen hub programs.

The US Hydrogen Hub program

The US Hydrogen Hub program was announced in November 2021 and represents a new approach on the part of the US administration; like many of its peers, it typically favors supply-side support measures over demand-side measures. It acknowledges the chicken-and-egg problem associated with the nascent status of the clean hydrogen economy and identifies hydrogen hubs as an important means to overcome it. By design, these hydrogen hubs are intended to minimize initial infrastructure costs and therefore drive down supply costs, while providing an important level of offtake and supply security. The program is designed to be technologically neutral and has an aspiration to cover several regions and end-use sectors. Through this approach, the US government also intends to leverage the learning effects of hydrogen ecosystems, thereby addressing research and development challenges.[70]

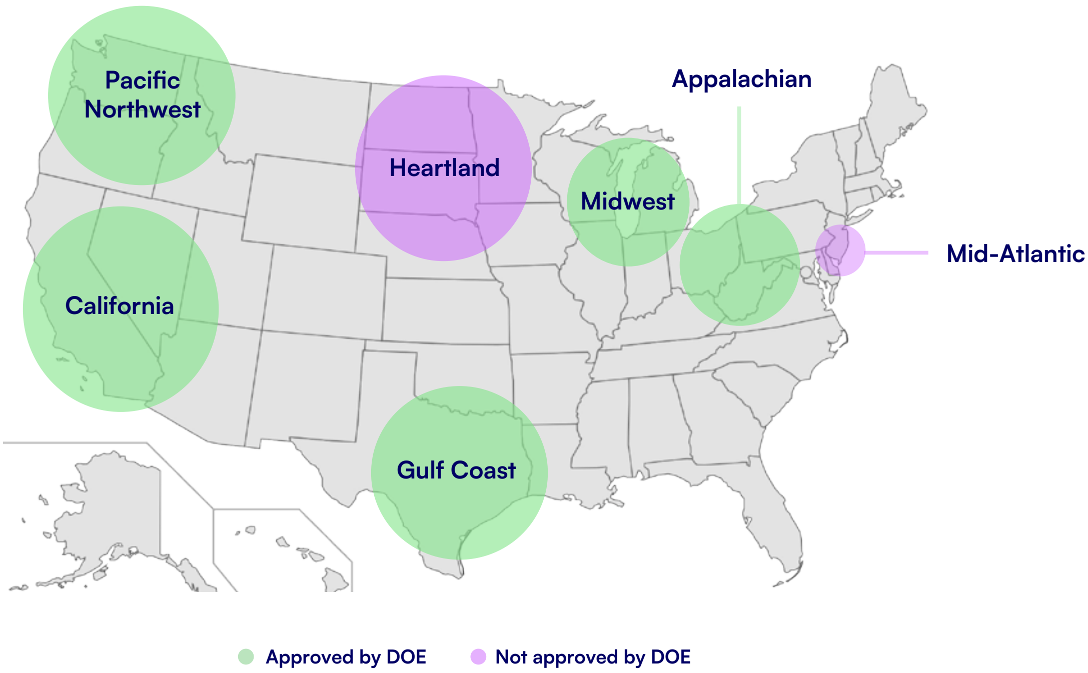
To drive down costs for the private sector and accelerate the build-up of infrastructure in the hydrogen hubs, the US government decided to allocate financial support. Initially, the budget was set to USD 9.5 billion, with USD 8 billion given to hubs directly, while reserving USD 1 billion for research in electrolysis technologies and USD 0.5 billion for research on clean hydrogen technology manufacturing and recycling. In October 2023, the US Congress later reserved USD 1 billion from the USD 8 billion via the Bipartisan Infrastructure Law of 2021 to support demand build-up in the previously selected seven hydrogen hubs distributed around the US (see Figure 10). Overall, the support budget still favors the supply and infrastructure challenges much more than the demand side challenges. Conceptually, the hubs are supposed to meet their demand with clean hydrogen produced within the hub (see Figure 10).[71] At the time of writing, the mechanism to allocate demand support is still in development and pending implementation.

US hydrogen hubs may produce and use clean hydrogen from various sources, including electrolysis using renewable energy, nuclear energy, biomass, or steam methane reformation with carbon capture and storage. Standards for clean hydrogen are implicitly linked to the Inflation Reduction Act (IRA), as stacking of support is allowed. The production side of the equation is also expected to be compatible with the clean hydrogen production tax credits of paragraph 45V and 45Q of the IRA, to further reduce the cost-of-difference for companies. As detailed regulations for emission accounting on the IRA are still pending, some projects face delays. The federal government has made a point of ensuring that plans for additional community benefits, that double down on local value creation, are implemented in each hub. Community benefits may include, inter alia, career development measures, workforce training, and apprenticeship programs. As the regulatory agency in charge, the US DOE retains some control over the progress of each hub, even after the final support decision.[72]

The Office of Energy Efficiency and Renewable Energy has also built the H2 Matchmaker, a platform that supports suppliers, infrastructure providers and offtakers in finding regional business partners.[73] This platform is intended to assist value-chain coordination within the hubs, which is critical since some hubs cover areas as large as small countries. For example, in the California Hydrogen Hub, the sites that are furthest apart are as distant to each other as Berlin is to Budapest. Although the DOE considers the hubs as a means to limit infrastructure needs through proximity, it is unclear how this will translate in view of the scale of some of the hubs being considered.

Six of the seven hubs being considered intend to use a mix of different supply sources and offtakers from power generation, ammonia, refineries, steelmaking and mobility. The latter presents a major offtaker, especially in the short- to medium-term. At the time of writing, five of the seven hubs have been approved and each has entered into a support agreement, respectively, with the competent authorities: The California Hydrogen Hub (ARCHES), the

Figure 10: The seven US hydrogen hubs selected for further procedures



Source: self-illustration based on Office of Clean Energy Demonstrations (OCED) (2024)

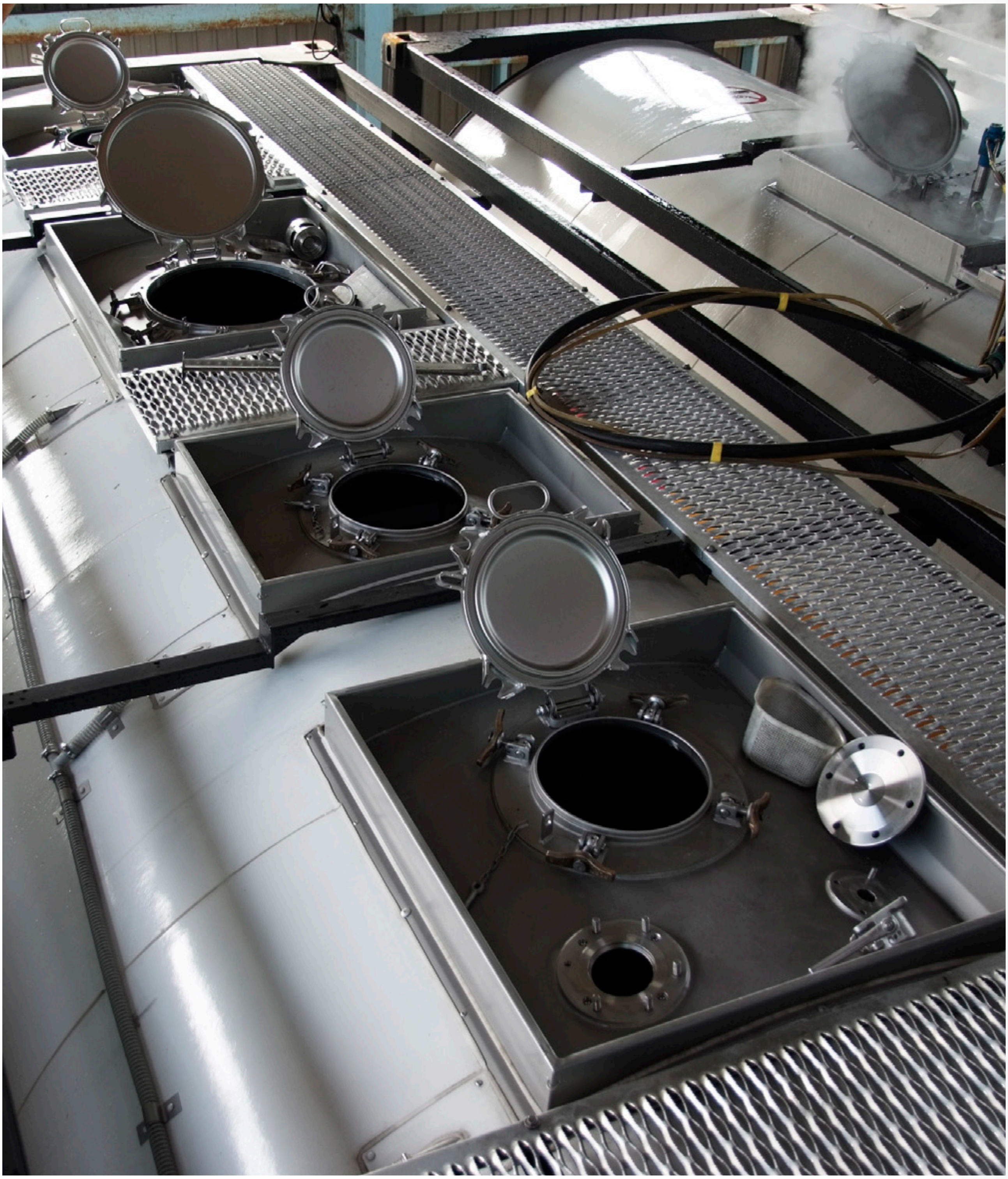


IMAGE CREDIT: KYOSHINO / ISTOCKPHOTO

Pacific Northwest Hydrogen Hub (PNWH2), the Appalachian Hydrogen Hub (ARCH2), the Gulf Coast Hub (HyVelocity), and the Midwest Hydrogen Hub (MACHH2).[74] HyVelocity and MACHH2 were approved in November 2024.

ARCHES will receive USD 1.2 billion to supply offtakers, mostly in the transport sector (public transport, heavy duty cargo, port operations), with hydrogen produced using renewable energy electrolysis and biomass.[75] PNWH2 spans the states of Washington, Oregon and Montana and has secured up to USD 1 billion. Its focus is on transportation solutions (heavy duty trucking and port operations), with offtake also including fertilizer production, power generation, and refineries. Hydrogen is to be produced using renewable-powered electrolysis.[76] ARCH2, with a support budget of USD 0.9 billion, spans the states of West Virginia, Ohio and Pennsylvania. It aims to leverage low-cost natural gas in combination with CCUS technologies to produce clean hydrogen for a network of refueling stations.[77]

Table 3: Classification of US hydrogen hubs in a supply-use case matrix

	Existing use	New use
Electrolysis-based hydrogen production	HH2H MACHH2	ARCHES PNWH2 MACH2 MACHH2
SMR/ATR-based hydrogen production with CCUS	HyVelocity H2Hub ARCH2	HyVelocity H2Hub ARCH2

The remaining four proposed hubs have broader scope in terms of the envisaged offtakers. In the Mid-Atlantic Hydrogen Hub (MACH2, USD 0.8 billion) located in Pennsylvania, Delaware and New Jersey, co-generation of heat and power, as well as industrial process heat, play an important role besides transport. The Heartland Hydrogen Hub (HH2H, USD 0.9 billion) in Minnesota, North Dakota and South Dakota is focusing on decarbonizing fertilizer production. The Midwest Hydrogen Hub (MACHH2, USD 1 billion) in Illinois, Indiana and Michigan targets steelmaking, glass production, refineries, power generation and e-fuel production, thus combining both existing and future users of clean hydrogen (derivatives). Finally, the Gulf Coast Hydrogen Hub (HyVelocity H2Hub, USD 1.2 billion) targets the replacement of traditional fossil fuel-based hydrogen supply for its petrochemical industries and fertilizer production, besides heavy-duty trucking.

The hubs participating in the US Hydrogen Hubs program are all self-sufficient hubs, featuring industries with different use cases and business cases. The California Hub (ARCHES), the Pacific Northwest Hub (PNWH2), and the Mid-Atlantic Hub (MACH2) combine electrolysis technologies and offtakers with new uses—a combination that would be expected in import-dependent settings, as per the analysis in this report. The Gulf Coast Hub (HyVelocity H2) and the Appalachian Hub (ARCH2) use steam methane reforming (SMR)/autothermal reforming (ATR) production technologies with CCUS to supply both existing and new uses of clean hydrogen, while MACHH2 uses electrolysis-based production to do the same. Finally, the Heartland Hydrogen Hub (HH2H) targets existing uses with electrolysis-based supply (compare Table 3). The variety of set-ups is enhanced by the large area covered by the US hydrogen hubs that span distances that resemble, or are equivalent to, smaller countries. This illustrates that the hydrogen hub typology developed in this report does not grasp the reality in full; but it does provide a useful way to structure/understand hubs.

The scope of the US Hydrogen Hub program is to support investments by producers, infrastructure companies, and offtakers. Financing is primarily given to support supply and infrastructure, as indicated by the ratio of general hub support (USD 7 billion) to direct support on the demand side (USD 1 billion). Matching supply and demand within each hub is nevertheless a priority, as it will contribute to supply chain coordination. Several of the hubs also see demand as an anchor to create a local ecosystem

The full effect of the US Hydrogen Hub program will only be seen once the demand-side support mechanism is fully operational.

beneficial to the development of hydrogen expertise in the regions. A few hubs plan to export clean hydrogen and derivatives to Europe, Japan, and other locations that have energy-intensive industrial production.[78] It is notable that the first hubs that were able to strike an agreement with the relevant competent authority strongly featured offtake in the transport sector, which is expected to have a higher willingness to pay (WtP) than industrial offtake. In a way, this suggests that the hubs are initially useful to bring together and synchronize suppliers and offtakers with the highest WtP. The full effect of the US Hydrogen Hub program will only be seen, however, once the demand-side support mechanism is fully operational.

CASE STUDY: GERMANY

Germany is expected to become one of the most important offtake countries of clean hydrogen, especially in energy-intensive industries. Particularly, its large chemical and steel sectors count on clean hydrogen as a means to reach net-zero emissions. These industries are exposed to cost-sensitive international competition, which underscores the importance of addressing the cost-of-difference and securing reliable supplies. The densely populated country has, however, acknowledged in its 2024 hydrogen import strategy that it will need to import about two thirds of the clean hydrogen it needs.[79] Germany has several large industrial clusters, including chemical and industrial parks that allow for focused development of clean hydrogen hubs.

The German Federal Government has used several instruments to address the challenges associated with its clean hydrogen targets. These include a mandate for transmission system operators to develop a core hydrogen network and promote infrastructure access through carbon-contracts-for-difference (CCfDs) for individual offtakers or consortia and through funding tenders using the H2Global mechanism to address the cost-of-difference. The H2Global Pilot Auction tendered hydrogen purchase agreements for import projects from outside the EU, with first results in July 2024. The H2Global Hydrogen Sales Agreements tender is scheduled for 2026.[80] A new H2Global tender is currently in preparation and will likely address security of supply through dedicated regional lots, which will allow for a diversification of countries of origin for renewable hydrogen (derivatives).

As for hydrogen hub schemes, the German government has yet to develop one. What it currently has are the so-called *reallabore* ("living labs") that are strongly focused on supporting research and development, including demonstration projects at scale. As part of the concept, *reallabore* are intended to make use of experimental regulation, although at the time of writing the implementation of the legal framework for this is pending.[81] Six of the *reallabore* have a hydrogen focus, although not every *reallabor* can be considered a hub.[82] Use cases in current *reallabor* hubs include co-firing and blending in industrial blast furnaces (including copper production—*Norddeutsches Reallabor*), building a direct reduction of iron (DRI) unit at pilot scale *(H2Stahl)*, methanol synthesis and e-fuel production (*Westküste 100*), replacing fossil fuel-based hydrogen production in a refinery (*Energiepark Bad Lauchstädt*), and heavy-duty and public transport (*Norddeutsches Reallabor*). *Westküste100* supply-side hub was terminated in 2023, due to a negative economic outlook.[83]

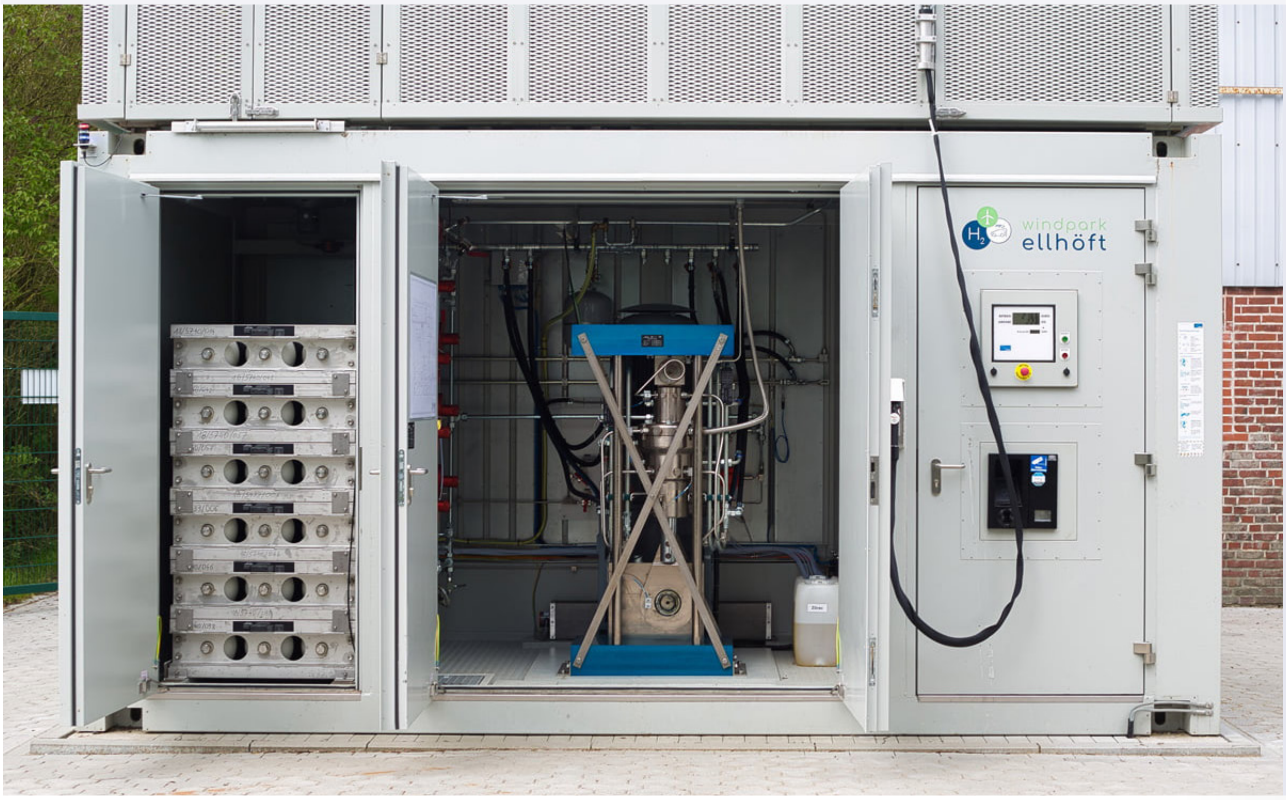


IMAGE CREDIT: NORDDEUTSCHES REALLABOR

CASE STUDY: INDIA

India is an emerging market with fast-growing energy demand. Power generation, steel production, and fertilizer production for the country's large agriculture sector contribute to increasing greenhouse gas (GHG) emissions. The Indian Federal Government has taken on the challenge posed by climate change and announced eight missions, including the National Green Hydrogen Mission in 2023. This mission not only foresees domestic hydrogen production matching demand in hard-to-abate industries, but also aims for exports of renewable hydrogen (derivatives).[84]

In pursuit of the National Green Hydrogen Mission, India has started to develop a regulatory framework for certification of renewable hydrogen projects and has announced the introduction of a renewable hydrogen quota for select industries. The quota is intended to increase over time and ensure the development of demand, which is currently not keeping pace with the other parts of the value chain. Additionally, demand is expected to be aggregated through competitive auctions for renewable hydrogen and ammonia. The government also wants to employ about USD 47 million in 2025 and 2026 to support infrastructure development in at least two renewable hydrogen hubs and about USD 117 million to support demand projects.[85] To help industries deal with the cost-of-difference, the Indian government has announced the implementation of a contract-for-difference (CfD) scheme for power generation using renewable hydrogen, or its derivatives, with details pending at the time of writing.[86]

The India Hydrogen Alliance (IH2A) sent a proposal to the Indian government containing 25 renewable hydrogen projects of national relevance that would be established in five hydrogen hubs. IH2A is an industry-led coalition aiming to establish a renewable hydrogen economy through industry and public-private partnerships. The goal of the proposal is to simultaneously ramp-up renewable hydrogen production and, importantly, industrial offtake. Consequently, 12 of the 25 projects pertain to offtake in the fertilizer, chemicals and steel sectors that would consume 23,000 t of renewable hydrogen annually (compared to an estimated demand of around eight Mt). Companies involved would receive a total of USD 360 million by 2025, mostly in the form of CAPEX support,[87] which was later updated to USD 1 billion, including the engagement of the European Investment Bank.[88] Most proposed hubs combine a port and a hinterland location with the long-term perspective to create further links among the different hubs. Besides the industrial offtake in different industries, potential offtake includes heavy-duty solutions, e.g. for coastal shipping. The concept includes the establishment of a National H2 Development Corporation as a public-private, non-profit enterprise that will coordinate activities in the hubs and align them with other national programs.[89]

IMAGE CREDIT: HARI MAHIDHAR

CASE STUDY: SINGAPORE

Singapore is emerging as a significant hydrogen import and demand hub. According to Singapore's National Hydrogen Strategy, the country aims to achieve net-zero emissions by 2050 and envisages clean hydrogen covering half of its projected electricity demand in the same year. Singapore's confined geography as a city-state, however, limits the potential for local energy production, leading to a high reliance on energy imports.

Singapore has two key seaports—Jurong Island Port and the Port of Singapore—and is currently developing a third—Tuas Port—that is set to become the world's largest fully automated terminal with a handling capacity of 65 million twenty-foot equivalent units (TEUs) per annum. The shipping sector is critical to Singapore's economy, contributing approximately seven percent to the national GDP,[90] but at the same it is a significant source of the country's GHG emissions. Hence the maritime sector offers an immense opportunity to decarbonize Singapore's economy and reduce emissions to mitigate climate change. To this end, the government of Singapore and, in particular, the Maritime and Port Authority of Singapore (MPA) are leading efforts to bring emissions from the shipping sector to net-zero by 2050 and have been working on the Maritime Singapore Green Initiative. Under this initiative, the Green Ship Program (GSP) serves as a framework (foundation/basis) for stimulating demand for clean hydrogen and its derivatives to cater for the shipping and refinery sectors and to promote technical and economic research and development.

As part of the GSP, the MPA has already supported the execution of at least two successful ship-to-ship bio-methanol-based fuel bunkering operations, as well as a liquid ammonia fuel bunkering operation for a dual-fueled vessel. Following successful trials over the past two years, the MPA issued calls for expressions of interest (EOIs) for fuel providers to initiate the establishment of supply chains at Singapore's ports. The MPA received, respectively, fifty and twenty-six EOIs to provide methanol and ammonia at its ports.[91] Following the assessment of the proposed projects, the MPA will award one project developer with a contract for ammonia in early 2025, including corresponding electricity generation and ship fuel bunkering capacities on Jurong island. To support security of supply, Singapore has also signed memoranda of understanding with Australia as a key supplier of clean hydrogen (derivates) to Singapore.[92] Neighboring countries (Indonesia and Malaysia) are set to remain key suppliers of clean energy to Singapore.

IMAGE CREDIT: NEOPHOTO / ISTOCKPHOTO

Singapore is using its status as a major flagging country and trade hub to incentivize demand for clean fuel in the shipping sector. Based on the level of emissions, the city-state provides a two-stage incentive centered on the distinction of low-carbon and zero-emission fuels. The former entail liquified natural gas (LNG) and fuels with lower emissions, including conventionally produced methanol and ethanol; while clean ammonia, bio- and e-methanol, as well as clean hydrogen, count as zero-carbon fuels. First, shipping companies registering new ships sailing on low-carbon fuels with Singapore receive a 75% reduction on initial registration fees (IRF) for their ships, and subsequently a 50% reduction on their annual tonnage tax (ATT). Second, if ships sail on zero-carbon fuels as a primary fuel, they benefit from a full waiver regarding both IRF and ATT.[93] Furthermore, the MPA will also require all new harbor craft in its ports to be either fully electric or capable of running fully on biofuel or hydrogen.[94] These measures will lead to instigation, as well as aggregation, of demand for clean hydrogen and its derivates, in particular ammonia and methanol, in this case.

Summary

The US Hydrogen Hub program falls conceptually into the self-sufficient hubs camp. Some US hubs are still in negotiation with the DOE's existing target industries (such as petrochemical industries and fertilizer production), which traditionally produce hydrogen for their own consumption, as well as with the steel, glass and power generation sectors. The US hubs that have already reached agreement with the DOE are targeting demand from transport solutions instead. This is likely due to the smaller cost difference and lower volumes required in the transport sector.

The short case studies paint a diverse picture of approaches to building clean hydrogen hubs. In general, the measures adopted in Germany, India and Singapore are still in an early stage of development. Except for Singapore, where most development approaches are assuming a hub-like form due to its nature as a city-state, the creation of clean hydrogen demand hubs is not the primary focus of the political strategy. India and Germany have key industries in mind to anchor offtake, but the approaches are quite distinct: India has recently shifted to production and exports, while Germany is focusing on experimentation and testing. In Singapore, the focus is on the development of a trade hub for clean hydrogen and its derivatives, and the transformation of the shipping sector.

IMAGE CREDIT: AEROVISTA LUCHTFOTOGRAFIE / SHUTTERSTOCK

IMAGE CREDIT: PIDJOE / ISTOCKPHOTO

5

Recommendations

Hydrogen demand hubs can help clear the bottleneck of hydrogen demand by facilitating offtake commitments that in turn can unleash the clean hydrogen (derivatives) value chain. When designing support schemes targeting hubs, policymakers should carefully consider the dominant use cases and tailor support accordingly. Table 4 summarizes key recommendations for policymakers developing support schemes for self-sufficient and import-dependent hubs, which address the six main challenges offtakers face: cost-of-difference, infrastructure access, certainty of supply volumes, value-chain coordination, need for flexible production, and high research and development requirements.

Table 4: Overview of recommendations for hydrogen demand hubs

Challenge	Self-sufficient hubs	Import-dependent hubs
Cost-of-difference	Support **CAPEX** for (a) CCUS assets in the hub (b) build-up of captive renewable energy and electrolysis capacities	Support **CAPEX** for asset reconfigurations of industrial offtakers
	Support **OPEX** for (a) additional power cost for operating CCUS units (b) additional cost of procuring renewable energy from the grid/power purchase agreements (PPAs) for captive electrolysis-based hydrogen production and sourcing of sustainable carbon (where applicable)	Support **OPEX** for additional cost of procuring clean hydrogen and use reference to the fossil fuel or feedstock previously used by the industry
Infrastructure access	Support **CAPEX** for short-distance pipeline(s) within the hub.	Support **CAPEX** for retrofitting or building midstream pipelines to import terminals for hubs in the hinterland, and for terminals and storage facilities if the hub is in a coastal location.
Security of supply volumes	Monitor supply within the hub and incentivize additional local production if expected volumes do not match demand	Focus on development of infrastructure connecting the hub to domestic or international production sites outside the hub
Value-chain coordination	Build matchmaking platforms for the hub enabling within-hub supply-chains	Aid import of clean hydrogen (derivatives) through cooperation agreements with net-exporting countries Enable collective procurement strategies for hubs through auctions and (where necessary) adjustments of anti-trust law to allow such coordination
Flexible production	Include fallback options within support mechanisms to allow companies to react to varying availability of clean hydrogen (derivatives) during the market ramp-up.	
Research & development needs	Make use of experimental regulation in the style of reallabor/living-lab approaches to foster at-scale research and development of new clean business models. Their success hinges on sufficiently long timeframes for the experiment and an effective ruling regarding the adaptation of regulation after the end of the living-lab phase.	
Ease of doing business	Create one-stop-shops for companies in the hubs to streamline permitting and other administrative procedures.	

The rationale for the recommendations on how to deal with offtakers' most relevant challenges—cost-of-difference and infrastructure access—warrant some explanation. CAPEX support should be used to transform existing procurement strategies, allowing for the efficient use of existing expertise. Self-sufficient hubs, therefore, should use CAPEX support for the installation of CCUS and/or the assets needed to establish captive procurement of renewable hydrogen (electrolyzers and renewable energy purchase). Import-dependent hubs should use CAPEX support instead to reconfigure industrial assets, so they can consume hydrogen, and to build the infrastructure—terminals, pipelines, etc.—needed to connect the hub to production sites.

OPEX support should address the cost-of-difference associated with the dominant business model of the hub. For self-sufficient hubs this means using OPEX to provide an incentive to produce and self-consume clean hydrogen or to build within-hub supply chains. To this end, OPEX support should cover either the operational cost-of-difference for power used to operate CCUS technology and/or the cost-of-difference for sourcing sustainable carbon if carbon capture is not a (preferred) option. For import-dependent hubs, OPEX support should cover the cost-of-difference between fossil fuels and clean hydrogen (derivatives) to incentivize the purchase of the latter.

Policymakers preparing instruments to cover cost-of-difference should account for different industries'

IMAGE CREDIT: AVIGATORPHOTOGRAPHER / ISTOCKPHOTO

willingness to pay (WtP). WtP varies both regionally, sectorally, and in relation to exposure to international competition, with the heavy-duty road cargo sector in the US having higher WtP, along with chemical and steel sector offtakers in the EU, for example.

To promote infrastructure access, policymakers should concentrate on the type of infrastructure that is most relevant for the type of hub in question. Self-sufficient hubs, first and foremost, need short-distance pipelines connecting production and offtake sites within the hub, allowing for the transition from existing use cases of unabated fossil fuel-based hydrogen production to clean hydrogen. Import-dependent hubs, instead, need midstream pipelines that connect the hub to major trade hubs or clean hydrogen production hubs. An import-dependent hub that is a port may instead give preference to import terminals.

Import-dependent hubs require more extensive coordination than self-sufficient hubs since they require costly long-distance infrastructure and the establishment of import connections. Self-sufficient hubs generate synergies more easily, particularly when industrial clusters feature industries already using hydrogen today (chemicals, fertilizer production, refineries) and boast sufficient resources and space to develop clean hydrogen hubs. However, even in self-sufficient hubs, producers and consumers of clean hydrogen (derivatives) need to be mobilized, requiring coordination.

Besides the above recommendations for hydrogen demand hubs, there are some general improvements to conditions for hydrogen offtakers that have not been analyzed in depth in this report, but have been extensively discussed in the literature. Such general policies and measures—briefly outlined in Table 5—will improve the overall quality of the technoeconomic environment and thus have a reinforcing effect on the natural tendency of industries to form regional clusters.

Policymakers preparing instruments to cover cost-of-difference should account for different industries' willingness to pay (WtP). WtP varies both regionally, sectorally, and in relation to exposure to international competition.

Table 5: General improvements to the conditions for offtakers of clean hydrogen and its derivatives

Challenge	Suggested policy measure
Cost-of-difference	Increase carbon pricing to improve the competitive viability of clean fuels and feedstocks Decrease fossil fuels' subsidies to improve the competitiveness of clean fuels and feedstocks
Infrastructure access	Provide an ownership unbundling framework for natural gas grid operators that incentivizes retrofitting. Develop a hydrogen grid development plan in coordination with relevant industries. Make use of infrastructure support instruments to bridge the infrastructure investment gap, such as the ones assessed in H2Global's report, "Bridging the gap: Mobilizing investments in hydrogen infrastructure".
Security of supply volumes, value-chain coordination, and flexible production	Design regulation for energy-intensive industries and offtakers in a way that encourages flexible consumption of clean fuels and feedstocks over steady offtake. Enable mass balancing in certification regulation. For business models based on self-production and consumption of clean fuels and feedstocks based on electrolysis, reduce grid fees for flexible electricity offtake from the grid. Consider mandates and quotas for additional long-term security of demand volumes to provide certainty to suppliers.
Supply chain development	Encourage the establishment and expansion of hydrogen supply chains, fostering collaboration among producers, distributors, and end users to ensure efficiency and scalability.
Research & development needs	Expand general research and development support for companies, including tax deduction and research project funds.
Ease of doing business	Accelerate permitting procedures

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