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Shoring up demand: The key instruments supporting clean hydrogen demand build-up

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H2Global Foundation

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Glossary

Term	Definition
ATR	Autothermal reforming.
BF-BOF	Blast Furnace basic oxygen steelmaking.
CAPEX	Capital expenditure, i.e., funds used by a company to acquire, upgrade, and maintain physical assets.
CBAM	Carbon Border Adjustment Mechanism.
CCfD	Carbon-contract-for-difference.
CCUS	Carbon capture, utilization, and storage.
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 emissions from various greenhouse gases based upon their global warming potential.
CoD	Cost-of-difference, the gap between conventional and clean production cost.
DOE	Department of Energy, United States.
DRI	Direct reduction of iron.
EAF	Electric arc furnace.
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act), Germany.
E-fuels	Synthetic fuels produced by the conversion of electrical energy into chemical energy, often produced using renewable energy sources.
ETS	Emissions Trading System.
EHB	European Hydrogen Bank.
e-SAF	Sustainable aviation fuel, produced from renewable hydrogen.
ESG	Environmental, social, and governance standards.
FCEV	Fuel Cell Electric Vehicle.
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.
GDP	Gross Domestic Product.

Term	Definition
GHG	Greenhouse gas.
H2	Hydrogen.
ICAO	International Civil Aviation Organization.
IMO	International Maritime Organization.
IPCEI	Important Projects of Common European Interest.
IRA	Inflation Reduction Act.
LH2	Liquid hydrogen.
LCFS	Low Carbon Fuel Standard Initiative.
LCOH	Levelized cost of hydrogen.
LOHC	Liquid organic hydrogen carrier: compound that can reversibly absorb and release hydrogen, enabling compact hydrogen storage and transportation.
MeOH	Methanol.
MoU	Memorandum of Understanding.
OPEX	Operational expenditure.
PEM	Proton exchange membrane, a technology used in a type of electrolyzer.
PtX	Power-to-X.
RED III	Third Renewable Energy Directive in the EU.
RFNBO	Renewable Fuels of Non-Biological Origin.
SECI	Solar Energy Corporation of India.
SABA	Sustainable Aviation Buyers Alliance.
SAFc	Sustainable Aviation Fuel certificates.
SLO	Social License to Operate.
SME	Small and medium-sized enterprise.
SMR	Steam methane reforming.
SNG	Synthetic natural gas.
WtP	Willingness-to-pay.
ZEMBA	Zero Emission Maritime Buyers Alliance.
ZEV	Zero-emission vehicle.

Foreword

H2Global's core mission is to accelerate the emergence of markets for clean hydrogen and other low-emission fuels worldwide. We achieve this by developing a unique double-sided auction mechanism, engaging governments and industry leaders globally, and conducting in-depth research. Our work is already making an impact: through our intermediary, Hintco, we've launched the bidding process for a second tender to purchase renewable hydrogen and its derivatives, backed by EUR 2.35 billion from the German federal government. Recently, we opened a new global tender for renewable hydrogen, a EUR 567 million initiative financed by Germany and the Netherlands, and reopened the EUR 437.5 million pilot methanol lot. Additional auctions using the H2Global mechanism are currently being prepared in cooperation with the governments of Germany, Canada, and Australia.

In 2024, our team published the first round of research reports as part of the H2Global Knowledge Hub Program, which is financially supported by a research grant issued by the German Federal Ministry for Research, Technology and Space. We are proud to continue this series in 2025 by confronting three of the biggest challenges facing the clean hydrogen economy: bridging the last-mile infrastructure gap, closing the demand shortfall, and building public trust. These reports were created with the valuable insights from our 74 private sector supporters.

After years of exciting project announcements, 2025 has been a bit of a reality check. Many clean hydrogen projects are struggling to secure the offtake commitments they need to become bankable. Meanwhile, end users face their own set of risks when adopting clean hydrogen, including increased costs, ensuring a reliable supply, and finding a market for the clean products they produce using hydrogen. Current political developments are also not conducive to achieving the necessary regulatory and planning security. To truly decarbonize hard-to-abate sectors, we need to shore up demand and unlock a new dynamic for clean hydrogen projects.

This report, "Shoring up demand: Identifying effective instruments that support clean hydrogen demand build-up," dives into these risks and other challenges for offtakers. It assesses which support instruments policymakers can use most effectively to help mitigate these challenges and create the necessary regulatory and planning security. A big part of supply security is having effective infrastructure in place for physical deliveries.

"The global clean hydrogen industry has reached USD 110 billion in committed capital across 510 projects past FID. However, further growth hinges on unlocking demand. This report lays out the range of tools available to policymakers — an important and timely contribution to this key effort."

Ivana Jemelkova

CEO

Hydrogen Council

The infrastructure needs and gaps in Northwestern Europe and East Asia are the subject of our second report, "From ports to offtakers: Scaling last-mile hydrogen infrastructure". And beyond the physical requirements, all clean hydrogen projects must earn and maintain support from their host communities. We discuss this in our third report this year, "Matter of trust: Securing a Social License to Operate for clean hydrogen projects".

Executive summary

Effective hydrogen demand support: Shoring up a committed offtake anchor for the clean hydrogen industry

Clean hydrogen is poised to be a cornerstone of global decarbonization efforts, particularly in hard-to-abate sectors. While committed long-term offtake is essential for clean hydrogen supply projects to become bankable, the adoption of these technologies by end users presents significant commercial and political challenges. Since these challenges are unlikely to be overcome without intervention, governments must focus on demand creation to kick-start the clean hydrogen economy. The selection of instruments is critical, especially since many governments operate under constrained budgets. Policymakers have a diverse toolkit at their disposal, ranging from instruments with a broad-ranging effect—such as quotas, mandates, and variations of carbon pricing—to more specialized tools that can mitigate risks where broad measures are insufficient.

Policymakers must strategically combine demand support instruments to overcome political, financial, and competitive hurdles.

For this report, the H2Global team assessed thirteen key risks for potential offtakers of clean hydrogen and thirty-one demand-side instruments that could address these risks across nine hard-to-abate sectors. Based on this assessment, four risks were identified as the most critical hurdles for potential clean hydrogen offtakers:

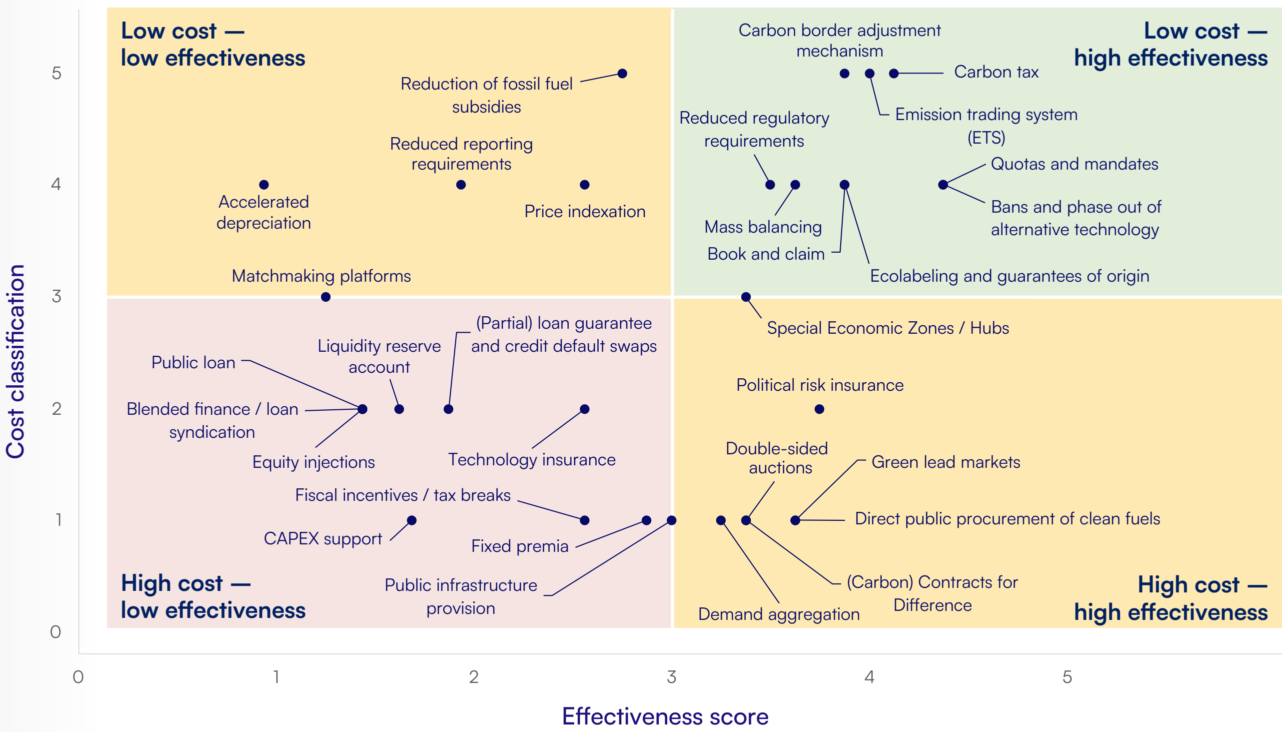
- **Price risk** is the most pervasive challenge across all sectors. An H2Global meta-study of the levelized cost of hydrogen (LCOH) and willingness-to-pay (WtP) reveals a substantial range of values for the **cost-of-difference (CoD)** ranging from 0.4 USD/kg (for U.S. steel) to 11.5 USD/kg (for European aviation), depending on the clean hydrogen production technology used.
- **Regulatory risk** derives from unclear or non-existent regulation and is often tied to levels of political certainty and support. It varies considerably across jurisdictions and sectors, tending to be lower where international institutions define the framework.
- **Supply and offtake risks** are highly interdependent and linked to external factors: supply risks depend largely on **infrastructure availability**, while offtake risks hinge on the **WtP of secondary users** for clean products.

A look at key offtake markets—U.S., Germany, and Japan—offers distinct lessons for building a resilient clean hydrogen market:

- **Political commitment is critical**: Long-term political commitment is paramount. The current situation in the U.S. highlights the vulnerability of strategies reliant on specific legislation (e.g., adjustments have been made to the Inflation Reduction Act (IRA) by the Trump administration), while Germany and Japan demonstrate the power of robust, long-term signals that guarantee price certainty (e.g., Japan's 15-year contract-for-difference and Germany's commitment to H2Global auctions until 2038).
- **Optimal policy mix**: Successful strategies combine a "stick-and-carrot" approach. Regulatory "sticks" (quotas and carbon pricing) create market pull and mitigate risks, while financial "carrots" (double-sided auctions and contracts-for-difference) bridge the CoD and build contractual connections.
- **Coherence and fragmentation**: A successful hydrogen economy requires a coherent national framework. The patchwork of federal and state efforts in the U.S. demonstrates that fragmentation creates conflicting signals and challenges such as carbon leakage.
- **Infrastructure strategy**: Infrastructure plans must be tailored to local geography and sectoral priorities. The U.S. and Japan prioritize a hub-and-spoke model to minimize infrastructure needs through concentration, while import-reliant Germany focuses on long-distance pipelines from ports to offtakers.
- **Role of private aggregation**: Private platforms such as the *Sustainable Aviation Buyers Alliance (SABA)* and *Zero Emission Maritime Buyers Alliance (ZEMBA)* are vital complements to government initiatives. They successfully aggregate demand, providing clear market signals and de-risking investments.

As effective policies come at different costs, policymakers must balance impact with fiscal constraints. The exercise presented in Figure 1 compares the effectiveness of demand-support instruments in mitigating risks against their financial impact (cost/revenue).

Figure 1: Efficiency of support instruments from a government perspective



Legend

Cost classification	**Effectiveness score**
5 revenue	Highly effective
4 negligible cost	More effective
3 administrative cost	Effective
2 potential payment to companies	Less effective
1 definitive payment to companies	Least effective

The results highlight a key policy trade-off: the most effective and financially sustainable instruments often face the greatest political hurdle. Carbon pricing (ETS/taxes) and regulatory measures (quotas/mandates), along with certification tools, are highly effective at mitigating risks while having a low or even positive financial impact for governments. These make them the most cost-efficient policy choices; however, they have not been widely adopted due to political resistance and the potential burden on consumers.

In contrast, instruments such as double-sided auctions entail a direct financial cost but are highly effective at simultaneously mitigating price and offtake risks through de-risking both sides of the market. Moreover, many tools, such as book-and-claim systems and carbon border adjustment mechanisms (CBAMs), rely on preconditions (e.g., existing certification schemes or carbon pricing), meaning they can only be deployed at a later stage of market development.

IMAGE CREDIT: ADOBE STOCK / NORDRODEN

The synthesis of this effectiveness analysis and the regional case studies suggests that policymakers must strategically combine instruments to overcome political, financial, and competitive hurdles.

Recommendations for effective hydrogen demand support

A successful clean hydrogen demand-support strategy requires policymakers to deploy a complementary set of instruments. The full set of recommendations for a robust, tailored policy mix is presented in Table 1.

Table 1: Key recommendations

Key recommendations for a strong policy mix	
Strategic approach	• Understand the **specific risk profiles** of existing industries in the country • **Start with wide-scope instruments** where possible and **use specific instruments to complement** the toolbox as needed
Wide-scope regulatory "sticks"	• Use **quotas, mandates, bans, and phase-outs** to achieve the most effective and efficient impact on offtakers • Establish sufficiently high **carbon pricing** through emissions trading systems (ETS), carbon taxes, and CBAMs
Economic "carrots"	• Deploy **double-sided auctions** to cover price risks and establish value chains by bridging the CoD • Deploy **contracts-for-difference (CfDs)** to cover price risks while alleviating liquidity pressures
De-risking and finance instruments	• Employ **(partial) loan guarantees** in sectors with specific liquidity risks to de-risk projects and provide direct access to funds
Enabling conditions	• Use **green lead markets** and direct public procurement to provide leverage on offtake risks and indirectly improve WtP • Support the creation of **clean hydrogen hubs** where industries are geographically concentrated to leverage synergies • Establish **effective guarantees of origin** and **certification schemes**, as well as **flexible systems of value-chain custody**, to reduce supply and price risks

Drawing on lessons learned from each regional case study, the following recommendations, synthesized in Table 2, are tailored to address the specific policy gaps and contextual challenges of Germany, Japan, and the U.S.

Table 2: Tailored recommendations for the case study countries

Key recommendations		
Germany	**Japan**	**United States**
• Use the new *Sondervermögen* to enhance investments in infrastructure, green lead markets, and project-specific support in the form of H2Global and *Klimaschutzverträge* (e.g., through targeted sector auctions for steel) • Employ (partial) loan guarantees to address liquidity	• Consolidate the fragmented support-instrument landscape • Scale up and expand coverage of the forthcoming nation-wide carbon-pricing system	• Provide political certainty for nascent clean hydrogen industries by maintaining existing commitments (e.g., Hydrogen Hubs program) • Prioritize the adoption of a nationwide ETS and a complementary CBAM to link regional efforts, providing consistent signals, and protecting U.S. producers/offtakers

Developing a comprehensive and effective set of instruments to support clean hydrogen demand is a complex but valuable undertaking. This report offers a framework for understanding the risk profiles of potential hydrogen users, enabling policymakers to tailor their support and unlock the full potential of clean hydrogen production.

IMAGE CREDIT: ADOBE STOCK / NORDRODEN


IMAGE CREDIT: ADOBE STOCK / DEDMITYAY

1

The demand-side imperative

Clean hydrogen is poised to be a cornerstone of global decarbonization efforts, particularly for hard-to-abate sectors.

While not a universal solution (see Figure 1), clean hydrogen and its derivatives provide decarbonization pathways where repair, reuse, and recycling approaches and technologies based on direct electrification are not viable. They are thus indispensable for industries such as steelmaking, refining, chemical production, and fertilizer manufacturing, as well as for processes requiring high-temperature heat. Clean hydrogen also offers a pathway to decarbonize international shipping, aviation, and heavy-duty land transport, and it can complement renewable energy in the power sector through seasonal storage.

Despite its pivotal role in decarbonizing end uses, public discourse often disproportionately focuses on the supply side, aligning with economic theories that prioritize supply-side policies. However, numerous analyses indicate that potential clean hydrogen suppliers struggle to secure firm offtake agreements, hindering final investment decisions (FIDs). Consequently, offtake risk has been the most significant challenge for hydrogen supply to date.[1]

As of mid-2025, project developers had announced a global total of 37 Mt/a in clean hydrogen production capacity by 2030.[2] Yet only 42% of investments in the clean hydrogen space have established a link to end-use projects, and just 2.2% of the announced supply volume has secured firm offtake agreements or integrated hydrogen use within self-consumption business models.[3] While memoranda of understanding (MoUs) account for a larger share, they still represent only a fraction of what is required to accelerate market development and meet Paris Agreement climate targets.

Figure 2: Technical deep-decarbonization options of different hard-to-abate sectors

Securing sufficient **controllable energy supply**

- Clean hydrogen
- Battery or pumped storage solutions
- Roll-out of geothermal, hydropower etc.
- Fossil-fuels with CCS

Enabling **range** or difficult **terrains** under limitations of **storage space**

- Direct electrification
- E-fuels for hard-to-electrify applications

Enabling long **range** under **weight and storage space** limitations

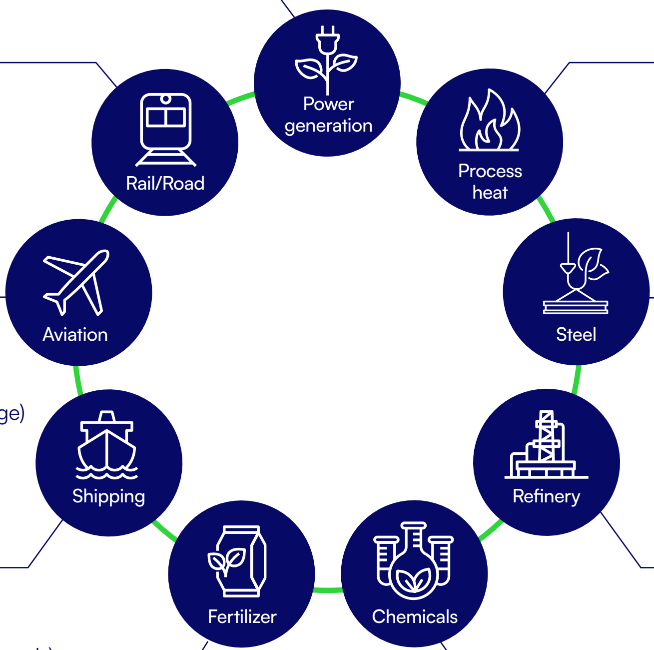
- Sustainable aviation fuels
- Hydrogen fuel cells (short- to medium- range)
- Direct electrification (short range)

Enabling long **range** under **storage space** limitations

- Sustainable shipping fuels
- Wind-assisted propulsion
- Direct electrification (smaller vessels)
- Fossil-fuels with onboard CCS

Replacing a molecular **feedstock**

- Clean hydrogen feedstock
- Use of manure and other biogenic fertilizers
- Fossil fuels with CCS



Producing **high-temperature** profiles

- Clean hydrogen
- Direct electrification, biomass
- Fossil fuels with CCS

Replacing the **reduction** agent and producing **high temperatures**

- Direct reduction of iron (DRI) with clean hydrogen
- Recycling combined with electrification
- Fossil fuels with CCS

Replacing a molecular **feedstock**

- Clean hydrogen feedstock with sustainable carbon feedstock
- Fossil fuels with CCS

Replacing a molecular **feedstock**

- Clean hydrogen feedstock with sustainable carbon feedstock
- Fossil fuels with CCS

Therefore, shifting focus to the demand side is imperative. Potential offtakers for clean hydrogen and its derivatives generally fall into two categories:[4]

- Substitution cases: **Current users** of unabated fossil fuel-based hydrogen (mostly refineries, and chemical and fertilizer industries)

- Introduction cases: **New users** of hydrogen and its derivatives (including steelmaking, glass manufacturing, shipping, aviation, etc.)

Both groups find themselves in a **first-mover** position within the nascent clean hydrogen market. For existing hydrogen users, the challenge lies in replacing conventional hydrogen feedstocks with clean alternatives. New users, conversely, must integrate clean hydrogen derivatives as novel fuels or feedstocks, replacing conventional energy sources such as coal or natural gas.

Being a first mover offers strategic advantages, including early experience with new technologies and securing future market share. However, it also presents significant challenges. Offtakers must secure sufficient volumes of clean fuel at prices competitive with conventional production technologies. In an emerging market, such volumes—and the infrastructure to transport them—are limited, impacting not only supply security but also the costs associated with infrastructure designed for larger capacities.

Despite the pivotal role of clean hydrogen and its derivative in decarbonizing end uses, public discourse often disproportionately focuses on the supply side.

Furthermore, expected rapid declines in cost due to technological advancements and economies of scale may deter potential offtakers from entering into long-term contracts, exposing them to price risks.[5]

IMAGE CREDIT: ADOBE STOCK / AU USANAKUL

IMAGE CREDIT: ADOBE STOCK / CANDYRETRIEVER

This creates an opportunity-cost dilemma: if many potential buyers delay their commitment to benefit from future lower prices, a lack of initial demand prevents projects from reaching the necessary economies of scale, resulting in no future cost decline at all. This challenge is amplified by the dynamics of competitive sectors such as shipping.

Amid prevailing budgetary constraints, governments must ensure prudent spending and identify the most effective instruments for overcoming barriers faced by offtakers.

Since clean fuels currently offer no immediate competitive edge, there is little incentive to move early. Moreover, once they do achieve a competitive position, market adoption will be so rapid that the initial investor's first-mover advantage will be quickly eroded.

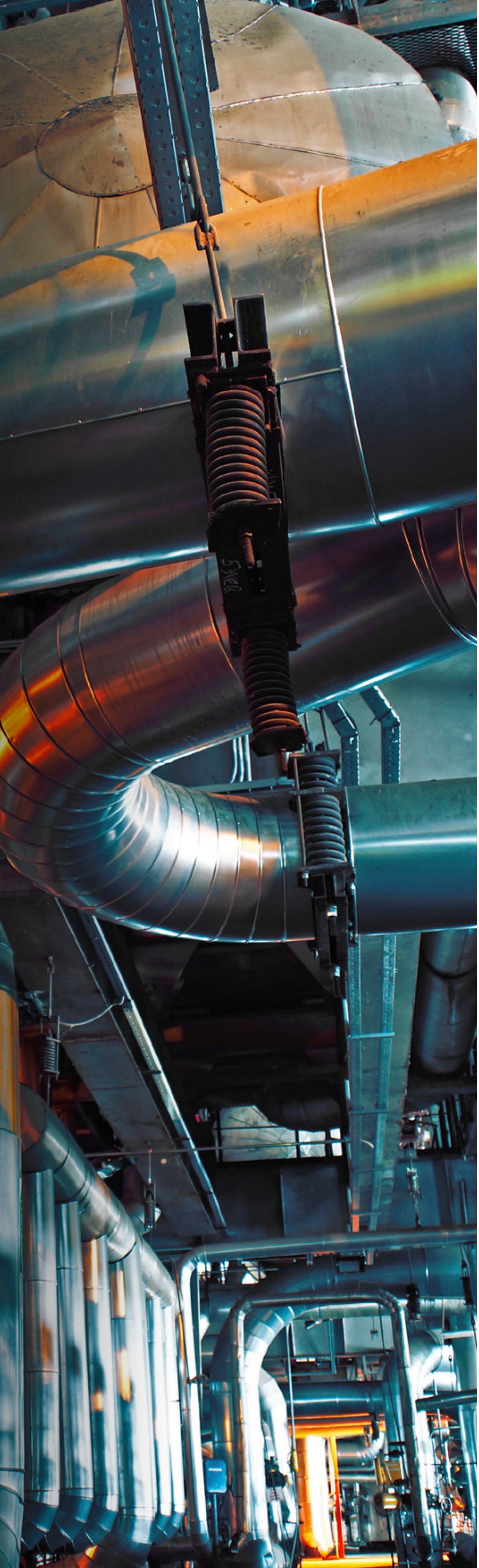
To mitigate these risks and accelerate market development, policymakers globally have initiated or announced support for hydrogen demand, with approximately EUR 89 billion deployed for this purpose worldwide.[6] Amid prevailing budgetary constraints, governments must ensure prudent spending, recognizing that financial incentives alone may not address all challenges and risks.

Crucially, risks do not affect all offtaker types uniformly. To support policymakers in selecting and designing coherent sets of instruments, this report therefore aims to:

1. Develop a deeper understanding of the specific risks that different offtakers face when introducing clean hydrogen solutions.
2. Conduct a meta-study to estimate the cost-of-difference (CoD) that must be overcome in major hydrogen demand markets.
3. Match appropriate support instruments with identified risk profiles and cost assessments.
4. Assess the support instruments currently deployed by major potential demand centers through case studies (Germany, Japan, and the U.S.).
5. Identify the most effective instruments for overcoming barriers faced by offtakers.

IMAGE CREDIT: ADOBE STOCK / KANYAPHATSTUDIO

IMAGE CREDIT: ADOBE STOCK / ANDREI MERKULOV



2

The risk landscape for potential clean hydrogen offtakers

The business models of potential hydrogen users vary significantly. Hydrogen applications in stationary industries such as steel, refining, or chemicals face different needs and market contexts than transport solutions like shipping or aviation. Industries currently producing hydrogen for their own consumption face a distinct transformation compared with those entirely new to the fuel. Consequently, the extent to which companies must manage particular risks varies considerably.

IMAGE CREDIT: ADOBE STOCK / KALYAKAN

Companies face a complex landscape when making investment decisions, which is why risk assessment and mitigation are so vital. As many firms use their own frameworks, there is no universal list of risks in the economic literature. This complexity is compounded by the fact that risks can overlap and interact differently across industries.

To navigate this complexity, this report simplifies the landscape by identifying 13 primary risks (a comprehensive list and definitions are provided in Annex I) and categorizing them into four distinct groups: strategic positioning, supply chain coordination, economic risk, and asset operation. The analysis, based on detailed desk research and 22 expert interviews, reveals a wide range of challenges across different industries.

In Table 3, the risk profiles are organized according to their relevance, identified on a five-level scale. The results show a wide range of challenges across sectors. For example, steelmakers face high liquidity risk when switching to direct reduction of iron (DRI) using clean hydrogen. This complex risk is primarily driven by a combination of CAPEX volumes, take-or-pay clauses typical of hydrogen purchase agreements, and potentially diverging payment terms between hydrogen purchasing agreements and steel sales contracts. If the new DRI plant experiences ramp-up delays or hydrogen supply bottlenecks, the steelmaker remains obligated to pay for committed hydrogen volumes irrespective of current production levels or steel prices.

Companies face a complex landscape when making investment decisions, which is why risk assessment and mitigation are so vital. Risks can also overlap and interact differently across industries.

In contrast, sectors such as aviation have a lower barrier to entry; the technology risk for adopting e-SAF is minimal since the fuel behaves almost identically to conventional kerosene.

Table 3: Risk profiles of the most relevant offtakers for clean hydrogen

Category	Risk	fuel use (mobile): shipping (methanol)	fuel use (mobile): shipping (ammonia)	fuel use (mobile): aviation	fuel use (mobile): rail/road	fuel use stationary): process heat	fuel use stationary): power generation	fuel and reduction agent: steel DRI	feedstock use (captive business model): chemicals	feedstock use (captive business model): refinery	feedstock use (captive business model): fertilizer production	feedstock use (merchant business model): chemicals	feedstock use (merchant business model): refinery	feedstock use (merchant business model): fertilizer production	secondary uses
Strategic positioning	Market risk	Low risk	Low risk	Medium high risk	High risk	Medium high risk	High risk	Medium risk	Medium risk	Medium high risk	Medium risk	High risk	High risk	High risk	Low risk
	Technology risk	Medium low risk	Medium risk	Medium low risk	High risk	Medium risk	Medium risk	Medium risk	High risk	Medium high risk	High risk	High risk	Medium risk	High risk	Low risk
	Regulatory risk	Medium risk	High risk	Medium high risk	High risk	Medium high risk	High risk	Medium risk	High risk	High risk	High risk	Medium risk	Medium risk	Medium risk	Low risk
	Political risks	Medium risk	Medium risk	High risk	High risk	High risk	High risk	High risk	Medium risk	High risk	Medium risk	Medium risk	High risk	Medium risk	Low risk
	SLO risks	Low risk	Medium risk	Low risk	Medium risk	Low risk	Medium low risk	Low risk	High risk	Medium high risk	High risk	Low risk	Low risk	Low risk	Low risk
Supply-chain coordination	Supply risk	Medium low risk	Medium risk	Medium risk	High risk	High risk	Medium risk	Medium risk	Low risk	Medium low risk	Low risk	High risk	High risk	High risk	Low risk
	Offtake risk	Medium risk	Medium risk	Medium low risk	Medium risk	Medium risk	Low risk	Medium high risk	Medium risk	Medium risk	High risk	Medium risk	Medium risk	High risk	Low risk
	Counterparty risk	Medium low risk	Medium low risk	Medium low risk	Low risk	Medium low risk	Medium low risk	Medium low risk	Low risk	Low risk	Low risk	Medium low risk	Medium low risk	Medium low risk	Low risk
Economics	Price risk	Medium high risk	Medium high risk	Medium risk	High risk	High risk	Medium risk	High risk	Medium risk	Medium risk	Medium risk	High risk	High risk	High risk	High risk
	Liquidity risk	Medium risk	Medium risk	Medium risk	Low risk	Medium low risk	Medium low risk	High risk	Medium risk	High risk	Medium risk	Medium risk	High risk	Medium risk	Low risk
	Currency risk	Medium low risk	Medium low risk	Medium low risk	Medium low risk	Medium low risk	Low risk	Medium low risk	Low risk	Low risk	Low risk	Medium risk	Medium low risk	Medium risk	Low risk
Asset operation	Technical risks	Medium low risk	Medium risk	Low risk	Medium risk	Low risk	Low risk	Medium risk	Low risk	Medium risk	Low risk	Low risk	Medium low risk	Low risk	Low risk
	Quality risk	Medium low risk	Low risk	Low risk	Low risk	Medium risk	Low risk	Medium risk	Low risk	Low risk	Low risk	Medium risk	Low risk	Medium risk	Low risk

Legend

■ Low risk ■ Medium low risk ■ Medium risk ■ Medium high risk ■ High risk

This report analyzes the direct end users of clean hydrogen in sectors with few viable decarbonization alternatives. These include high-temperature process heat and feedstock for the chemical, refinery, and fertilizer industries, as well as sectors tied to a systemic function of balancing energy supply, such as power generation. Long-distance, heavy-duty transport (sea, air, and land) and steelmaking—where hydrogen can act as both a fuel and a reduction agent—are also included.

While this report centers on these direct end users, other key players in the ecosystem, such as traders and secondary users, are treated differently. Traders, for instance, were deliberately excluded because their role is simply to resell a product without changing it. Their risk profiles are therefore tied to commodity and infrastructure issues, making them fundamentally different from the end users that are the focus of this analysis.

Secondary users are manufacturers who do not directly use clean hydrogen but instead use products from their suppliers that were produced with it. Since these products are identical in quality to conventional ones—differing only in their GHG emissions—secondary users can incrementally adopt clean supplies without altering their own production processes. Examples include the automotive and building sectors, which might use green steel and glass. These users are crucial because their willingness-to-pay (WtP) for the "green premium" on such products is essential for direct users of clean hydrogen to pass on costs. Secondary users are included for informational purposes in the table, but the report's systematic analysis of support instruments does not cover them.

Another key, albeit indirect, user group comprises the cargo owners in shipping, aviation, rail, and road transport. Their WtP for zero-emission transport can potentially help bridge the cost gap that direct users of hydrogen (derivatives)—such as ship, rail, and truck owners—currently face as first movers in this space. However, cargo owners' WtP is strongly linked to market competition and, most critically, to the willingness of the end user or consumer to pay for a clean product. While this end-user willingness to buy and pay for clean products remains largely untapped, it will be a key factor in decarbonizing entire value chains.

Based on the analysis of various sectors presented in Table 3, several key patterns stand out. **Price risk** is the most pervasive challenge, never scoring below a medium level across all sectors. It also has the highest number of high and medium-high ratings of any risk. Where price risk is rated at a medium level, it is often because companies maintain greater cost control through existing so-called captive business models—for example, by continuing to use fossil fuels with carbon capture, utilization, and storage (CCUS) technologies. Conversely, the highest price risks are associated with reliance on new, clean technologies such as renewable energy-powered electrolysis (see Box 1).

The ability to partially pass on these higher costs to customers, as seen in the aviation and power generation sectors, helps to reduce this risk. This is just one example of the complex dynamics surrounding the cost-of-difference (CoD), which are explored in more detail in the following section.

A second major takeaway from Table 3 is the critical importance of **regulatory and political risks**. They significantly shape market and technological risks, as well as the outlook for financial support. For potential offtakers, reliable political support and consistent regulations are a prerequisite for reaching a final investment decision (FID) and committing to long-term hydrogen purchase agreements.

Despite this, demand-side supporting actions driven by regulation and/or policy are still lagging globally and require both expansion and streamlining. These measures also need to offer certainty, which is often lacking at present.

Price risk is the most pervasive challenge. Where it is rated at a medium level, it is often because companies maintain greater cost control through existing captive business models.

Regulatory and political risks abound, taking different forms across sectors and jurisdictions. While commitment to clean hydrogen (derivatives) remains strong in the EU, India, and East Asia, interviewed experts attested to wavering support in the U.S. due to current political developments. Against this backdrop of national policy uncertainty, international bodies like the International Maritime Organization (IMO) and the European Union (EU) can provide crucial additional certainty, offering a more stable regulatory horizon.

Box 1: Alternative transformation pathways for existing hydrogen users

Three sectors included in this analysis—chemicals, refinery products, and fertilizers—currently utilize conventional hydrogen. These industries typically have a **captive business model**, producing hydrogen from unabated fossil fuels or as a by-product of other processes for their own consumption. They may also procure limited hydrogen volumes from nearby suppliers.

For these sectors, three distinct transformation pathways to clean hydrogen adoption emerge. Companies can:

- **Integrate CCUS** into existing fossil fuel-based hydrogen production assets.
- **Replace fossil fuel-based production** by sourcing sustainable carbon feedstocks (from biomass, residual industry emissions, or direct air capture (DAC)) and implementing on-site electrolysis for hydrogen.
- **Decommission** existing production assets and **switch to a merchant business model**, purchasing clean hydrogen (derivatives) and sustainable carbon feedstocks from the market.

The risk assessment for the captive model in Table 3 assumes the adoption of carbon capture technologies, contrasting a minimally disruptive transformation pathway with more comprehensive alternatives. The pathway a company ultimately chooses depends on its ability to mitigate the risks of each model and achieve a green premium in the market. In practice, companies may pursue mixed strategies, but this analysis uses ideal cases to clearly illustrate the risks associated with each pathway.

IMAGE CREDIT: ADOBE STOCK / AA+W

Supply risks are relevant across most sectors. The refinery, chemical, and fertilizer sectors may be the only potential exceptions, showing resilience due to their existing captive business models for hydrogen supply. However, this resilience does not fully insulate them; scaling clean production will still expose them to external supply challenges, primarily concerning infrastructure. Similarly, only a handful of sectors show a promising outlook when it comes to **offtake risks**. Power generation and aviation are the sole exceptions, as they anticipate a higher WtP at least for relevant market segments. Experts interviewed highlighted that these risks are strongly linked to external factors. Specifically, they noted that supply risks depend heavily on infrastructure availability, while offtake risks are tied to the willingness of secondary users to pay for clean products.

Liquidity risks are a primary concern for large-scale, long-term investments, making them more pronounced for stationary industries than for the transport sector, with the notable exception of shipping. Expert interviews indicate that liquidity risks are low for process heat and power generation because projects in these sectors typically resemble conventional reinvestments and therefore do not significantly affect company balance sheets. In contrast, sectors like steel and refining require substantial investments in new facilities and must sign long-term fuel-supply contracts. However, the contracts that steelmakers or refineries make with their own customers are typically for shorter terms. This mismatch creates a liquidity risk that necessitates robust hedging strategies.

The risk of being denied a **social license to operate** (SLO), or societal acceptance, is seen as low for clean hydrogen offtakers, according to expert interviews. The interviewed experts found that most offtake projects are straightforward, like-for-like replacements of a fuel or feedstock in an established industrial facility, where communities are already accustomed to the presence of industrial activity and related environmental, social, and safety issues that need addressing. Only experts from the transport and chemical sectors saw a higher risk. For sectors like shipping, where a new fuel and entirely new infrastructure must be adopted, there are significant public concerns related to the safety of new pipelines, storage, and terminals. Even in sectors undergoing a seemingly simple replacement, such as refining, public anxiety can emerge around industrial safety and a just transition for the workforce. Effectively addressing these issues is critical, as failure to secure a social license to operate can lead to project delays or even cancellation.[7]

The **remaining risks** featured in **Table 2—counterparty, currency and operational risks**—appear to be less significant across sectors. **Counterparty risk** is considered low, with 17 out of 22 experts emphasizing that most clean hydrogen (derivatives) will likely be procured from large, established energy providers with correspondingly low risk, particularly in the early stages of the market. New and smaller players would likely only be contracted for additional volumes or to diversify supply. Experts also unanimously agreed that clean hydrogen projects face almost no additional currency risks compared to conventional production. Similarly, operational risks are perceived as low due to existing expertise with hydrogen or substances requiring similar quality control and hazard management. Interviewees further stated that operational risks can be effectively mitigated through technology and training, suggesting that they do not require state support in developed countries. However, in sectors like shipping or steel, where clean hydrogen (derivatives) is introduced as new fuels, qualification needs are higher and qualified staff remains scarce during the early phases of market ramp-up. Based on the analysis of Table 3, risk patterns differ significantly across sectors depending on the role of clean hydrogen—whether it is used as a fuel in mobile or stationary contexts, as both a fuel and reduction agent, or as a feedstock.

The use of clean hydrogen (derivatives) as a **fuel in the transport sector** is most likely for shipping, aviation, and heavy-duty land transport, which lack the efficient alternatives available in other modes of transport.

In **shipping** and **aviation**, international regulations from the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) are a major influence. The binding decarbonization targets set by the IMO for 2030 and 2050 provide remarkable certainty for the **shipping** sector, giving it the lowest political risk among all assessed sectors. The remaining political and regulatory risks are tied to diverse harbor regulations and standards for e-ammonia and e-methanol. Offtake risks for shipping companies are rated medium on average, but they vary greatly depending on the product being transported.

The binding decarbonization targets set by the International Maritime Organization provide remarkable certainty for the shipping sector.

Shipping companies find it easier to pass on clean fuel costs when cargo owners sell directly to end consumers. Conversely, if the product is sold further up the value chain (e.g., steel to a machinery manufacturer), competition often limits the ability to transfer a green premium to customers. Overall, although ammonia presents some technical and short-term availability hurdles, interviewed experts view it as a lower-risk, long-term fuel option because supply is independent of sustainable carbon feedstocks.

IMAGE CREDIT: ADOBE STOCK / WESTEND61

IMAGE CREDIT: ADOBE STOCK / BJÖRN WYLEZICH

For **aviation**, the primary risks are also political and regulatory. The current price gap between e-kerosene and conventional or biogenic kerosene is a major barrier, especially with an inexpensive carbon-offsetting market. Interviewees rated the political risk for aviation as high because policymakers are likely to protect affordable long-distance air travel—an important aspect of many modern societies—which means ticket prices may only partially cover the higher cost of clean fuels.

When it comes to **land-based heavy-duty transport**, the central challenge is determining whether direct electrification or clean hydrogen offers a more efficient solution.[8] This is heavily influenced by regional geography and existing infrastructure. In densely populated areas with short transport distances and a robust grid, such as Western and Central Europe, direct electrification is often more viable due to established charging infrastructure. For as long as grid maintenance and expansion keep up with the rate of electrification and charging infrastructure is developed, hydrogen-powered land transport will face high technological and market risks. Consequently, political risks for hydrogen in these regions are higher, as policies are likely to favor electrification. However, opportunities for hydrogen emerge in regions where either grid stability or expansion capacity is limited—for example, in densely populated areas of South Asia, Southeast Asia, and Central Europe. Similarly, hydrogen may be better suited in sparsely populated regions such as the U.S., Latin America, and China, where long-distance routes benefit from their high energy density and faster refueling times.

The continued pursuit of both clean hydrogen and direct electrification as solutions ensures that a sufficient fuel supply will ultimately be established in the regions where it is most needed, even if hydrogen does not become a universal solution for all transport.

Power generation and process heat inherently possess alternative solutions to clean hydrogen. For process heat, lower-temperature applications can be directly electrified (e.g., steam production in chemical and paper industries), and this is becoming increasingly viable for higher temperatures as well. For specialized products such as primary steel, colored glass, or ceramics, fuel composition and flame physics may influence technology choices, but overall market risks remain high given the range of available alternatives.[9] In power generation, clean hydrogen primarily serves as a seasonal energy storage solution for regions with fluctuating wind and solar power. This implies a near-guaranteed offtake in the peak season but almost no utilization during the low-consumption season, fundamentally requiring a tailored market design and storage capacities to become viable.[10]

The production of primary steel from iron ore requires clean hydrogen as both a **fuel and a reduction agent,** involving one of the most extensive interventions for process decarbonization. Direct reduction of iron (DRI) using clean hydrogen (or, as an interim solution, natural gas) necessitates the complete replacement of existing blast furnaces.[11]

Depending on infrastructure availability, the complete replacement of existing assets can mean securing substantial volumes of hydrogen from the outset.

Depending on infrastructure availability, this can mean securing substantial volumes of hydrogen from the outset. Along multi-pipe infrastructure, redundant natural gas infrastructure can be retrofitted to provide simultaneous access to gas and hydrogen infrastructure, partially easing the problem. For steelmakers, switching to DRI still implies substantial capital expenditure (CAPEX). To secure supply, early movers will likely enter into long-term hydrogen agreements that often include take-or-pay clauses. This exposes them to liquidity risks, especially because take-or-pay agreements obligate them to procure hydrogen volumes regardless of market downturns or new plant ramp-up delays, while their steel is sold on shorter-term contracts.

IMAGE CREDIT: ADOBE STOCK / PHOTOGRFX

China's decarbonization strategy for its steel sector—which currently relies on Blast Furnace-Basic Oxygen Furnace (BF-BOF) technologies for about 90% of its substantial production—is centered on prioritizing the increased use of scrap metal and Electric Arc Furnaces (EAFs). This strategy reduces China's near-term need for early, high-cost clean hydrogen. Consequently, this approach, coupled with strong international competition (given China hosts around half the world's steel production capacity), exposes early adopters in the EU, the U.S., Japan, and South Korea to significant price and stranded-asset risks. These risks are further amplified by long-term hydrogen supply agreements, particularly if the expected rapid global demand for hydrogen-based steel does not materialize.[12]

The three sectors using hydrogen as a **feedstock**—chemicals, refinery products, and fertilizers—show risk profiles that vary significantly based on the chosen primary decarbonization pathway:

— **Captive business models (fossil fuels with CCUS):** This pathway is favored for minimal intervention and greater cost control, leveraging established CCUS technology (though large-scale deployment remains unproven). The trade-off is greater long-term political, regulatory, and public-acceptance risks due to the continued reliance on fossil fuels and potential opposition to CO_2 pipelines and storage. Refineries are particularly vulnerable to this risk, as their overall GHG emission reductions are inherently limited.

— **Merchant business models (market purchase):** These offer companies greater independence from political and social concerns related to fossil fuel use but introduce direct exposure to potential supply bottlenecks and greater price volatility in the nascent clean hydrogen market.

In practice, companies may opt to combine both pathways. Regardless of the chosen decarbonization pathway for the chemicals, refinery, and fertilizer sectors, both offtake and price risks remain high. This is due to a low willingness among buyers to pay a green premium in highly competitive commodity markets.

In addition to the sectoral analysis, the 22 experts were asked to name the two most important challenges for their respective sectors. Unanimously, they identified price risk—in particular the cost-of-difference (CoD)—as the single most relevant concern. For their second choice, 13 experts cited regulatory and political risks as most relevant, while five experts from the transport sector highlighted offtake risk as a particular challenge. The remaining three experts, from the steel and chemical sectors, identified supply risks.

Price, regulatory, supply, and offtake risks were therefore selected as the TOP FOUR risks for this analysis. Offtake risk was included ahead of market risk because market risk depends on the assessment of most other risks. Risks related to social license to operate, counterparty, currency, technology, and quality were not perceived as significant challenges for offtakers across the sectors and are therefore omitted from the following analyses. To examine the primary challenge identified by this assessment in greater depth, Section 3 provides an overview of the CoD to inform the discussion on effective support instruments.

IMAGE CREDIT: ADOBE STOCK / LIU

IMAGE CREDIT: ADOBE STOCK / NANSAN

3

Cost-of-difference: A critical barrier to clean hydrogen adoption

The risk analysis identifies price risk as the most significant risk for clean hydrogen offtakers across all sectors. The main driver of this risk is the cost-of-difference (CoD), which represents the substantial gap between the actual cost of producing clean hydrogen and the price offtakers are willing to pay. The considerable uncertainty regarding the ultimate price can discourage users from transitioning from conventional fossil fuels.

A clean hydrogen market with liquid volumes and transparent pricing does not yet exist. However, a few auction-based approaches—such as those by H2Global, the Solar Energy Corporation of India (SECI), and the *Zero Emission Maritime Buyers Alliance* (ZEMBA)—are conducting competitive processes to identify and share real-world prices. For example, H2Global's pilot auction yielded a renewable ammonia purchase price of 1,170 USD/t (the landed cost at the Port of Rotterdam), while the final sales price will only be revealed once the demand-side auctions have taken place.[13] Meanwhile, SECI's auctions resulted in prices of 641 USD/t and 591 USD/t (ex-factory).[14] These figures stand in stark contrast to the conventional ammonia price range of 315 USD/t to 522 USD/t at the time of bidding in July 2025.[15]

However, this initial gap narrows when benchmarked against historical volatility: the discovered renewable ammonia prices are actually lower than the global average price of conventional ammonia, which stood at 688 USD/t (577 USD/t when discounting price peaks induced by the Russian invasion of Ukraine) for the period 2021—2025.[16]

While these initial real price points are a necessary first step toward understanding CoD, they represent only a snapshot. They are specific to a particular region and product (ammonia), and production fundamentals vary significantly across geographies and sectors. To provide a more holistic understanding, various institutions regularly produce model-based calculations. The report compares the levelized cost of hydrogen (LCOH) and estimated willingness-to-pay (WtP) across selected sectors and regions from recent studies to gauge the price corridor. A clear understanding of CoD is essential for identifying the level of support and incentives required to facilitate the widespread adoption of clean hydrogen across different sectors and geographies.

Levelized cost of hydrogen

The levelized cost of hydrogen (LCOH) serves as a standard metric for comparing hydrogen production costs across various technologies. It quantifies the total cost of producing one kilogram of hydrogen over a facility's lifetime, encompassing both fixed and variable expenditures such as fuel, capital, operational, and financing costs.[17]

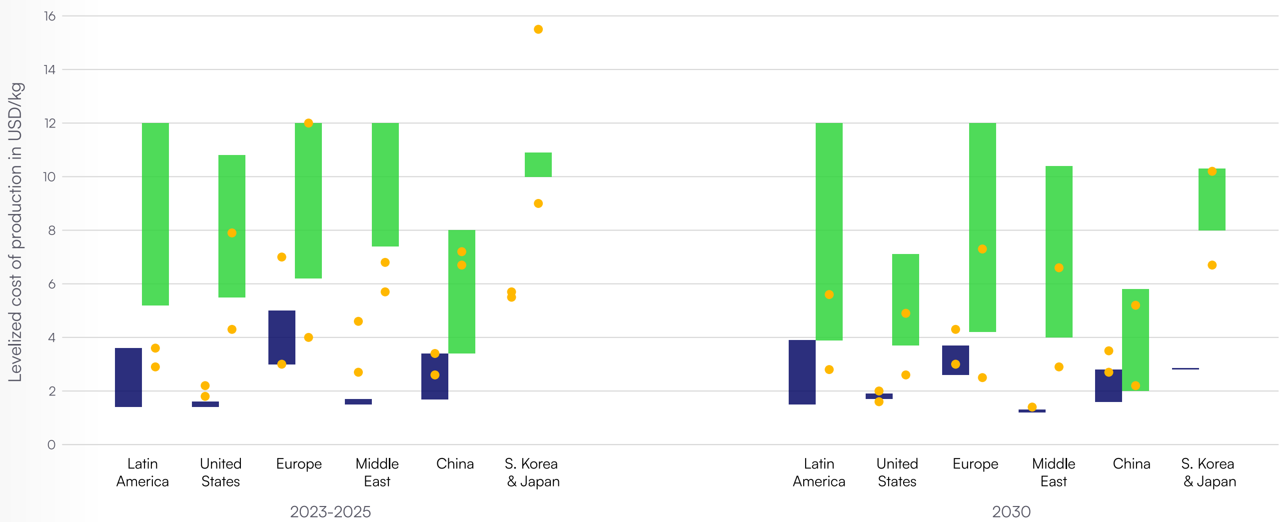
This analysis focuses on the two pathways receiving the most significant public attention: renewable hydrogen and low-carbon hydrogen.

Clean hydrogen production relies on different technologies, inputs, and infrastructure, with each pathway involving a unique set of cost components. This analysis focuses on the two pathways receiving the most significant public attention: renewable hydrogen and low-carbon hydrogen. Renewable hydrogen is produced via water electrolysis powered by renewable energy. Low-carbon hydrogen, in contrast, is derived from fossil fuels such as coal or natural gas (via steam methane reforming (SMR) or autothermal reforming (ATR)), combined with carbon capture and storage (CCS).

The cost components that make up the LCOH differ significantly between these pathways. For renewable hydrogen, the LCOH is primarily driven by the cost of

IMAGE CREDIT: ADOBE STOCK / PETERSCHREIBER.MEDIA

Figure 3: Overview of LCOH ranges from sixteen studies across six regions



Legend

Low-carbon IEA Renewable IEA Highest & lowest value from meta-study

Sources: Bar ranges for Latin America, the United States, Europe, China, and the Middle East correspond to the most recent values from the International Energy Agency's *Global Hydrogen Review* 2025.

Low-carbon values correspond to natural gas (NG) with carbon capture and storage (CCS) for all countries except China, where they refer to fossil fuels with CCS. Renewable hydrogen refers to the electrolysis production pathway.

Solar PV CAPEX is 600—1,000 USD/kW for 2024 and 400—700 USD/kW for 2030. Onshore wind CAPEX is 1,050—1,950 USD/kW for 2024 and 950—1,750 USD/kW for 2030. Offshore wind CAPEX is 2,400—4,900 USD/kW for 2024 and 1,720—3,800 USD/kW for 2030.

Electrolyzer CAPEX is assumed at 900 USD/kW in 2024 and 675 USD/kW in 2030 for China, while for the rest of the world it is 2,300 USD/kW in 2024 and 1,600 USD/kW in 2030. These figures include the electrolyzer system, balance of plant, EPC, and contingencies.

The cost of capital ranges from 6—18%. Natural gas prices range from 2.5—25 USD/MMBtu for 2024 and 1.8—18 USD/MMBtu for 2030. Coal prices are 80—100 USD/t for 2024 and 65—80 USD/t for 2030. CO_2 prices range from 0—70 USD/tCO_2 for 2024 and 0—106 USD/tCO_2 for 2030.

The figure capped at 12 USD/kg H_2, although some production routes exceed this value. Water costs are not included.

Bar ranges for renewable hydrogen in South Korea and Japan reflect values from BNEF and the Hydrogen Council report *Closing the cost gap: Unlocking demand for clean hydrogen* by 2030. The highest and lowest values from the meta-study represent the maximum and minimum among all values compiled for each region for the corresponding year. The studies cover the period 2023—2025 and 2030.

electricity, which is often the largest factor, along with grid fees, water treatment, electrolyzer capital and operational costs, and system maintenance. In contrast, low-carbon hydrogen LCOH incorporates costs tied to natural gas or coal and must also account for the infrastructure and additional equipment necessary for CO_2 capture and storage, along with emissions monitoring.

To place these cost structures in a global context, this report's meta-study synthesizes findings from sixteen publicly available reports and from scientific literature published since 2023 (a complete list is available in Annex II). The analysis provides insights into midterm market developments and combines current costs with net-zero emission scenario projections for 2030. It covers six key markets, including both net-exporting and net-importing regions: Latin America, Europe, the Middle East, the U.S., China, and South Korea/Japan.[18]

Figure 3 provides a clear overview of LCOH ranges for low-carbon and renewable hydrogen across these six regions.

LCOH estimates vary widely due to location-specific factors such as natural ressource availability, existing infrastructure, and grid fees.

For each technology and region, the graph shows the latest values from the International Energy Agency (IEA),[19] as well as the range of values provided by the sixteen studies in this meta-study. Clear regional differences in LCOH are immediately evident. Renewable hydrogen LCOH estimates vary widely due to location-specific factors such as natural resource availability, existing infrastructure, and grid fees.

In contrast, low-carbon hydrogen shows less cost variability because its production relies on more stable, long-term natural gas contracts in the assessed studies.

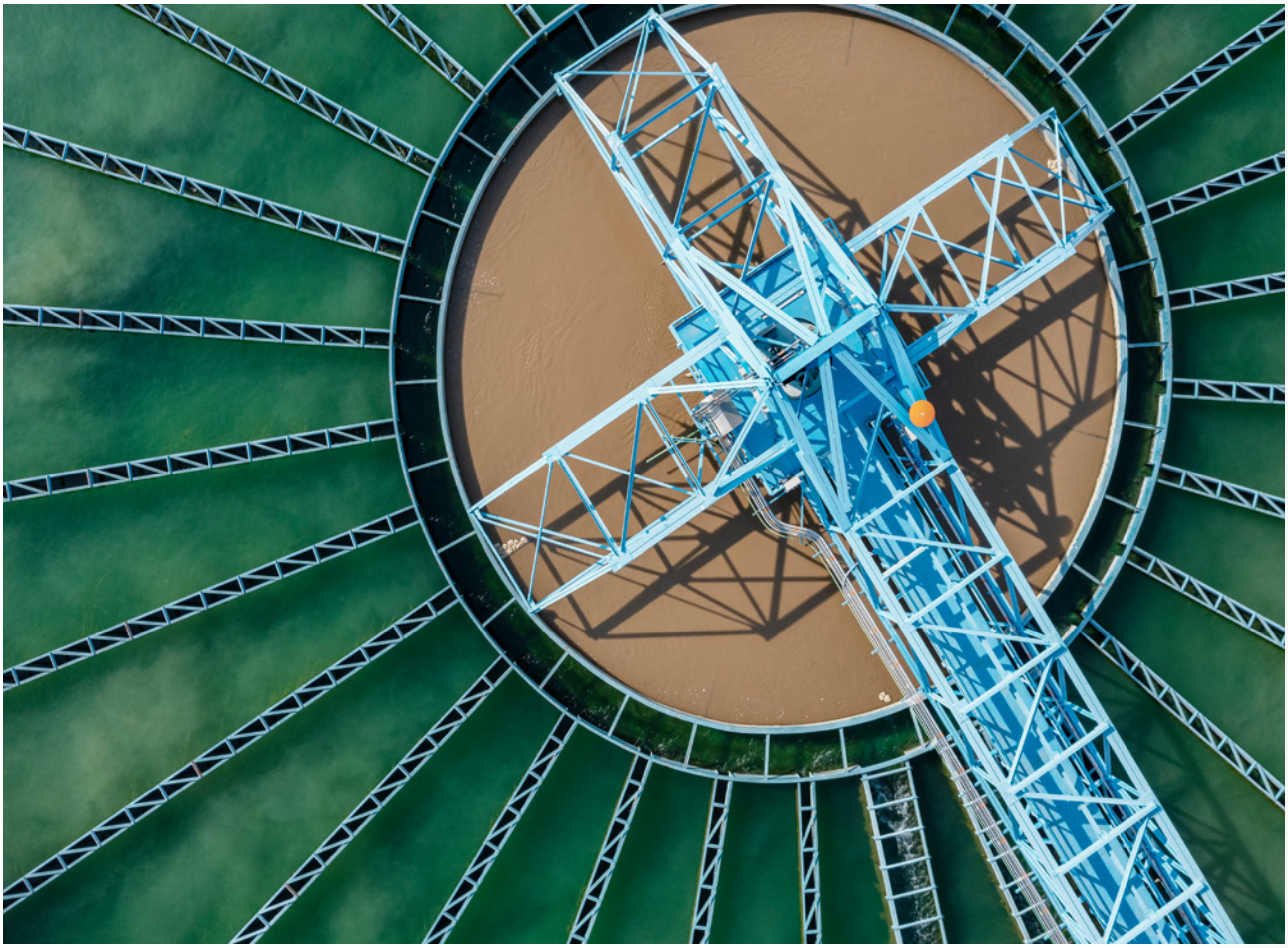


IMAGE CREDIT: ADOBE STOCK / UNIKYLUCKK

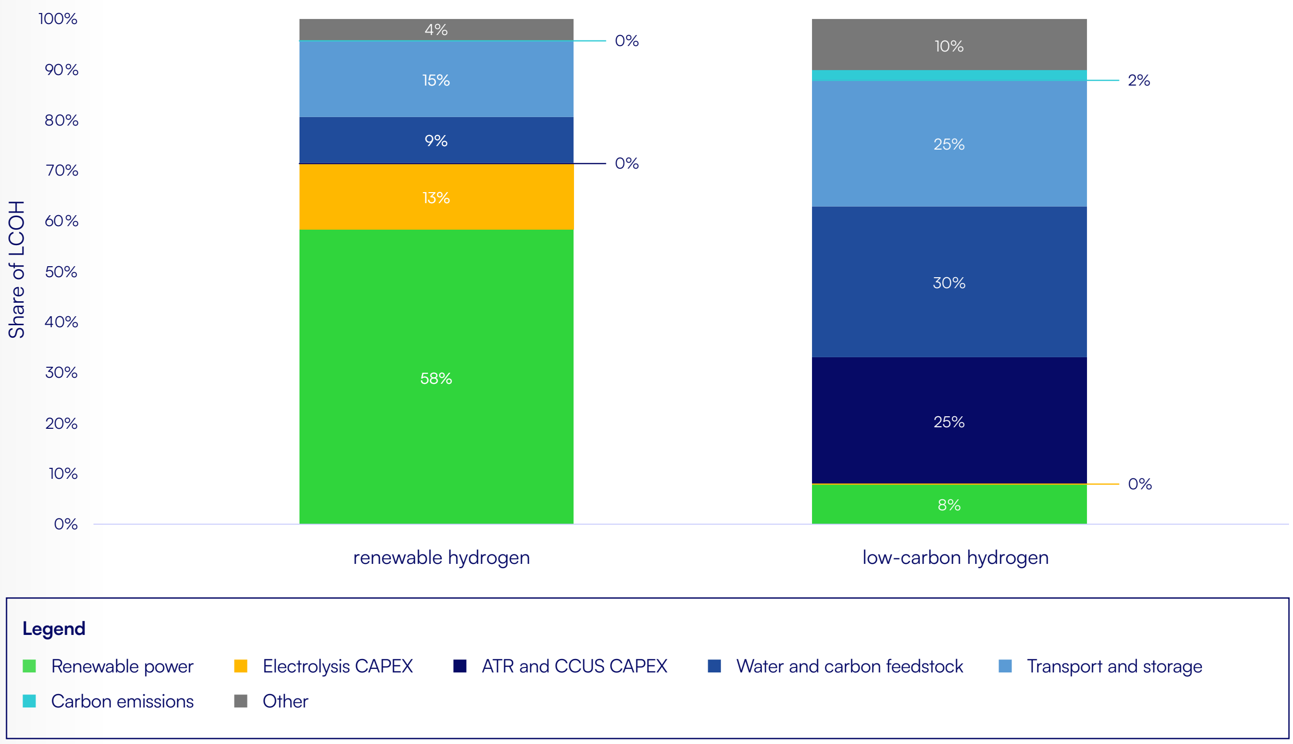
For 2023—2025, the U.S. and the Middle East have the lowest projected costs for low-carbon hydrogen, primarily due to abundant and low-cost natural gas resources and access to depleted oil and gas fields for CO_2 storage. In the case of renewable hydrogen, China emerges as one of the most competitive regions, benefiting from abundant domestic renewable resources, lower electrolyzer costs, and efficient supply chains. Notably, while India is not included in the IEA's latest LCOH analysis, it has emerged as a prominent global actor and warrants consideration. Estimates place India's renewable hydrogen costs for 2024 between 3.5—5 USD/kg,[20] with projections lowering that to around 2.4 USD/kg by 2030.[21]

The studies assessed here show a significant cost range for both renewable and low-carbon hydrogen, from around 1.3 USD/kg (for low-carbon hydrogen in the Middle East) to 10 USD/kg (for renewable hydrogen in Japan and South Korea) in 2030. To put these figures into perspective, it is useful to compare them with data from real-world projects.

Recent project bids in Europe, such as those from the European Hydrogen Bank's pilot auction, yielded an average renewable hydrogen LCOH of 5.5 to 13.5 EUR/kg (6.1 to 14.9 USD/kg).[22] Likewise, an evaluation of projects in the Netherlands by *Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek* found a cost in the order of 13.2—15.4 USD/kg.[23] This indicates that real project costs are currently approximately 1 USD/kg higher than the range provided by the studies. For non-European contexts, data from the H2Global pilot auction (3.7 EUR/kg for Egypt)[24] and the SECI auction (2.7 EUR/kg for India)[25] also help validate the LCOH ranges, demonstrating that these real-world prices fall within the expected ranges for their respective regions.

To fully understand the LCOH, it is essential to look at its underlying components, as seen in Figure 4. However, most studies on the levelized cost of clean hydrogen do not fully disclose the data or assumptions underlying their analysis beyond a simple division between the capital expenditure (CAPEX) and operational expenditure (OPEX) shares. While this report uses data from two studies with high resolution cost information[26] to provide an indicative breakdown of components—such as feedstock prices, electricity costs, and investment costs for production facilities—this overview represents only a snapshot of current market conditions. It does not account for different gas or electricity price scenarios and load factors, which are subject to considerable volatility and potential additional costs such as government charges or power purchase agreement (PPA) fees. Nor does it capture the impact of differing assumptions on key variables such as electrolyzer efficiency or load factors.

Figure 4: Cost components of clean hydrogen projects



Source: own depiction based on an average of values for hydrogen, methanol, and ammonia projects for 12 countries from all continents from Fraunhofer ISE: “Site-specific, comparative analysis for suitable Power-to-X pathways and products in developing and emerging countries” for renewable hydrogen and NESO: “Levelised cost of blue hydrogen modelling, 2025 to 2050” for low-carbon hydrogen.

Despite these limitations, the analysis is essential for understanding how dynamic developments in financing and input costs might impact LCOH. It helps illustrate the potential scale of price risk for offtakers, providing a solid foundation for further discussion. A more precise assessment of these risks would require the development of detailed cost scenarios, which remains beyond the scope of this report.

The underlying components of LCOH are essential for understanding dynamics and illustrate the potential price risks for offtakers.

A discussion of LCOH cost component data reveals important insights into low-carbon hydrogen variability. While its LCOH values generally exhibit less variation than those for renewable hydrogen—as most studies assume stable, low-cost gas procurement—significant discrepancies exist in specific cost components. For example, costs for CO_2 transport and storage differ widely across studies, ranging from approximately 22 to 210 USD per ton of CO_2. These variations are largely regional, with the U.S. and Middle East reporting lower costs due to the proximity of large geological CO_2 storage sites. This highlights a key limitation in many low-carbon hydrogen studies: they often account only for the small amount of uncaptured CO_2 (assuming capture rates of around 90%) and provide limited sensitivity analyses across different carbon price scenarios. This is a crucial shortcoming given the potential volatility of carbon markets and the fact that capture rates can vary across projects. Even as CCS technologies evolve, constraints such as the limited availability of geological CO_2 storage sites and the logistical challenges of transport persist.

Studies on renewable hydrogen show substantial variation depending on the underlying business model. Clear regional price gaps exist for electrolyzer CAPEX. In China, cost estimates are the lowest, with alkaline electrolyzers priced as low as 300 to 700 USD/kW (for the stack) and proton exchange membrane (PEM) electrolyzers ranging from 590 to 1,140 USD/kW. In Europe, installed CAPEX is significantly higher.

PEM costs range from 1,000 to 1,500 USD/kW, while alkaline electrolyzers are higher still, generally between 2,600 and 6,200 USD/kW for the total installed system. U.S. estimates fall between these extremes, at approximately

IMAGE CREDIT: ADOBE STOCK / ORANGE DRAGON STUDIO

1,100—1,800 USD/kW for alkaline electrolyzers and 1,000—2,500 USD/kW for PEM electrolyzers.

Beyond CAPEX, divergence is also evident in key assumptions regarding electrolyzer utilization rates, which typically range between 60% and 80% across regions. Significant differences are also found in the cost of capital, with values for the same reference year ranging from 3.85% to 7% in China and a higher 7% to 10% in the U.S.

By 2030, most assessed studies expect a decrease in costs for both pathways. For renewable hydrogen, studies typically assume an exponential cost decline similar to what was observed for photovoltaic (PV) power generation in the 2000s and 2010s. Such reduction would be driven by technological advancements, system optimization, economies of scale, and decreasing costs of renewable energy. Low-carbon hydrogen is also expected to experience cost reductions, albeit at a slower rate, due to economies of scale and technological advancements in CCUS. Nevertheless, this cost advantage for low-carbon hydrogen could be swiftly eroded: if CCUS technologies retain residual emissions, increasing carbon prices—where applicable—may fully offset any efficiency gains.

A more recent body of research, however, adopts a more cautious outlook on the speed of these cost reductions.[27] This is due to a combination of market and technological factors. First, the slow scale-up of hydrogen projects is limiting the realization of economies of scale.[28] Additionally, broad inflationary pressures on materials and labor,[29] alongside governments' increasing focus on local content requirements, may inflate costs by restricting access to the most cost-competitive international technologies.

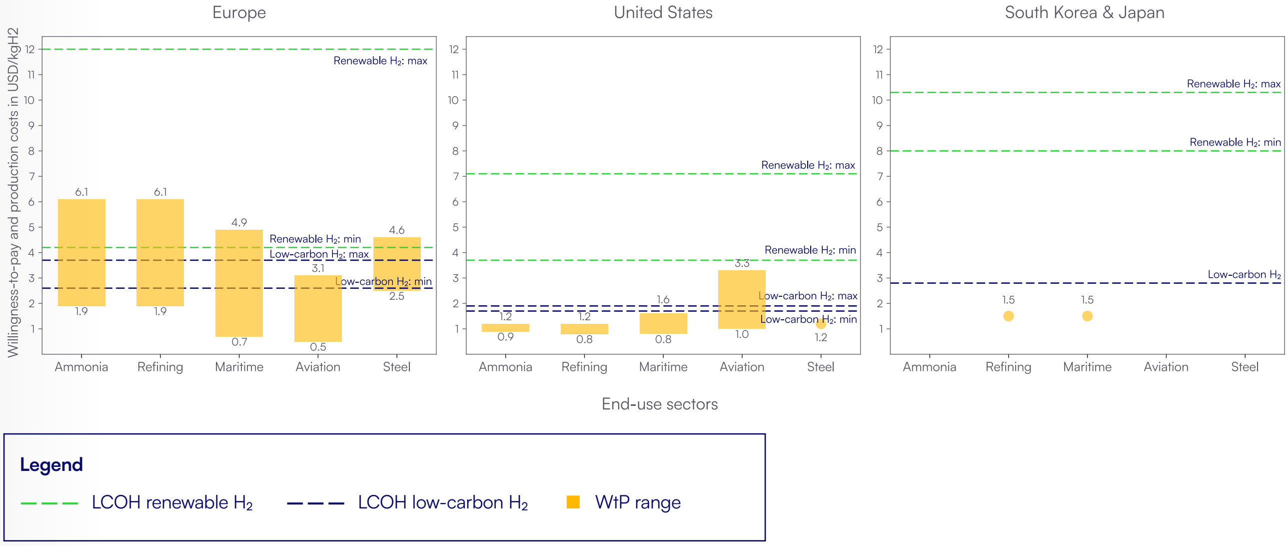
For renewable hydrogen, two key factors limit faster cost reductions: persistently high electricity prices in some regions, such as Europe, and limited progress toward more efficient electrolyzers (which typically operate at 65—70% efficiency and may drop further under intermittent renewable energy supply).[30] Meanwhile, for low-carbon hydrogen, potential increases in carbon or international gas prices pose a major risk to cost reductions. Moreover, technological advancements in CCUS are not expected, as the components of the technology are already mature. Simultaneously, underground storage for CCUS-based hydrogen production comes with technical challenges that may limit economies of scale. Collectively, these factors suggest a more measured outlook for future hydrogen cost trajectories.

Overall, hydrogen costs remain affected by significant uncertainties regarding future price levels. Consequently, a significant green premium is still expected for clean hydrogen in 2030. This implies that businesses considering it as a decarbonization pathway must enter the market with a WtP significantly higher prices than for conventional alternatives. However, as the next section shows, WtP remains considerably lower than the LCOH. This leaves a CoD that makes a clear case for public support instruments to bridge the financial divide and catalyze market development.

Willingness-to-pay and cost-of-difference for clean hydrogen

The transition to a clean hydrogen economy faces a fundamental challenge: the cost-of-difference (CoD). This represents the gap between the cost of producing clean hydrogen and the price that end users, or "offtakers," are willing to pay. Willingness-to-pay (WtP) is the maximum price a customer will pay for this cleaner alternative.[31]

Figure 5: Overview of CoD for clean hydrogen ranges from 3 studies conducted for Europe, the United States, and South Korea and Japan by 2030



Sources: Values for Europe derive from McKinsey & Company (2024), The Iberian Green Industrial Opportunity: Green Hydrogen. The report accounts for the following RFNBO targets: refining and ammonia under RED III (industry quota of 42% green H_2 by 2030); maritime under FuelEU and RED III (RFNBO quota of 1.2% by 2030); and aviation under ReFuelEU (RFNBO quota of 1.2% by 2030). No RFNBO targets are applied to steel in the study.

WtP calculations account for greenfield CAPEX and OPEX, CO_2 emission costs, a 400 EUR/tCO_2 penalty for non-compliance with RFNBO targets, and a green premium for steel. Assumptions include a 2030 natural gas price of 25 EUR/MWh, 1.5 tCO_2/t steel emissions avoided, and green steel premiums of 100—200 EUR/t depending on CO_2 price developments. The study factors in multipliers from FuelEU and RED III regulations from 2030, affecting shipping, refining, and transport. Calculations consider direct emissions and assume zero emissions for renewable H_2 production and e-fuels combustion due to capture.

The study uses EU emission data sources: SMR at 8.8 tCO_2/tH_2 (based on 56.2 gCO_2/MJNG, 55 MJ/kgNG, and 0.35 kgH_2/kgNG); e-MeOH vs. HFO at 3.2 tCO_2/tHFO (80.6 gCO_2/MJ, 40 MJ/kg HFO); and e-SAF vs. conventional kerosene at 3.1 tCO_2/t Jet-A (71.5 gCO_2/MJ, 43 MJ/kg Jet-A).

Values for the U.S. are derived from U.S. Department of Energy (2024), Pathways to Commercial Liftoff. NH_3 values reflect high (California) and low (Texas) industrial natural gas prices. The study assumes prices at 10—17 USD/MMBtu (fuel oil), 0.38 USD/kg (conventional MeOH) and 0.77 USD/kgMeOH (clean MeOH). For steel, the value reflects the green premium compared to traditional BF-BOF routes, based on the National Clean Hydrogen Strategy and Roadmap. Aviation ranges are based on EIA Annual Energy Outlook reference oil prices for Jet-A (USD 2.7/gal), with the high case including California LCFS credits of up to 140 USD/credit through 2032. Refining values use EIA AEO 2023 regional natural gas price ranges (high: California; low: Texas).

Values for Japan and South Korea are derived from the Hydrogen Council and McKinsey & Company report Closing the Cost Gap: Unlocking Demand for Clean Hydrogen by 2030, based on the cost-parity gap reported in the appendix and assuming a low-carbon hydrogen price of USD 2.8/kg in Japan by 2030.

While higher costs for clean hydrogen may concern direct, upstream users, particularly first movers, the impact on final consumer prices is often marginal.[32] For example, the IEA estimates that using low-emission fertilizer would raise the retail price of a cup of coffee by only 0.05%, and using low-emission steel in an electric vehicle would add just about 1% to the final price.[33] Despite these low percentages, it is critical to consider the cumulative inflationary effect. Even marginal increases, when applied to essential goods (such as food items relying on fertilizer), can disproportionately affect different types of products and potentially pose serious food security or cost-of-living challenges in some countries.

WtP varies widely across sectors and regions due to factors like international competition, energy and labor costs, and regulatory frameworks such as carbon pricing and mandates.[34] Reliable price information for clean hydrogen is scarce, as the market is still nascent and lacks transparency. Conventional hydrogen production often serves self-consumption[35] or is traded through localized, over-the-counter transactions with minimal transparency. As a result, most available WtP estimates rely on assumptions that differ widely. As the market matures, initiatives such as the H2Global auctions and the emergence of dedicated commodity exchanges such as Hydrix are expected to enhance price transparency.

Our analysis, based on a combination of LCOH findings from Figure 2 and WtP estimates (see Annex II for details), provides an overview of the CoD by 2030 in four key regions: the U.S., Europe, South Korea, and Japan. It covers both established and emerging demand sectors, including refining, ammonia, maritime transport, aviation, and steel.

Regional findings on WtP and CoD

Figure 5 reveals a wide range of values for WtP and CoD. WtP values range from 0.5 USD/kg_{H2} for aviation in Europe to 6.1 USD/kg_{H2} for ammonia and refining in Europe. This results in a CoD range from 0.4 USD/kg_{H2} (for U.S. steel) to 11.5 USD/kg_{H2} (for European aviation), depending on the clean hydrogen production technology used. Unfortunately, WtP data were unavailable for ammonia, aviation, and steel in Japan and South Korea, limiting the CoD analysis for these regions.

Overall, WtP is significantly higher in Europe than in other regions—a direct result of more robust demand-side instruments. In Europe, only the lowest WtP estimates remain below the cost of optimal low-carbon hydrogen production, while industries such as ammonia, refining, maritime transport, and steelmaking may reach WtP levels comparable to the lowest LCOH projected for 2030.

While aviation is the most challenging sector in Europe, it is the only sector in the U.S. where WtP aligns with the LCOH for low-carbon hydrogen and reaches the lowest cost for renewable hydrogen. Other U.S. sectors have WtP estimates less than 0.5 USD/kg_{H2} below the lowest LCOH values reported by the IEA. In Japan, the CoD for the two sectors with available data is 1.3 USD/kg_{H2}.

The role of policy in closing the CoD gap

The higher WtP data points in Europe demonstrate the effectiveness of policy in closing the CoD gap. The region benefits from robust demand-side instruments, such as carbon pricing, quotas, and mandates, already in place or under development. These measures are expected to raise WtP to levels that could match the cost of producing low-carbon and renewable hydrogen by 2030, although their ultimate success depends on careful design and effective implementation. For example, the EU's RED III directive requires that at least 42% of industrial hydrogen be sourced from renewable fuels of non-biological origin (RFNBOs) by 2030. However, these provisions have yet to be fully transposed into national legislation across most EU member states.

Conversely, in regions with fewer demand-side incentives, such as the U.S., Japan, and South Korea, WtP is expected to remain significantly lower. In the U.S., lower LCOH values help offset the lack of WtP. Even though the U.S. has traditionally been cautious with industrial policies, particularly on the demand side, a relatively modest intervention could help close the remaining cost gap for low-carbon hydrogen. Given Japan's large CoD challenge, its current fragmented policy approach—which includes regional emissions trading systems and limited-scope auctions—could be enhanced through consolidation and scaling of these instruments.

For the international maritime and aviation sectors, global regulation by the IMO and ICAO is also relevant. WtP in these sectors is expected to become more uniform across regions.

The findings of this analysis must be interpreted with caution, given several key limitations and inherent market uncertainties. First, the analysis is constrained by the limited availability of reliable WtP estimates, as it relies on only one study per region. Second, the LCOH figures reflect only domestic hydrogen costs, overlooking the industry's expected shift toward merchant-based trade and increasing imports. Beyond these analytical constraints, future CoD values remain highly uncertain due to broader market factors, including unpredictable technological developments, geopolitical and economic challenges, and unclear implementation pathways for regulations such as RED III.[36] It is also impossible to capture all possible scenarios, such as optimal renewable configurations or feedstock price volatility.

Policy measures are expected to raise willingness-to-pay to levels that could match the cost of producing low-carbon and renewable hydrogen by 2030.

Despite these limitations, the data strongly suggests a significant gap between current WtP and the LCOH of renewable hydrogen. While the outlook for low-carbon hydrogen is more favorable, the uncertainty in the data provides a clear call to action. To support market ramp-up, policymakers should prioritize clear, consistent, and internationally compatible frameworks that minimize political, regulatory, and price risks. Pragmatic use of low-carbon hydrogen, with its lower LCOH, may be critical to bridging the CoD during this critical phase of market development. This approach emphasizes cost-effectiveness and the volume of CO_2 avoided, shifting the focus from the technology, or "color," of hydrogen to its environmental outcome.

The next section of this report will examine various demand-side support instruments being implemented globally, exploring how these policies work in practice, their regional variations, and their potential to unlock a sustainable clean hydrogen market.

IMAGE CREDIT: ADOBE STOCK / GUSTAVSMD


IMAGE CREDIT: ADOBE STOCK / ARNO

4

Overview of demand support instruments

Building on the risk analysis in Section 2, this section delves into the solutions required to mitigate those risks. While the cost-of-difference (CoD) is the most significant financial barrier, potential clean hydrogen offtakers also face a range of other challenges, including price, regulatory, supply, and offtake risks—each posing critical hurdles to reaching a final investment decision (FID). When these risks cannot be absorbed or mitigated through negotiation with business partners, government intervention becomes paramount.

IMAGE CREDIT: ADOBE STOCK / СЕМЕН САЛИВАНЧУК

Through a variety of support instruments, policymakers can directly influence a project's economics, absorb risks, or establish a regulatory framework to guide market development. This section provides a strategic overview of these instruments to assess their effectiveness in addressing the risks faced by potential clean hydrogen offtakers.

The policymaker's toolkit: An overview of instruments

Demand-side support for clean hydrogen takes various forms. This report identifies 31 distinct instruments, detailed in Annex IV, each capable of influencing a project's economics, risk profile, financing, or general operating conditions. While some instruments may have multiple effects, for clarity this report classifies each according to its primary impact. The instruments can be grouped into the following categories:

— **Economic instruments:** As defined by the OECD, these are government actions that directly alter prices, such as taxes on fossil-fuel alternatives, tax reductions for clean products, subsidies, or transfers.[37] They are among the most immediately effective tools for bridging the CoD. Examples include contracts-for-difference (CfD) and emissions trading systems. While these instruments offer relative transparency and clear technical requirements, they directly impact government budgets and, according to critics, may distort markets.[38]

— **De-risking instruments**: As defined by the OECD, these tools enhance a project's risk-reward profile, primarily by managing or reducing risk in exchange for a fee.[39] Examples include credit risk guarantees, liquidity reserve accounts, and insurance. A key advantage of these tools is that payments are contingent on the actual realization of risk, enabling a greater number of projects to be supported with the same nominal budget. By reducing perceived default risk for lending institutions, de-risking instruments also indirectly lower project financing costs. However, as these tools have not yet been widely applied to clean hydrogen projects, their efficiency and effectiveness remain to be fully demonstrated.[40]

— **Finance instruments:** These mechanisms provide direct access to funds through loans, concessional financing, blended finance, or equity.[41] They enable new and potentially higher-risk business models—often avoided by traditional banks—to secure the necessary capital. A key advantage is that even partial public funding can improve banks' risk perception, thereby leveraging additional private funds, and indirectly reducing a project's overall financing costs.[42] However, much like economic instruments, they directly impact the public balance sheets and often require long-term financial planning by government.

— **Enabling conditions:** This category covers government actions that do not directly target project developers but instead foster the broader business environment in which projects operate and can indirectly target consumers. Examples include introducing quotas and mandates, defining sustainability criteria, providing public infrastructure, establishing "one-stop-shops" for permitting, creating matchmaking platforms, or introducing green procurement rules to anchor offtakers (so-called green lead markets). Such instruments lay the groundwork for monetizing a green premium and can streamline administrative processes for businesses.[43]

IMAGE CREDIT: ADOBE STOCK / STOCKPHOTO MANIA

The scoring methodology: Matching instruments to risks

To assess the effectiveness of the support instruments, all 31 instruments were mapped to the eight key risks identified in Section 2. For each instrument-risk combination, a base rating was assigned from "0" (no logical relation) to "3" (a direct and strong effect). These ratings were validated by a group of 26 experts.

To capture an instrument's ability to address multiple risks, a composite score was calculated with a maximum value of 5. For each of the TOP FOUR risks—price, regulatory, supply, and offtake—0.5 points were added to the base score if the instrument demonstrated at least a weak effect. An additional 0.5 points were added if the instrument addressed at least two of the other four risks (market, technology, political, and liquidity). The total score for each instrument-risk combination was then calculated as the average effectiveness across all eight risks.

The total scores and rankings are presented in Table 4. It is important to note that a high total score indicates that an instrument can address many offtaker risks, but it may not be the most suitable option for the risks most relevant to a particular industry or country. The scoring also does not account for implementation costs, which are highly context-specific and must be evaluated against available budgets.

Policymakers should therefore use the total score as an initial reference point and consult the detailed scoring in Annex V to tailor a set of instruments to their needs, as demonstrated in the case studies in the following section.

Key findings: The most effective instruments

According to our scoring, the most effective instruments for risk mitigation are regulatory tools such as quotas, mandates, bans, and phase-outs, all of which fall under the category of "enabling conditions". These tools strongly affect five of the eight assessed risks by directly prescribing the use of clean fuels or technologies. By doing so, they immediately mitigate market and technology risks for all participants in a given sector. To enhance planning security, these regulations are often designed to scale up over time or be implemented with a long lead time, which increases regulatory certainty. Furthermore, by legally requiring the use of specific technologies or fuels, these tools also raise willingness-to-pay (WtP), thereby narrowing the CoD and providing a direct incentive for suppliers to invest in new capacity.[44]

However, regulatory tools are often seen as a last resort. They represent strong interference in entrepreneurial decision-making and can, in certain instances, risk imposing politically costly economic burdens on end users—often triggering public or populist backlash. Their effectiveness depends on robust enforcement, sufficient penalties

Table 4: Risk mitigation effects of 31 demand side support instruments

Instrument	Score	Ranking
Quotas and mandates	4.4	1
Bans and phase-outs of alternative technology	4.4	1
Carbon tax	4.1	2
Emissions trading system (ETS)	4.0	3
Carbon border adjustment mechanism	3.9	4
Ecolabeling and guarantees of origin	3.9	4
Book and claim	3.9	4
Political risk insurance	3.8	5
Mass balancing	3.6	6
Direct public procurement of clean fuels	3.6	6
Green lead markets	3.6	6
Reduced regulatory requirements	3.5	7
Double-sided auctions	3.4	8
(Carbon) contracts-for-difference	3.4	8
Special Economic Zones / Hubs	3.4	8
Demand aggregation	3.3	9
Public infrastructure provision	3.0	10
Fixed premia	2.9	11
Reduction of fossil fuel subsidies	2.8	12
Technology insurance	2.6	13
Fiscal incentives / tax breaks	2.6	13
Price indexation	2.6	13
Reduced reporting requirements	1.9	14
(Partial) loan guarantee and credit default swaps	1.9	15
CAPEX support	1.7	16
Liquidity reserve account	1.6	17
Equity injections	1.4	18
Blended finance / loan syndication	1.4	18
Public loan	1.4	18
Matchmaking platforms	1.3	19
Accelerated depreciation	0.9	20

Scoring is based on each instrument's ability to effectively mitigate eight key risks for hydrogen offtakers. Details in Annex V.

IMAGE CREDIT: ADOBE STOCK / MONGKOL

for non-compliance, and consideration of international competition that may not be subject to equally rigorous regulation. When policymakers choose to deploy such tools, they are often expected to provide—and are more willing to offer—political and financial support to offset the impact of such a significant market intervention.

The effect of carbon pricing tools on clean hydrogen is often indirect, as they depend on the technical and economic viability of alternatives.

The next highest-ranking instruments are **carbon pricing tools**, such as carbon taxes, emissions trading schemes, and carbon border tariffs, all of which fall under the economic instruments category. These tools raise the cost of conventional, GHG-emitting production processes, thereby improving the economic viability of clean projects. This directly increases WtP for clean production pathways, incentivizing suppliers to invest in new capacity and further cost reductions. As carbon pricing is linked to a market institution or state revenue, these tools are considered durable and provide long-term political certainty. Still, under extreme circumstances, governments have previously implemented countermeasures that override carbon pricing tools. During the 2022 energy crisis, for example, several governments introduced price caps and subsidies to shield consumers from high costs.

However, the effect of carbon pricing tools on clean hydrogen users is often indirect, as the specific benefits depend on the technical and economic viability of alternatives such as direct electrification or carbon capture, utilization, and storage (CCUS). Moreover, carbon pricing must be set at a high enough level to drive change without disproportionately harming competitiveness. While instruments like a Carbon Border Adjustment Mechanism (CBAM) can mitigate these effects for domestic markets, they cannot address challenges for export-oriented industries due to international non-discrimination rules under the WTO.[45] A CBAM, by design, applies to imports to ensure a level playing field, but does not provide a corresponding subsidy or tax rebate for exports—a measure that would likely be challenged as an unfair export subsidy.

Further down the ranking, instruments in positions four through seven share a common goal of **improving the marketability** of products made with clean hydrogen (and its derivatives). Part of the "enabling conditions" category, these measures include ecolabeling, guarantees of origin, public procurement (e.g., green lead markets), and reducing regulatory burden and uncertainty. When well designed, these measures create a level playing field for offtakers. Most come at a relatively low fiscal cost, except for public procurement, which requires significant budget allocations to create anchor demand.

IMAGE CREDIT: ADOBE STOCK / UUGANBAYAR

Noticeably, support **instruments targeting individual projects** rank lower, appearing only in eighth place or below. These include double-sided auctions, contracts-for-difference (CfDs), and various financial tools such as capital expenditure (CAPEX) support—which ranks comparatively low at place 16. These are not low-quality tools; rather, they have a more specific and narrow purpose than higher-ranking instruments. They are highly effective at addressing a narrow set of risks, such as economic and liquidity risks, but are less suited for the broader risk mitigation needed for the market as a whole. The success of such instruments therefore depends on clearly defined objectives and streamlined design, for example, in the case of clean hydrogen auctions aimed at improving supply for offtakers.[46]

Mapping instruments to risks

Overall, most support instruments are designed to address "**economic risks**", with a correspondingly high number showing a **strong effect** in this dimension. This is not surprising, as economic risks can be targeted relatively directly, making these instruments more precise and, consequently, easier to implement. For example, financial instruments are specifically designed to mitigate economic risk.

However, not all instruments have such a direct or exclusive focus. Effects on **strategic risks** and **supply chain risks** are generally weaker across instruments, as these impacts are often a side-effect of an instrument's primary purpose. For example, carbon pricing's market-wide application also indirectly influences supply chains and broader strategic market developments.

The effect on **individual project risks** is also limited, particularly for instruments categorized as **enabling conditions.** This is because their impact targets the broader market, dispersing benefits across multiple actors and reducing the intensity of their effect on individual initiatives. Their full effect typically emerges when combined with other instruments. Notable exceptions include direct public procurement and green lead markets, which significantly influence public sector behavior by positioning the state as a major anchor customer. Similarly, direct infrastructure provision and special economic zones or hubs have an immediate and direct impact on projects that can access this infrastructure and operate within these hubs.

Given the diverse conceptual effects of these instruments, it is paramount to study their application in practice so that policymakers are better informed to devise combinations of tools to achieve the desired level of risk mitigation. The next section examines the specific instrument mixes applied in three key clean hydrogen offtake markets—Germany, Japan, and the U.S.—to address identified risks and stimulate demand for clean hydrogen. It presents case studies focused on the most relevant potential clean hydrogen use sectors in each country. By identifying sector-specific risks and gaps in existing policy tools, the analysis proposes a more tailored set of measures to accelerate the clean hydrogen transition.

IMAGE CREDIT: ADOBE STOCK / DARREN


IMAGE CREDIT: ADOBE STOCK / STREETONCAMARA

5

Understanding implementation: Case studies

This section explores how global clean hydrogen offtakers—Germany, Japan, and the U.S.—are building their clean hydrogen economies. Each country's unique energy landscape is analyzed, along with its potential for hydrogen demand, and the strategic policies it is using to accelerate adoption. Both supply- and demand-side measures are covered. The report also includes a special look at the hydrogen policies of China, India and Uruguay in Box 2, Box 3 and Box 5.

Germany

Germany stands as Europe's largest industrialized nation, with manufacturing contributing a significant 19.7% to its GDP as of 2024.[47] Energy-intensive industries such as steelmaking and chemicals are particularly vital. Given its limited domestic energy resources beyond renewable potential, Germany remains heavily reliant on fossil fuel imports. In 2023, natural gas (24.6%), coal (16.5%), and oil (24.6%) still accounted for the majority of total energy consumption, despite a record 41% share of renewable energy in power generation.[48] Germany is also Europe's largest hydrogen user, with approximately 1.4 Mt used in 2023, including 8 kt of clean hydrogen.

Germany is also Europe's largest hydrogen user, with approximately 1.4 Mt used in 2023, including 8 kt of clean hydrogen.

Around half of this consumption comes from the refining sector, with ammonia consuming another 25%.[49] Many of these energy-intensive industries are classified as hard-to-abate sectors that cannot achieve full decarbonization through direct electrification. Instead, clean hydrogen is increasingly considered a viable alternative. For instance, the German steel sector alone could require 0.8—0.9 Mt/a of hydrogen to transition from conventional blast furnaces to hydrogen-powered direct reduced iron (DRI). Similarly, potential demand from chemical plants could reach 0.6—1.3 Mt/a by 2030, with other process industries such as glass and ceramics needing 0.2 Mt/a, and heavy-duty transport potentially demanding 1 Mt/a.[50]

Hydrogen strategy and policy

Recognizing the imperative to mobilize political support, the German government issued its initial National Hydrogen Strategy in 2019, updating it in 2022. Given its reliance on energy imports, Germany also published a dedicated Hydrogen Import Strategy in 2024. As part of this strategy, Germany aims to install 10 GW of domestic electrolysis capacity and import 45—90 TWh/a of clean hydrogen by 2030.[51] To achieve these goals, Germany employs several support instruments, including H2Global auctions managed by the independent H2Global Foundation,[52] participation in the European Hydrogen Bank auctions,[53] and exemptions from the renewable energy levy ("EEG-Umlage").[54] The German government has also established clean hydrogen partnerships with 32 countries.[55] Hydrogen supply-side policies are currently under review following the formation of the new federal government in May 2025.

Demand-side support tools

To drive the decarbonization of its hard-to-abate industries, Germany's government has implemented a range of demand-side support tools. While the country leverages broader EU regulations such as carbon pricing, quotas, and capital expenditure (CAPEX) support, it has also deployed funding for domestic measures including public infrastructure, double-sided auctions, and carbon-contracts-for-difference (CCfD):[56]

IMAGE CREDIT: ADOBE STOCK / EKH-PICTURES

- **Public infrastructure**: To ensure supply security, the government has requested gas transmission grid operators to plan a hydrogen core network. An innovative **amortization account** allows for the intertemporal shifting of costs for initially oversized infrastructure, ensuring that first movers are not disproportionately burdened.[57] This mechanism, where the government temporarily guarantees the cost differential, acts as a form of public infrastructure procurement, even though it is executed by private companies.

- **H2Global mechanism**: A key demand-side measure is the independent H2Global mechanism, which the German government is funding to bridge the price gap between the cost of procured clean hydrogen and what buyers are willing to pay (see Box 4). The first demand-side auctions for renewable ammonia, funded as a pilot project, are expected to occur a year before the agreed delivery date.

- **Carbon-contracts-for-difference** (CCfD): The German government awarded 15 CCfDs in a first round, providing EUR 2.8 billion in support.[58] Five of these projects specifically involve the use of hydrogen and they will receive a maximum of EUR 1.1 billion in total funding (see Table 5). CCfDs are designed to cover the "green premium"—the carbon emission avoidance cost that an industrial user faces when transitioning to clean production. Awarded projects using renewable hydrogen as part of their decarbonization concept must commence operation within five years of receiving the award.[60]

As a key member of the European Union (EU), Germany leverages a range of EU-level policies and initiatives to accelerate its hydrogen ambitions. Specifically, Germany draws on Important Projects of Common European Interest (IPCEI), the EU Emissions Trading System (EU ETS), the Carbon Border Adjustment Mechanism (CBAM), and various EU-binding targets.

- **IPCEI**: Germany has registered 16 hydrogen demand projects as Important Projects of Common European Interest (IPCEI), unlocking significant CAPEX support for offtakers in the steel, chemical, and cement sectors.[62]

- **EU ETS and CBAM**: As part of the EU, Germany's power and industrial sectors participate in the EU Emissions Trading System (ETS), which introduces carbon pricing. The recent rollout of the EU's CBAM will phase out free allowances for energy-intensive industries, thereby increasing the pressure to invest in decarbonization.[63]

- **EU binding targets**: EU regulations, notably the RED III framework, set binding targets for renewable fuels of non-biological origin (RFNBOs) in the transport and industrial sectors, effectively functioning as quotas. While the German government has stated that it will not directly implement the 42% RFNBO target for 2030 (rising to 60% by 2035) as a direct national quota, it aims to achieve these levels through support mechanisms. In the transport sector, fuel providers are required to blend at least 1.5% RFNBOs into the fuel mix by 2030.[64] Similarly, FuelEU Maritime will introduce a conditional 2% RFNBO target for the shipping sector starting in 2034. This target applies to all voyages within the EU and to 50% of the fuel used for voyages to or from the EU. The use of RFNBOs is further incentivized by a double-counting bonus, making them twice as valuable toward meeting emission reduction targets than other biogenic fuels.[65]

Table 5: Winning projects of CCfDs using hydrogen[63]

Company	Project	Sector	Planned reduction in GHG emissions	Maximum funding volume
Saint-Gobain Glass Deutschland GmbH	Sustainable flat glass production	Glass and ceramics	115,370 tCO2e/a	EUR 382.8 million
Nordenham Metall GmbH	Decarbonization of lead production	Other metals	46,643 tCO2e/a	EUR 359.9 million
Schmiedewerke Gröditz GmbH	Hydrogen-powered forging press	Other metals	14,017 tCO2e/a	EUR 172.8 million
Tesa Werk Hamburg GmbH	Carbon neutral tape production	Chemicals	20,349 tCO2e/a	EUR 101.1 million
Ziegel- und Klinkerwerke Janinhoff GmbH & Co. KG	Brick production with hydrogen	Glass and ceramics	9,067 tCO2e/a	EUR 60.2 million

Germany's strategic gaps and future outlook

While Germany has a variety of instruments in place to support the expansion of its clean hydrogen economy, the country still faces significant challenges due to a lack of strong incentives, lingering risks, and a difficult industrial environment. Table 6 illustrates how demand-support instruments influence the risk profiles of key sectors in the country, scored on a scale of 1 to 3. It reveals a complex picture of progress and the hurdles that remain.

Shipping

High regulatory and price risks represent the primary obstacles to introducing clean hydrogen in Germany's shipping sector, where supply and offtake risks are considered medium. The main regulatory challenges stem from the absence of a global decarbonization framework from the International Maritime Organization (IMO). Current EU regulations, such as the ETS[66] and the FuelEU Maritime framework, are strong drivers of change, but their recent implementation means their full impact is yet to be seen. The flexibility of the FuelEU Maritime legislation, for example, could undermine its own targets by making compliance conditional on factors such as the availability and price of alternative fuels.[67]

To mitigate key risks, a carbon tax could be highly effective in reducing regulatory and price risks. However, it would only have a limited effect on supply risk. Since the EU ETS already applies to the shipping sector, introducing a separate carbon tax could create policy overlaps. A complementary approach would be to apply a carbon tax to smaller vessels that fall outside the scope of the EU ETS, ensuring broader coverage across the fleet. Another viable option would be to deploy double-sided auctions. These auctions could be structured to simultaneously incentivize demand from key industry players, such as ports and shipowners, and encourage the production of new clean fuels, thereby addressing both demand- and supply-side risks.

Box 2: The H2Global mechanism

The H2Global mechanism is a double-auction scheme designed to accelerate market creation for clean hydrogen and other low-carbon products. To that end, an intermediary such as Hintco enters into contracts with both sellers and buyers of clean hydrogen. This intermediary purchases products at a price that is expected to be higher than the price that can be recovered from buyers, as clean products are typically more expensive than their carbon-intensive counterparts. The price difference is covered by public funding, climate finance, private capital, or a combination thereof. In so doing, the H2Global mechanism simulates a functioning market for clean hydrogen, helping bring market creation forward.

As the mechanism operates on both sides of the market, it effectively supports both supply-side and demand-side projects by entering into firm offtake and supply contracts and covering price differentials. Additionally, it provides a crucial service to nascent hydrogen markets by publishing relevant auction data, thereby informing potential market participants about the actual levelized cost of hydrogen (LCOH) and willingness-to-pay (WtP) in specific market segments. The direct financial support, however, is granted to the intermediary to cover the cost-of-difference (CoD). Through competitive auction design, the CoD is minimized as the lowest-bidding supplier(s) and highest-bidding offtakers win, ensuring efficient allocation of support.

Offtakers receive indirect financial support as they bid at their WtP, which can be expected to cover the cost of unabated fossil fuels and the green premium they are willing to bear. Through the mechanism, they gain access to large product volumes, enhanced regulatory certainty through standardized contracts, and swift responses to market changes via the short-term offtake contracts offered by the intermediary.

The instrument can be tailored to various needs, including specific clean hydrogen derivatives such as eSAF; relevant offtake sectors lacking access to clean fuels, such as steel and shipping; as well as geography, contract duration, and sustainability criteria. Whoever provides funds for the compensation payments determines the design, specifications, and objectives of the respective funding tender, ensuring alignment with their respective targets—such as energy security or industrial competitiveness. Funding tenders can be deployed by a single country (import, export, or domestic tender), two countries (joint import/export tender), or multiple countries (multilateral tender), depending on the funders' objectives.

Table 6: Risk profiles and instrument effects on key sectors in Germany

GERMANY	Shipping		Process heat		Steel DRI		Chemicals (merchant business model)	
Risks	Instrument	Effect	Instrument	Effect	Instrument	Effect	Instrument	Effect
Regulatory risk	very high risk		high risk		medium risk		medium risk	
	H2Global	1	CCfD	1	CCfD	1	CCfD	1
	EU ETS	3	CBAM	1	CBAM	1	CBAM	1
	FuelEU target	3	H2Global	1	H2Global	1	H2Global	1
			Amortization account	1	Amortization account	1	Amortization account	1
			EU ETS	3	EU ETS	3	EU ETS	3
			RED III targets	3	RED III targets	3		
Supply risk	medium risk		very high risk		medium risk		very high risk	
	EU ETS	1	EU ETS	1	EU ETS	1	EU ETS	1
	H2Global	3	CBAM	1	CBAM	1	CBAM	1
	FuelEU target	3	CCfD	2	CCfD	2	CCfD	2
			H2Global	3	H2Global	3	H2Global	3
			Amortization account	3	Amortization account	3	Amortization account	3
			RED III targets	3	RED III targets	3		
Offtake risk	medium risk		medium risk		high risk		medium risk	
	H2Global	2	Amortization account	1	Amortization account	1	Amortization account	1
	EU ETS	2	CCfD	2	CCfD	2	CCfD	2
	FuelEU targets	2	H2Global	2	EU ETS	2	EU ETS	2
			EU ETS	2	H2Global	2	H2Global	2
			RED III targets	2	RED III targets	2	CBAM	3
			CBAM	3	CBAM	3		
Price risk	high risk		very high risk		very high risk		very high risk	
	H2Global	2	Amortization account	1	Amortization account	1	Amortization account	1
	EU ETS	2	CCfD	2	CCfD	2	CCfD	2
	FuelEU targets	2	H2Global	2	EU ETS	2	EU ETS	2
			EU ETS	2	H2Global	2	H2Global	2
			RED III targets	2	RED III targets	2	CBAM	3
			CBAM	3	CBAM	3		

Legend

- Very low risk
- Low risk
- Medium risk
- High risk
- Very high risk

Instrument effect on risks
0 = no effect
1 = weak effect
2 = medium effect
3 = strong effect

IMAGE CREDIT: ADOBE STOCK / SCANRAIL

Process heat

The transition to clean hydrogen in the process heat sector faces a complex risk profile, with very high price and supply risks and a high regulatory risk. With natural gas still accounting for 40% of industrial energy, a clear phase-out policy for fossil fuels is crucial to drive decarbonization.[68] As shown in Table 6, the instruments currently implemented in Germany have a strong impact on mitigating price risks but a weaker effect on supply risks. Among them, only the EU ETS and RED III targets show a strong impact on regulatory risk.

According to the analysis in Annex V, the most effective tools to build hydrogen demand in this sector would be double-sided auctions, bans and phase-outs, and quotas and mandates. While a phase-out of fossil fuels is an obvious policy choice, a ban alone would not guarantee the uptake of clean hydrogen, as electrification also provides a viable decarbonization pathway for process heat. Therefore, any phase-out policy must be accompanied by specific hydrogen quotas to ensure that clean hydrogen plays a central role in this sector's transition.[69]

Steelmaking

The deployment of clean hydrogen in Germany's steelmaking sector faces significant hurdles, with very high price risk and offtake risks and medium-level regulatory and supply risks. A key challenge is that addressing only a single risk, such as price, is insufficient. The recent cancellation of two renewable hydrogen projects by ArcelorMittal demonstrates this point: despite EUR 1.3 billion in government support, the business case was deemed unviable, [70] highlighting the need for a comprehensive strategy.

Germany uses a combination of domestic and EU instruments to support clean hydrogen demand in the steelmaking sector (see Table 6). For example, carbon pricing through the EU ETS is intended to mitigate price risks. However, the average 2024 auction price of 64.74 EUR/kg CO_2 is currently too low to incentivize the required level of investment.[71]

According to the analysis in Annex V, the Carbon Border Adjustment Mechanism (CBAM) is the most suitable

Box 3: Clean hydrogen demand support in China

China, a global leader in energy-intensive sectors such as steel and glass, currently uses 35 Mt/a of fossil fuel-based hydrogen, primarily from coal. This makes it the world's largest consumer of hydrogen and a key player in the clean hydrogen transition.

Despite its importance, understanding China's hydrogen strategy remains challenging due to difficulties in accessing current information. As such, this report offers only a brief overview of China's known policy landscape.

China's National Hydrogen Industry Development Plan sets targets for 2025: 50,000 hydrogen fuel-cell vehicles and 100,000-—200,000 tons per year of green hydrogen production. Following the plan's release, China's approach has largely focused on directing state-owned enterprises (SOEs) to define exploration directions across the value chain (production, storage, transport, trade, and use).

This strategy encourages large-scale demonstration projects in "mega bases" spanning key provinces such as Ningxia (chemicals), Sichuan (inland shipping, fertilizer), Inner Mongolia (chemicals), Hebei (steel), Jiangsu and Fujian (shipping, aviation, trucks, fuel cell electric vehicles (FCEVs)). It is important to note that these provincial-level strategies and Five-Year Plans may not be perfectly aligned with the overall national direction, as is often the case in China. However, this regional fragmentation is a known feature of China's governance model, which leverages political decentralization to encourage local competition and policy experimentation. Despite China's robust track record in nurturing new industries and enhancing resilience through this state-driven approach, some observers remain skeptical about the feasibility and long-term economic viability of these heavily subsidized projects.

Beyond the targeted support of the *Hydrogen Industry Development Plan*, China also employs market mandates. The Renewable Portfolio Standard is a major policy instrument that sets a renewable electricity mandate for key industries, including aluminum, steel, cement, polysilicon, and new data centers. While its primary goal is to promote direct electrification, the standard also indirectly incentivizes the use of renewable hydrogen—hydrogen produced from renewable electricity—as a feedstock in steel and chemical production. Companies can meet the quota by building their own solar power, purchasing green electricity, or trading renewable energy certificates.

instrument to address demand risks in the steelmaking sector. The analysis also highlights the effectiveness of double-sided auctions and carbon-contracts-for-difference (CCfDs). These tools have the strongest effect on mitigating price and offtake risks while also contributing to regulatory and supply risk mitigation. This potential has been recognized by industry stakeholders. For example, the German steel industry has recently called for a dedicated steel tender under the H2Global double-sided auction to mitigate price and supply risks through a globally competitive, technology-open tender design.[72]

The EU's CBAM already applies to the steelmaking sector in Germany, along with other carbon leakage-prone industries like cement and aluminum.[73] However, its full impact will not be realized until the definitive regime begins in 2026. While the mechanism protects EU-based companies from unfair competition within the EU, it does not protect exporters targeting markets outside the bloc. Germany's existing CCfDs also cover the steelmaking sector, but only five approved projects so far focus on hydrogen-based solutions. To accelerate hydrogen uptake, Germany could consider introducing a dedicated hydrogen-specific CCfD with its own targeted budget or implementing a double-sided auction exclusively for steelmakers. Given current low carbon pricing and the limited enforcement of quotas, these instruments can effectively mitigate supply and price risks on a project basis while offering the flexibility needed in the steelmaking sector.

Chemicals

Given Germany's expected reliance on hydrogen imports, the chemical sector is likely to operate under a merchant business model, which faces very high supply and price risks, along with medium regulatory and offtake risks. As shown in Table 6, existing instruments such as the EU ETS and CCfDs have a strong effect on mitigating price and offtake risks, but a weaker impact on regulatory and supply risks, both of which remain key concerns.

IMAGE CREDIT: ADOBE STOCK / SNAPSHOTFREDDY

To address these key supply challenges, the analysis in Annex V highlights that double-sided auctions are the most suitable tool. Germany already has experience with this model through the H2Global mechanism, which could be leveraged to establish dedicated auctions for the chemical sector. Such auctions would provide the financial certainty needed to scale up hydrogen production by securing long-term contracts.

Germany's policy mix already includes several recommended instruments, but the must be strnegthened to accelerate the hydrogen transition while preserving industrial competitiveness.

To further accelerate the adoption of clean hydrogen in the chemical sector, Germany could also combine existing quotas and mandates with fossil fuel phase-outs. Since the sector offers multiple decarbonization pathways, such a combined approach would ensure that hydrogen, and not just electrification, plays a central role. Other key instruments Germany could consider include a book-and-claim system to decouple the physical supply of clean hydrogen-based chemicals from their environmental attributes, and public procurement of clean chemicals to help create initial demand.

Looking ahead: Addressing key gaps

From a broader perspective, Germany's policy mix already includes several recommended instruments, but they must be strengthened to accelerate the hydrogen transition while preserving Germany's industrial competitiveness. The most significant missing piece is a clear phase-out policy for fossil-based alternatives across all sectors, building on the approach successfully used by the heating sector.[74] Additionally, Germany could enhance existing tools by:

- Introducing **hydrogen-specific CCfDs**.
- Including **sector-targeted rounds** within the H2Global mechanism.
- Advocating for a **higher price floor** or a steeper reduction trajectory for allowances within the EU ETS to increase the market-driven carbon price.

By addressing these gaps, Germany can ensure its policies are not only supportive but also robust and effective in developing the clean hydrogen market required to enable transforming industries to maintain their global competitiveness amid challenging economic and international conditions.

Japan

As the world's fifth-largest energy consumer, Japan faces a fundamental energy challenge: it is an island nation that imports approximately 90% of its energy supply.[75] To address this dependency, the country is strategically positioning itself to become the world's second-largest market for hydrogen imports.[76] This is a long-standing ambition, with Japan having a history of hydrogen and fuel cell technology development dating back decades.

In the fiscal year 2022, Japan's energy mix remained heavily reliant on fossil fuels: natural gas (33.8%), coal (30.8%), and oil (8.2%).[77] Given its status as an island nation, 99% of Japan's trade relies on maritime transport—making decarbonization of this sector particularly important. The country operates the world's third-largest shipping fleet, with 102 major ports, 5 ports of international importance, and 18 international hub ports.[78]

Currently, Japan uses around 2 Mt of fossil fuel-based hydrogen annually for industrial processes, with roughly 70% used in oil refining and 30% in ammonia and methanol production.[79] The steel industry is a major source of emissions, accounting for nearly 14% of Japan's carbon footprint. As the world's third-largest crude steel producer in 2023 and 2024, the sector's output reached 84—87 Mt, with about 40% of its production exported.[80]

The Japan Hydrogen Association (JH2A) estimates that clean hydrogen demand across all industries could reach nearly 70 Mt/a by 2050, with the steel sector alone accounting for 20 Mt/a.[81] The 7th Strategic Energy Plan projects that the power sector will also be a major consumer, with hydrogen and ammonia demand reaching 3 Mt/a by 2030 for use in co-firing with coal.[82] The government additionally anticipates growing demand from the shipping sector and from fuel cell electric vehicles (FCEVs).

Hydrogen strategy and policy

To address its reliance on energy imports, Japan has positioned itself as a leader in hydrogen policy, having released the world's first national hydrogen strategy in 2017[83] and a major update in 2023.[84] While the current strategy prioritizes the development of a large-scale international supply chain, it also aims to establish 15 GW of domestic clean hydrogen production capacity by 2030. To fund this transition, the government plans to issue JPY 20 trillion (approximately EUR 405 billion) in sovereign Japan Climate Transition Bonds, which are designed to leverage JPY 150 trillion (EUR 870 billion) in public and private investment.[85]

A notable challenge, however, is the potential for a supply-demand mismatch: the government's clean hydrogen

IMAGE CREDIT: ADOBE STOCK / TIERNEY

supply projection for 2030 (3 Mt/a) aligns closely with the forecasted demand from the power sector, potentially leaving a gap for other key industries such as steel and chemicals.

Demand-side support tools

To foster its domestic clean hydrogen market, the Japanese government has implemented a range of demand-side support tools. These include carbon pricing, CAPEX support, funding for clean hydrogen hubs, cost-share premia, contracts-for-difference (CfDs), auctions, and investments in public infrastructure.

— **Hydrogen Hub Development Plan**: The government is strategically leveraging Japan's geography—where cities and industries are clustered along the coast—to establish clean hydrogen hubs. The Ministry of Economy, Trade, and Industry (METI) launched a Hydrogen Hub Development Program in March 2025, with a budget of USD 38 million (JPY 5.7 billion) to cover up to 50% of front-end engineering design (FEED) costs for shared infrastructure such as hydrogen tanks and pipelines.[86] In a second phase, selected hubs will receive CAPEX support for planned infrastructure, provided the project budgets are confirmed. This hub-based approach is designed to ensure supply security for first movers and provides CAPEX support to help them overcome initial infrastructure challenges.

- **Contracts-for-difference (CfDs)**: Given the steep cost-of-difference (CoD) for clean hydrogen, METI launched a CfD scheme in 2024 for low-carbon hydrogen and its derivatives—including ammonia, e-fuels, and e-methane—with a total budget of USD 21 billion (JPY 3 trillion). The CfD covers the CoD for 15 years, with an additional 10-year supply obligation for producers. While the support is formally directed at the supply side, offtakers benefit indirectly from the full CoD coverage. To qualify, projects must supply at least 1,000 t/a of low-carbon hydrogen to hard-to-abate sectors.[87]

- **Auctions**: The Tokyo Metropolitan Government launched a pilot double-sided auction in late 2024 under the *Tokyo Green Hydrogen Trial Trading* initiative. Similar to the H2Global model, it uses competitive bidding to determine both supplier selling prices and offtaker purchase prices. The trial focuses on process testing and building expertise, with a scope limited to three-month contracts, existing green hydrogen facilities, and the Tokyo metropolitan region.[88] Additionally, power companies can receive 20-year fixed capacity payments through the *Long-term Decarbonization Power Source Auction (LTDA)* to provide long-term income stability and offset substantial upfront costs. So far, five developers have been awarded subsidies through this auction.[89]

- **Cost-share premium**: METI has introduced a cost-share premium covering up to 75% of the price gap between diesel and hydrogen fuel at 90 hydrogen refueling stations across six prefectures for FCEV trucks, taxis, and buses.[90]

- **CAPEX support for strategic sectors**: JERA, Japan's largest power generator, received JPY 27.9 billion for two demonstration projects to co-fire 20% ammonia in coal-fired power plants, with a target of reaching 50% ammonia co-firing by 2029.[91]

- **Public infrastructure investment**: Japan's hydrogen strategy prioritizes the transport sector—including buses, trucks, shipping, and aviation—in the short, medium, and long term.[92] To support this, the government is financing further expansion of the hydrogen refueling station network through investments of up to JPY 1.7 billion (USD 11 million).[93]

- **Carbon pricing**: Japan employs a multipronged carbon pricing framework. The national Tax for Climate Change Mitigation imposes a modest fee of 289 JPY/t_{CO2} (2 USD/t_{CO2}) on fossil fuels.[94] High-emission industries will be required to participate in a national GX-ETS starting in 2026, following the current voluntary phase. In addition, a GX surcharge on fossil fuel imports will take effect in 2028.[95] Two regional ETSs—Tokyo and Saitama—already operate under this system, covering large-scale buildings and industrial facilities consuming over 1.5 million liters of crude oil equivalent per year.[96] Both have mandatory reduction targets, but enforcement mechanisms differ: the Tokyo ETS imposes financial penalties for non-compliance, whereas the Saitama ETS publishes the names of non-compliant companies and increases their emissions reduction targets for the following period.[97]

IMAGE CREDIT: ADOBE STOCK / FOTORIATONKO

Japan's strategic gaps and future outlook

While Japan has advanced a variety of hydrogen policies, its national ambition for a hydrogen economy is constrained by the limited scale and scope of its current instruments. Table 7 illustrates how demand-support instruments impact the risks faced by Japan's priority sectors[98]—road transport, power generation, steel, and chemicals—scored on a scale of 1 to 3. For each sector, this analysis first considers its risk profile, then evaluates the effectiveness of existing demand-side instruments, and finally identifies key policy gaps—drawing on the findings in Section 4—with recommendations for a more robust policy mix.

Road transport

The adoption of clean hydrogen in Japan's road transport sector faces very high regulatory, supply, and price risks, along with high offtake risk. As shown in Table 7, Japan has deployed a range of economic instruments to stimulate uptake; however, their effect on critical regulatory risk remains weak. Existing tools, such as subsidies for heavy-duty FCEVs and the Tokyo Green Hydrogen Trial Trading, are often either vehicle-specific, regional in scope, or small-scale, limiting their national impact. Moreover, while the sector is subject to a national carbon tax on fossil fuels, its effectiveness is constrained by the very low tax rate of approximately 2 USD/t_{CO2}, making it an ineffective tool for driving meaningful behavioral change.[99]

Based on these challenges, the main policy gap for road transport is the absence of strong regulatory signals. According to the analysis in Annex V, the most effective instruments to address these risks are quotas and mandates, as well as bans and phase-outs of alternative technologies. A carbon tax is also recommended, though its impact on supply risk is limited and would require complementary measures. Double-sided auctions could also play a role, but since they have only a weak effect on regulatory risk, they would need to be supported by complementary policies.

To establish a robust business case for clean hydrogen in road transport, Japan could strengthen its existing policy mix by implementing these measures. The progressive phase-out of fossil-based internal combustion engine vehicles is a strong first step but remains insufficient, as FCEVs compete with alternatives such as battery-electric and hybrid vehicles.[100] Therefore, phase-out policies should be accompanied by sub-quotas for clean hydrogen use. Given that FCEV deployment depends on a dense network of refueling stations, initial efforts should focus on areas with higher station density—such as Tokyo, Aichi, and Kanagawa—before expanding to other regions.[101] Japan could also consider scaling double-sided auctions to the national level, building on lessons from the *Tokyo Green Hydrogen Trial Trading* and/or H2Global auctions, to achieve broader impact in the road transport sector.

Power generation

In Japan's power generation sector, the adoption of clean hydrogen is hindered by very high regulatory risk, along with high supply and price risks and medium offtake risk. While Japan has deployed some instruments affecting power generation (see Table 7), their main impact has been on price risk, while their effect on the most critical challenge—regulatory risk—remains weak. This is primarily due to a recent policy shift under the 7th Strategic Energy Plan, which removed the previous 1% target for hydrogen or ammonia in the power mix by 2030.[102] Instead, these technologies are now described as "complementary options" for decarbonizing thermal power, which currently accounts for approximately 70% of Japan's power generation mix.[103] This creates a significant policy vacuum, despite major power companies such as JERA already integrating hydrogen and ammonia into their decarbonization strategies.[104]

To build a robust clean hydrogen market, Japan must consolidate its policy mix by introducing stronger regulatory signals and scaling up its most promising initiatives.

According to the analysis in Annex V, the most relevant instruments to support demand growth in Japan's power generation sector are quotas and mandates, as well as bans and phase-outs of alternative technologies. These measures exert medium to strong effects—particularly on regulatory and supply risks, which are highly significant for this sector. The analysis also highlights the importance of ecolabeling and guarantees of origin, which could enhance the market value of clean hydrogen and ammonia by providing transparent sustainability attributes to end consumers of electricity.

To establish a strong business case for clean hydrogen, Japan could consider introducing quotas or mandates for hydrogen and its derivatives, such as ammonia. The planned phase-out of inefficient coal-fired plants foreseen under the 7th Strategic Energy Plan presents an opportunity for these fuels, even with renewable energy offering a clear long-term alternative. However, Japan's significant geographic constraints, such as its steep seafloor and limited flat land, limit renewable energy production capacity.

Box 4: Renewable hydrogen demand support in India[105]

India, one of the world's fastest-growing economies, faces a corresponding increase in energy demand. In 2023, the country's energy supply remained heavily reliant on fossil fuels—primarily coal (45.8%), with oil (25%) and natural gas (5.4%) also contributing significantly to its total energy mix. At present, India consumes approximately 10% of global hydrogen, primarily for refining and fertilizer production. To reduce its reliance on fossil fuels and establish itself as a global hub for clean hydrogen, the government launched the National Green Hydrogen Mission (NGHM) in 2023. The mission sets a production target of at least 5 Mt/a by 2030, with the potential to reach 10 Mt/a depending on export market growth. Additionally, several states, such as Odisha, Gujarat, Maharashtra, and Uttar Pradesh, have also introduced policies and financial incentives to advance the green hydrogen economy.

The NGHM combines both financial and non-financial measures to support the entire renewable hydrogen value chain. Its core financial instrument is the Strategic Interventions for Green Hydrogen Transition (SIGHT) program, with a total budget of INR 175 billion (EUR 1.92 billion). On the demand side, the mission supports a wide range of initiatives, including pilot projects in steel, mobility, and shipping; the development of hydrogen hubs and related infrastructure; the establishment of regulatory and safety standards; the use of auction mechanisms for both exports and domestic utilization; and investments in research and development, skills training, and public awareness campaigns.

A key supply-side initiative under the SIGHT program is the tender issued in 2024 by the Solar Energy Corporation of India Limited (SECI) to decarbonize the fertilizer sector. The tender aims to secure the supply of 724 kt/a of renewable ammonia for thirteen fertilizer plants. Seven producers were awarded subsidies for the first three years of their ten-year, fixed-price delivery contracts, with winning bids achieving prices in the range of 49.75—64.74 INR/kgNH_3 (580—750 USD/tNH_3).

India is also discussing blending mandates and demand aggregation through procurement processes to achieve economies of scale and long-term price stability. To further reduce production costs, the mission provides strategic flexibility. For instance, hydrogen projects located in Special Economic Zones can be exempted from the strict requirement to use only solar panels from the Approved List of Models and Manufacturers (ALMM) for their own power consumption. This flexibility serves as a key lever for achieving cost reductions and accelerating project deployment.

Additionally, seasonal supply variability, especially in winter, further challenges the reliability of renewables as the sole pathway for power-sector decarbonization.[106] Given these limitations and ongoing concerns about supply capacity shortages, phase-out policies alone will not create a robust business case for clean hydrogen and its derivatives.[107] They must be complemented by quotas or mandates—for example, setting minimum thresholds for ammonia co-firing in thermal power generation.

Steelmaking

The adoption of clean hydrogen in Japan's steelmaking sector is challenged by very high price and offtake risks, as well as medium supply and regulatory risks. While Japan has introduced supply-side measures such as funding for research and development to support the transformation of steelmaking processes,[108] there are relatively few demand-side incentives for using clean hydrogen in the industry (see Table 7). As a hard-to-abate sector, steelmaking is eligible for the national CfD scheme and the Tokyo Metropolitan Government's double-sided auction. It is also covered by the regional Tokyo and Saitama ETSs, as well as the national GX-ETS, which remains under development.[109]

However, these tools have significant limitations. For example, the Tokyo double-sided auction is limited by its focus on transport containers and existing facilities, while the current carbon prices from the regional ETS are too low to stimulate the uptake of cleaner alternatives—standing at 600 JPY/ t_{CO2} (approximately 4 USD/ t_{CO2}) for Tokyo and 144 JPY/ t_{CO2} (approximately 1 USD/ t_{CO2}) for Saitama in 2025.[110]

According to the analysis in Annex V, the most suitable instrument for this sector would be a robust Carbon Border Adjustment Mechanism (CBAM). However, with import

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penetration at just over 10% in 2024,[111] CBAM may not be the most relevant tool for Japan. Instead, the most critical need is to strengthen the domestic carbon pricing system. The effectiveness of the GX-ETS will depend on transitioning from its current voluntary phase to a mandatory one and on setting a strict and progressively tightening cap on emissions. To achieve its intended effect, experts emphasize the importance of phasing out free allocations in favor of auctioning and generating revenues to correct potential market distortions.[112]

Other high-ranking instruments identified in the analysis include a carbon tax, double-sided auctions, and CfDs, all of which are already in place but require stronger incentives to be utilized effectively.

Chemicals

As Japan is expected to import most of its hydrogen, the chemical sector will likely operate under a merchant business model. This model faces very high supply and price risks, along with medium regulatory and offtake risks. As shown in Table 7, existing instruments—such as the national CfD scheme and the *Tokyo Green Hydrogen Trial Trading*—have a strong effect on supply and price risks. However, impact on regulatory risks remains weak. Moreover, the Tokyo auction has limited relevance for the chemical sector, since major players such as Mitsubishi Chemical Group,[113] Toray Industries,[114] and Sumitomo Chemical[115] operate plants outside of Tokyo,[116] and the trial itself focuses only on existing renewable hydrogen facilities within the region. In parallel, the chemical sector is also subject to the regional Saitama and Tokyo Emissions Trading Systems and will fall under the forthcoming national GX-ETS, all of which are designed to mitigate regulatory risks.

According to the analysis in Annex V, the most suitable instrument to address the risks faced by the chemical sector would be a double-sided auction, as it strongly mitigates both supply and price risks. The analysis also identifies other suitable instruments, including quotas and mandates, as well as bans and phase-outs of alternative technologies.

The chemical industry has several technological pathways for decarbonization. These include electrification of process heat, fuel switching in naphtha cracking furnaces (e.g., from oil to natural gas, ammonia, or hydrogen) and raw material substitution (e.g., producing polymers from biomass or replacing fossil-based hydrogen with clean hydrogen for methanol or ammonia production).[117] However, as in other sectors, bans on specific fuels—such as coal—would not necessarily create a business case for clean hydrogen, as companies could instead shift to natural gas. To strengthen incentives, Japan could introduce sub-quotas for hydrogen utilization in the chemical sector to complement bans and phase-outs, ensuring that clean hydrogen is explicitly integrated into decarbonization pathways.

Looking ahead: Addressing key gaps

From a wider standpoint, Japan has already deployed a variety of policy instruments, but many remain regionally limited or target narrow applications, reducing their overall scope and effectiveness. To build a robust clean hydrogen market, Japan must consolidate its policy mix by introducing stronger regulatory signals and scaling up its most promising initiatives.

— **Strengthen carbon pricing**: Japan's national carbon tax—Tax for Climate Change Mitigation—is limited by its low price of approximately 2 USD/t_{CO2} and by exemptions for high-emitting industries.

Table 7a: Risk profiles and instrument effects on key sectors in Japan

Japan	Road		Power generation		Steel DRI		Chemicals (merchant business model)	
Risks	Instrument	Effect	Instrument	Effect	Instrument	Effect	Instrument	Effect
Regulatory risk	very high risk		very high risk		medium risk		medium risk	
	Contract-for-difference	1	Long-term Decarbonization Power Source Auction (LTDA)	1	Contract-for-difference	1	Contract-for-difference	1
	Hydrogen Hub Development Program	1	Contract-for-difference	1	Tokyo Green Hydrogen Trial Trading*	1	Tokyo Green Hydrogen Trial Trading*	1
	Tokyo Green Hydrogen Trial Trading*	1	Tokyo Green Hydrogen Trial Trading*	1	Hydrogen Hub Development Program	1	Hydrogen Hub Development Program	1
	Tax for Climate Change Mitigation	3	Hydrogen Hub Development Program	1	ETS*	3	ETS*	3
			Tax for Climate Change Mitigation	3	Tax for Climate Change Mitigation	3	Tax for Climate Change Mitigation	3
Supply risk	very high risk		medium risk		medium risk		very high risk	
	Tax for Climate Change Mitigation	1	Tax for Climate Change Mitigation	1	ETS*	1	ETS*	1
	Contract-for-difference	2	Contract-for-difference	2	Tax for Climate Change Mitigation	1	Tax for Climate Change Mitigation	1
	Hydrogen Hub Development Program	3	Tokyo Green Hydrogen Trial Trading*	3	Contract-for-difference	2	Contract-for-difference	2
	Subsidies for refueling stations	3	Hydrogen Hub Development Program	3	Tokyo Green Hydrogen Trial Trading*	3	Tokyo Green Hydrogen Trial Trading*	3
	Tokyo Green Hydrogen Trial Trading*	3	Long-term Decarbonization Power Source Auction (LTDA)	3	Hydrogen Hub Development Program	3	Hydrogen Hub Development Program	3

Legend

* Regional or local incentive

Risk level	Instrument effect on risks
Very low risk	0 = no effect
Low risk	1 = weak effect
Medium risk	2 = medium effect
High risk	3 = strong effect
Very high risk	

GX-ETS is not included.

A significant increase in the carbon tax rate will be required to incentivize meaningful behavioral change. The government should also ensure that the upcoming GX-ETS is robustly designed with a strict cap, phasing out free allocations in favor of auctioning to influence industry behavior as intended. Revenues could be reinvested in clean initiatives such as double-sided auctions or CfDs.

— **Scale up auction mechanisms**: The *Tokyo Green Hydrogen Trial Trading* demonstrates a successful approach to bridging price gaps and testing trading processes.[118] Japan could build on this experience by establishing a national double-sided auction scheme or adopting mechanisms similar to H2Global to achieve broader impact across key sectors.

— **Sharpen bans and phase-outs of alternative technologies:** Bans and phase-outs are powerful

Table 7b: Continuation of risk profiles and instrument effects on key sectors in Japan

Japan	Road		Power generation		Steel DRI		Chemicals (merchant business model)	
Risks	Instrument	Effect	Instrument	Effect	Instrument	Effect	Instrument	Effect
Offtake risk	medium risk		very low risk		high risk		medium risk	
	Contract-for-difference	2	Long-term Decarbonization Power Source Auction (LTDA)	1	Infrastructure provision	1	Amortization account	2
	Fixed premia	2	Tax for Climate Change Mitigation	1	Contract-for-difference	2	CCfD	2
	Hydrogen Hub Development Program	2	Contract-for-difference	2	Tokyo Green Hydrogen Trial Trading*	2	EU ETS	2
	Tokyo Green Hydrogen Trial Trading*	2	Hydrogen Hub Development Program	2	Hydrogen Hub Development Program	2	H2Global	2
	Tax for Climate Change Mitigation	2	Tokyo Green Hydrogen Trial Trading*	2	Tax for Climate Change Mitigation	2	CBAM	2
			Tax for Climate Change Mitigation	2	ETS*	2		
Price risk	very high risk		medium risk		very high risk		very high risk	
	Fixed premia	2	Long-term Decarbonization Power Source Auction (LTDA)	2	ETS*	2	ETS*	2
	Hydrogen Hub Development Program	2	Hydrogen Hub Development Program	2	Hydrogen Hub Development Program	2	Hydrogen Hub Development Program	2
	Contract-for-difference	3	Tokyo Green Hydrogen Trial Trading*	3	Contract-for-difference	3	Contract-for-difference	3
	Tokyo Green Hydrogen Trial Trading*	3	Contract-for-difference	3	Tokyo Green Hydrogen Trial Trading*	3	Tokyo Green Hydrogen Trial Trading*	3
	Subsidies for refueling stations*	3	Tax for Climate Change Mitigation	3	Tax for Climate Change Mitigation	3	Tax for Climate Change Mitigation	3
	Tax for Climate Change Mitigation	3						

policy tools that warrant consideration, even amid implementation challenges. This is particularly relevant in contexts like Japan, where meeting the rapidly increasing power demand (e.g., from AI/data centers) is a priority. To succeed, policy design must allow Japan's evolving energy demand needs to be met. Moreover, since industries can decarbonize in multiple ways—not only with clean hydrogen— bans and phase-outs must be complemented by additional tools that directly incentivize hydrogen use in specific sectors.

— **Implement quotas and mandates**: Quotas and mandates are high-ranking instruments for driving domestic industrial adoption of low-carbon technologies. However, their effectiveness is severely tested by exposure to intense international competition, which has contributed to slow progress in many jurisdictions. Successful implementation depends on clear and realistic timelines, adequate support mechanisms, and transparency in enforcement. The German case study illustrates these challenges: the 2% FuelEU Maritime target applies only under specific conditions—such as the availability of RFNBOs—which may be difficult to achieve without strong coordination between government and industry.[119]

By addressing these gaps, Japan can ensure that its policies are not only supportive but also effective in establishing the robust clean hydrogen market required for its industrial future.

IMAGE CREDIT: ADOBE STOCK / DIMA

United States

The U.S. is one of the world's largest economies, with manufacturing representing a significant portion of its nominal GDP.[120] Its energy system, while diverse, remains heavily reliant on fossil fuels for primary consumption, with natural gas and petroleum dominating the mix.[121] This reliance is underpinned by the nation's vast domestic reserves of oil and gas. At the same time, the U.S. possesses substantial land and solar resources that offer immense potential for renewable energy development. As the world's second-largest hydrogen consumer, with demand of approximately 13 Mt annually for refining, ammonia, and petrochemicals, the U.S. has a well-established industrial base for the fuel.[122] This existing infrastructure, production capacity, and consumption provide a critical foundation upon which a new clean hydrogen economy can be built.

Hydrogen strategy and policy

Until recently, the U.S. pursued a clean hydrogen strategy driven by a dual ambition of decarbonization and energy independence. This approach is anchored in its *National Clean Hydrogen Strategy and Roadmap*, which sets ambitious demand targets, projecting an increase from 10 Mt by 2030 to 50 Mt by 2050. The strategy prioritizes key sectors with limited or no other viable decarbonization alternatives, such as heavy-duty transport, energy storage, power generation, and certain industrial applications including ammonia, biofuels, and steel.[123]

Under the Biden Administration, the foundation of the U.S. hydrogen strategy rested on two major legislative acts: the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA). The IRA provides supply-side incentives through tax credits for clean hydrogen production (45V), electricity (45Y and 48E), and carbon sequestration (45Q). The IIJA, also known as the Bipartisan Infrastructure Law, allocated USD 8 billion for the Regional Clean Hydrogen Hubs (H2Hubs) program, including USD 1 billion in subsidies specifically to support demand development within the hubs.[124] The H2Hubs program aims to create a national network connecting producers, consumers, and infrastructure to build economies of scale.

In addition, a "patchwork" of state-level policies supports hydrogen development alongside other decarbonization technologies. These include the California Low Carbon Fuel Standard and the Regional Greenhouse Gas Initiative, a cap-and-trade program spanning eleven states.

The arrival of the new U.S. administration has considerably altered the outlook for clean hydrogen in the U.S. For example, under the One Big Beautiful Bill Act (OBBBA), the Trump administration shortened the eligibility deadline for the IRA's 45V tax credit. To qualify, projects must now begin construction by the end of 2027—a five-year acceleration from the original timeline—while the 45Q tax credit for carbon sequestration remains largely unchanged.

The arrival of the new U.S. administration has considerably altered the outlook for clean hydrogen in the U.S.

Coupled with the administration's unfavorable stance on wind and solar, and competition from data centers for gas supply and electricity generation, these changes could reduce the number of clean hydrogen projects moving forward, thus tightening supply.[125] Furthermore, the Department of Energy has publicly stated that it is considering rolling back funding for four of the seven selected H2Hubs, representing a potential reduction of about USD 4 billion. This policy instability has already led to projects having their funding frozen or canceled, prompting industry leaders to warn that investments may be diverted elsewhere.[126]

Demand-side support tools

While the U.S. has traditionally been skeptical of market interventions, especially on the demand side, a variety of federal and state-level demand-side initiatives exists. These include hub development support, regional ETS programs, loans, book-and-claim mechanisms, CAPEX support, loan guarantees, and regional mandates. Nevertheless, the continuation of most—if not all—of the federal support instruments is currently under review by the Trump administration, casting uncertainty over their future.

Federal initiatives

— **Regional Clean Hydrogen Hubs (H2Hubs)**: This program aims to accelerate clean hydrogen deployment by connecting producers, consumers, and infrastructure. Funded by the Bipartisan Infrastructure Law, the program allocated USD 8 billion, including USD 1 billion for demand-side subsidies.[127]

— **Targeted CAPEX support**: The federal government offers CAPEX support for zero-emission vehicles (ZEVs). The Airport ZEV and Infrastructure Pilot Program provides compensation of up to 50% of CAPEX for ZEVs and retrofitting of related infrastructure.[128] Similarly, the Clean School Bus Program and the Charging and Fueling Infrastructure Grant Program invest over USD 6.3 billion to replace conventional buses with zero-emission or alternative-fuel buses and support refueling infrastructure.[129]

— **Commercial vehicle tax credits**: The Commercial Electric Vehicle and Fuel Cell Electric Vehicle Tax Credit offers a USD 40,000 subsidy for a large private vehicle weighing over six tons, aiming to reduce the cost of clean transport and improve the refueling infrastructure to reduce fuel supply risk.[130]

State-level policies and market mechanisms

— **Clean transport mandates and incentives**: California's zero-emission bus mandate creates a guaranteed market for clean-fuel vehicles. This is complemented by the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) and the Zero-Emission Heavy-Duty Truck Infrastructure Loan Pilot Project, which operates through a loan-loss reserve system in which the state covers 20% of defaults.[131]

— **Regional clean fuel standards**: California, Oregon, Washington, and New Mexico coordinate clean fuel certification through the Low Carbon Fuel Standard Initiative (LCFS), which requires a reduction in the carbon intensity of fuels.[132]

— **"Buy Clean" initiatives**: California, Colorado, and Oregon have Buy Clean programs that create lead markets for low-carbon industrial materials by prioritizing their use in public projects.[133] These state-level initiatives are currently being legally challenged by the federal administration, which has already canceled the federal Buy Clean program.[134]

— **Regional carbon pricing**: The Regional Greenhouse Gas Initiative (RGGI), a mandatory cap-and-trade program across eleven states, targets the power sector.[135] It requires power plants to purchase allowances for emissions, with prices ranging from 16—25 USD/ t_{CO2} in 2024—2025.[136]

Private and hybrid mechanisms

— **Book-and-claim systems:** The Sustainable Aviation Fuel (SAF) Certificates Registry enables the tracking and trading of clean fuel and material attributes, even without physical delivery.[137]

- **Joint procurement platforms:** The Sustainable Aviation Buyers Alliance (SABA), Zero Emission Maritime Buyers Alliance (ZEMBA), and Sustainable Steel Buyers Platform use variations of demand aggregation models for SAF, sustainable shipping fuel, and steel from their members. These platforms send a clear market signal to producers, helping accelerate the transition. While SABA and ZEMBA are based in the U.S., both initiatives are active internationally.[138]

United States strategic gaps and future outlook

The U.S. aims to stimulate demand for clean hydrogen in hard-to-abate sectors.[139] Table 8 outlines the basic effects of demand support instruments on the risks faced by the country's key sectors—road transport, aviation, steel, and chemicals—on a scale from 1 to 3. For each sector, the analysis first considers its unique risk profile, then assesses the effectiveness of current demand-side instruments, and finally identifies strategic gaps with recommendations for a more robust policy mix.

Road transport

In the U.S. road transport sector, the path to adopting clean hydrogen is hindered by very high regulatory, supply, and price risks, and medium offtake risk. Although various support instruments are in place (see Table 8), they are often localized and primarily address offtake risk, with variable effects on the sector's main challenges. For example, policies such as California's zero-emission bus mandate create some demand but do not specifically prioritize clean hydrogen, allowing competition from other technologies.

The analysis in Annex V highlights that quotas and mandates, as well as bans and phase-outs, are among the most effective tools for mitigating risks in the road transport sector. However, bans, phase-outs, quotas and mandates are not considered politically viable at the federal level in the U.S. A pragmatic first step in this direction would be to introduce hydrogen-specific sub-targets within existing state mandates for vehicle categories like heavy-duty trucks.[140]

Box 5: Demand side policies in the Global South: The case of Uruguay[141]

Uruguay is positioning itself as a potential leader in clean hydrogen production in Latin America, boasting some of the most competitive renewable hydrogen prices worldwide. This advantage stems from its abundant solar and wind resources, which have enabled a remarkable energy transformation over the past decade. Historically reliant on oil imports and vulnerable to price volatility and power outages, the country now sources nearly 100% of its electricity mix from renewables. This achievement is the result of a comprehensive package of demand- and supply-side measures.

Regulatory instruments have played a central role in this transition. In 2022, Uruguay introduced a national carbon tax on gasoline to curb emissions in the transport sector. The country has also implemented specific mandates and quotas to de-risk renewable energy investments. For example, Law 18.195 (2012) set a 5% bioethanol blending mandate to be met with domestically produced biofuels. Similarly, Law 18.585 on Solar Thermal Energy Promotion requires hotels and hospitals to source at least 50% of their water heating energy from solar thermal, provided it represents 20% or more of their total energy consumption.

These policies were complemented by a suite of financial instruments. Plan Solar (2012) offered households refundable credits for installing solar water heaters, aligned with the electricity savings generated. For transport, Law 19.670 (Article 349) introduced subsidies to bridge the cost gap between electric and diesel buses. Additionally, the Energy Efficiency Certificates scheme provides a unique incentive, rewarding verified energy-saving measures by covering up to 30% of investment costs for a wide range of beneficiaries, from households and small businesses to electric vehicle owners.

Building on this success, Uruguay's renewable hydrogen strategy is spearheaded by the H2U Program, an inter-institutional initiative aimed at promoting the entire hydrogen value chain. The government has established a Green Hydrogen Sector Fund to provide non-reimbursable financial support for pilot projects. For instance, one pilot focusing on producing renewable hydrogen for heavy-duty transport received a USD 10 million grant. To attract large-scale investment, the country's Investment Promotion and Protection Law now offers tax exemptions and benefits for hydrogen projects. In support of its export-oriented strategy, the state-owned oil company ANCAP has launched the H2U Offshore program to tender offshore wind farms dedicated to large-scale renewable hydrogen production.

IMAGE CREDIT: ADOBE STOCK / JAG_CZ

That said, the success of any quota-based policy is contingent on the availability of sufficient refueling infrastructure, which is currently concentrated almost exclusively in California. As such, initial quotas should be rolled out in states with established infrastructure while others prepare for deployment. To complement this, expanding state-level clean fuel standards into a nationwide carbon pricing mechanism would create a more consistent market signal. Such a system could target fuel emission intensity, allowing hydrogen to generate credits based on avoided emissions. To accelerate this transition, the U.S. could also adapt proven international models, such as H2Global's double-sided auctions, to help bridge the price gap and accelerate clean hydrogen uptake in the road transport sector.

Aviation sector

The U.S. commercial aviation sector is a major economic engine,[142] accounting for roughly 5% of national GDP, but it faces significant risks in its decarbonization journey, particularly a high regulatory risk and medium supply and price risks. Current efforts focus on stimulating the uptake of sustainable aviation fuels (SAF), viewed as a key near-term solution.[143] Federal incentives like the 40B tax credit[144] and various state-level subsidies are in place, but they are primarily oriented toward bio-based SAF[145] rather than e-SAF (synthetic fuels derived from clean hydrogen). This bias creates a challenge for expanding hydrogen's role in the sector.

As shown in Table 8, the primary demand-side instrument currently in use is the non-governmental Sustainable Aviation Fuel Certificates (SAFc) book-and-claim system. Even though this system effectively addresses supply and offtake risks, it does not tackle the sector's main challenge: regulatory risk.

To fill this policy gap, the U.S. could introduce more robust regulatory signals. The analysis in Annex V highlights that quotas and mandates are the most effective tools for mitigating regulatory risk and have medium-to-strong effects on supply and price risks. While bans and phase-outs of alternative technologies are also highly effective, they are not considered politically viable in the U.S. Therefore, a more pragmatic approach would be to introduce progressive quotas for e-SAF to create a strong and stable demand signal for clean hydrogen and its derivatives in the aviation fuel mix. To support this, ecolabeling and guarantees of origin could be implemented to certify the clean attributes of e-SAF, adding regulatory credibility and transparency to the existing book-and-claim system and helping justify the green premium to consumers.

IMAGE CREDIT: ADOBE STOCK / DEDMITYAY

Steelmaking

Very high price and offtake risks represent the primary obstacles to the introduction of clean hydrogen in the U.S. steelmaking sector, where supply and regulatory risks are considered medium. As shown in Table 8, the U.S. had planned a set of now-threatened instruments that would have supported hydrogen use in steelmaking: demand aggregation, direct public procurement, and the H2Hubs program. If implemented, these instruments would have primarily helped address medium-rated supply risks but offered only a moderate impact on the more critical price and offtake risks. Consequently, the substantial cost gap between conventional steelmaking and cleaner, hydrogen-based production would have remained largely unaddressed.

While starting with carbon taxes a the state level could provide a blueprint for later national adoption, the approach must be balanced against the potential of carbon leakage.

The analysis in Annex V suggests that the U.S. could deploy a combination of stronger policy instruments to promote clean hydrogen use in steelmaking. The most impactful options would be a carbon border adjustment mechanism (CBAM), a carbon tax, and double-sided auctions. A carbon tax is a critical prerequisite for a CBAM, which is particularly relevant given that imports accounted for over a quarter (26.7%) of apparent steel consumption in 2024.[146] A CBAM would protect domestic producers from carbon leakage and ensure a level playing field.

The design of a carbon tax, however, presents significant complexities. A federal-level tax would need to be carefully structured to avoid double taxation with existing state-level systems, such as California's. While starting with carbon taxes at the state level could provide a blueprint for national adoption, this approach must be balanced against the potential for small-scale carbon leakage. The tax itself would need to be set high enough to drive a market shift while being gradually phased in to manage impacts on end users. As a complementary measure, adapting proven international mechanisms such as H2Global's double-sided auctions could directly narrow the price differential and accelerate project deployment. That said, the current administration's continued support for fossil fuels creates a more complex context for the deployment of such tools.

Chemicals

The chemical sector is the second-largest user of hydrogen in the U.S., after the petroleum refining sector.[147] The chemical industry consumes approximately 10 Mt annually for processes such as the production of ammonia and methanol, making it a prime candidate to anchor U.S. demand for clean hydrogen.[148] The sector is expected to operate under a captive business model and faces a unique risk profile, with very high regulatory risk followed by medium offtake and price risks. Despite this, several chemical projects utilizing clean hydrogen are moving ahead, primarily targeting hydrogen-derived fuels for export markets (e.g., ammonia) or domestic use in the SAF value chain.

As shown in Table 8, the chemical industry receives the least policy support among the key sectors. Current attention is largely limited to its inclusion under the Regional Clean Hydrogen Hubs program, which strongly reduces supply risk but has only a weak effect on regulatory risk—the main challenge for the sector. This creates a significant gap if the objective is to stimulate hydrogen uptake in chemicals.

Table 8: Risk profiles and instrument effects on key sectors in the United States

United States	Road		Power generation		Steel DRI		Chemicals (merchant business model)	
Risks	Instrument	Effect	Instrument	Effect	Instrument	Effect	Instrument	Effect
Regulatory risk	very high risk		high risk		medium risk		very high risk	
	Charging and Fueling Infrastructure Grant Program	1	Sustainable Aviation Fuel certificates	1	Sustainable Steel Buyers Platform	1	H2Hubs	2
	Zero-Emission Heavy-Duty Truck Infrastructure Loan Pilot Project	1			H2Hubs	1		
	Zero-emission bus mandate*	3			Buy Clean Initiatives*	1		
	Low Carbon Fuel Standard	3						
Supply risk	very high risk		medium risk		medium risk		very low risk	
	Low Carbon Fuel Standard	1	Sustainable Aviation Fuel certificates	3	Sustainable Steel Buyers Platform	3	H2Hubs	2
	Zero-Emission Heavy-Duty Truck Infrastructure Loan Pilot Project	1			H2Hubs	3		
	Zero-emission bus mandate*	3			Buy Clean Initiatives*	3		
	Charging and Fueling Infrastructure Grant Program	3						
Offtake risk	very high risk		medium risk		medium risk		very low risk	
	Charging and Fueling Infrastructure Grant Program	1	Sustainable Aviation Fuel certificates	3	Buy Clean Initiatives*	1	H2Hubs	2
	Zero-emission bus mandate*	2			Sustainable Steel Buyers Platform	2		
	Commercial Electric Vehicle and FCEV Tax Credit	2			H2Hubs	2		
	Low Carbon Fuel Standard	2						
Price risk	very high risk		medium risk		medium risk		very low risk	
	Zero-emission bus mandate*	1	Sustainable Aviation Fuel certificates	3	H2Hubs	2	H2Hubs	2
	Low Carbon Fuel Standard	1			Sustainable Steel Buyers Platform	2		
	Commercial Electric Vehicle and FCEV Tax Credit	3			Buy Clean Initiatives*	2		
	Clean School Bus Program; Airport ZEV and Infrastructure Pilot Program; HVIP*	3						

Legend

* Regional or local incentive

Risk level	Instrument effect on risks
Very low risk	0 = no effect
Low risk	1 = weak effect
Medium risk	2 = medium effect
High risk	3 = strong effect
Very high risk	

The analysis in Annex V indicates that a carbon tax would be the most effective instrument to address the risks affecting clean hydrogen demand buildup in the chemical sector, as it strongly mitigates regulatory risk and has a medium-to-strong impact on offtake and price risks.

Quotas and mandates could also be deployed, for example, by requiring a minimum percentage of hydrogen in ammonia or methanol production to come from low-carbon sources. The implementation of such measures, however, must navigate the current political landscape, which continues to signal support for fossil fuels.

Looking ahead: Addressing key gaps

The U.S. is currently navigating a period of extreme policy uncertainty regarding clean energy, as the new administration has signaled a strong preference for fossil fuels and a rollback of green initiatives. While federal support for clean hydrogen now seems unlikely, it may reemerge in the future. Comprehensive federal-level policies that prioritize both demand- and supply-support—including instruments such as carbon pricing, carbon border adjustment mechanisms (CBAMs), quotas and mandates, and bans or phase-outs of high-carbon technologies—could play a key role in unlocking the U.S. clean hydrogen market.

— **Implement carbon pricing and an ETS**: A federal carbon tax or an ETS is a critical lever to drive decarbonization and stimulate demand for low-carbon alternatives. While the U.S. currently employs some carbon pricing at the state level, a national mechanism is needed to ensure broad impact. A CBAM can only be effectively implemented once a domestic carbon pricing system is in place, as it is designed to ensure a level playing field between domestic production and imports from jurisdictions with weaker carbon constraints. To be effective, any carbon pricing system would need to be designed to avoid double taxation while maximizing overall coverage.

— **Adopt quotas and mandates**: Although an uncommon approach for the U.S., quotas and mandates are high-ranking instruments that can drive industries toward adopting low-carbon technologies. Their effectiveness, however, depends on clear implementation timelines and adequate support mechanisms. These measures are largely absent at the federal level but could provide a clear regulatory signal to industries.

— **Scale up auction mechanisms**: The U.S. could leverage auction mechanisms, which have proven successful in other markets, to bridge the price gap for clean hydrogen. Adopting national double-sided auction schemes or adapting existing models such as H2Global's could accelerate demand creation and provide price certainty for both producers and consumers.

By addressing these key gaps and strengthening its policy mix with a combination of robust carbon pricing, clear mandates, and effective market mechanisms, the U.S. could establish the robust clean hydrogen market required for its industrial future.

IMAGE CREDIT: ADOBE STOCK / AMORN

Building a hydrogen economy: Lessons from Germany, Japan, and the U.S.

The global race to develop a clean hydrogen economy reveals that a successful pathway relies on a combination of long-term political commitment, a coherent policy mix, and the strategic use of public-private partnerships. While all three countries examined emphasize the importance of hydrogen in key industrial sectors, their differing approaches offer distinct lessons for building a resilient hydrogen market.

The criticality of political commitment

A foundational insight is that long-term political commitment is paramount. The U.S. case highlights the vulnerability of a strategy heavily reliant on specific legislative acts, as demonstrated by the uncertainty created by the Trump administration's adjustments to the Inflation Reduction Act (IRA) and its review of the Hydrogen Hubs Program. In contrast, Germany and Japan have provided stronger long-term signals through instruments that guarantee price certainty over many years, such as Japan's 15-year contracts-for-difference (CfDs) and Germany's long-term commitment to H2Global auctions, with funding currently allocated until 2038. These long-term commitments are essential for building trust and de-risking the massive capital investments required for clean hydrogen projects.

Successful policy pathways

While the U.S. (through production tax credits) and Germany (through fixed premia via EHB auctions, double-sided auctions via H2Global, and tax exemptions for electrolyzers) provide substantial supply-side support, comparable demand-side initiatives are less developed. The most effective strategies combine a "stick-and-carrot" approach. The "sticks" are regulatory instruments, such as quotas, mandates, and carbon pricing, which create a market pull for clean hydrogen. Although these instruments intervene in entrepreneurial decision-making and increase costs, they are nevertheless effective in mitigating offtaker risks. The "carrots" are financial tools that bridge the cost gap between conventional and clean hydrogen. Germany and Japan, in particular, have demonstrated the power of this combination by employing instruments such as double-sided auctions and CfDs to directly address the cost-of-difference (CoD). These tools not only reduce financial risk but also help suppliers and offtakers build the contractual connections needed for a functioning market.

The case studies show that many offtaker risks can be addressed through regulatory instruments and carbon pricing in different forms. Nevertheless, their effectiveness depends on the political willingness to use interventions such as quotas, mandates, and carbon pricing systems that cover all relevant markets, set sufficiently high carbon prices, and maintain a level playing field under international competition. To be fully effective, carbon pricing systems must be implemented nationally—and preferably internationally—to avoid carbon leakage. Both regulatory intervention and carbon pricing place a burden on offtakers, increasing their willingness to adopt clean hydrogen or other decarbonization pathways.

Infrastructure and hubs are also critical. The U.S. and Japan prioritize a hub-and-spoke model to minimize infrastructure needs and foster synergies by co-locating supply and demand. Additionally, all three countries support the development of infrastructure and the regulation of certification and trade rules to enhance access to clean hydrogen and its derivatives. While Germany focuses on long-distance pipelines linking production sites and ports to offtakers, Japan and the U.S. emphasize refueling infrastructure and hydrogen hubs to achieve efficiency through concentration. These priorities reflect each country's geography, key sectors, and underlying political preferences, illustrating that a successful infrastructure plan must be tailored to national circumstances.

Long-term political commitment is paramount for the success of the clean hydrogen economy.

Finally, public-private partnerships are a powerful tool for accelerating market development. While the U.S. strategy has been a "patchwork" of federal and state-level efforts, it has also leveraged private-sector initiatives such as the Sustainable Aviation Buyers Alliance (SABA) and the Zero Emission Maritime Buyers Alliance (ZEMBA). These joint procurement platforms and book-and-claim systems aggregate private-sector demand, providing a clear market signal to producers and helping de-risk private investments.

A coherent future

Moving forward, the key to success lies in building a coherent and coordinated national framework. The U.S. case study demonstrates that a fragmented approach, with varying levels of ambition between federal and state governments, can create conflicting signals and challenges such as carbon leakage. To reach its full potential, a successful hydrogen economy requires a unified policy that strategically combines supply-side incentives with robust demand-side measures, is underpinned by long-term political will, and leverages both public- and private-sector innovation.


IMAGE CREDIT: ADOBE STOCK / TOMAS

6

Effectiveness of support instruments

The cases assessed in the previous section have linked the risks identified in Section 2 and the instruments from Section 4 to potential clean hydrogen use sectors in the U.S., Japan, and Germany.

From this discussion, a clear picture emerges: a combination of regulatory measures (such as quotas and mandates) and carbon pricing provides a strong foundation for a clean hydrogen strategy, as it addresses most offtaker risks.

However, these primary tools have limitations. They may be insufficient if their design is too weak—for example, when carbon prices are low or penalties for non-compliance modest—and, importantly, they do not address all types of risk. The successful attainment of FID in several early projects (e.g., the Villeta Project in Box 6) highlights an alternative path: structural solutions. These rely on integrated value chains and low-cost, long-term PPAs, for example, to bypass market and policy risks, creating bankability through aligned supply and offtake duration.

Complementary tools are also critical for mitigating price, offtake, and supply risks.

While relevant, this alternative path falls outside the scope of the current analysis, which emphasizes policy-driven demand support.

Effective support instruments: Matching tools to risks

Regulatory and carbon pricing instruments do not address liquidity risk, which is a key concern for sectors like steelmaking, refining, fertilizer and chemical plants, shipping, and aviation. This risk is best mitigated by well-designed market conditions that allow for flexibility, such as book-and-claim systems or guarantees of origin. For specific projects, financial tools like loan guarantees or liquidity reserve accounts rank highest in effectiveness. Equity injections, blended finance, and public loans can also be tailored to alleviate liquidity pressures, while CAPEX support can indirectly free up capital for operations.

Complementary tools are also critical for mitigating price, offtake, and supply risks (see Table 9). For industries facing medium-to-high risk in these areas—such as steel, process heat users, and land-bound transport—flexible market designs are particularly effective. Among these, double-sided auctions are exceptionally well suited to address all three risks, as they connect both sides of the market, establish concrete contractual relations between market participants, and bridge the CoD identified through competitive procedures.

Box 6: ATOME's Villeta Project - Green fertilizer production enabled by self-consumption of hydrogen and low power cost[149]

The Villeta Project by ATOME in Paraguay targets a production volume of 260 kt/a of calcium ammonium nitrate. As an integrated supply and demand project, it covers the entire fertilizer production chain—electrolysis, air separation, and ammonia synthesis—and is powered by a 145 MW power purchase agreement (PPA) for low-cost baseload hydroelectricity.

The project's CAPEX amounts to USD 465 million. Financing includes equity from Hy24, USD 135 million in public loans from the European Investment Bank (EIB), and USD 50 million from the Green Climate Fund. Debt interest was five times oversubscribed. Crucially, the project secured a 15-year offtake contract with Yara International for its entire production volume.

The project significantly reduced supply risks by securing a long-term PPA at ultra-low hydropower costs in Paraguay to power its renewable hydrogen production, an approach which also mitigated price volatility. The low production costs, combined with value-chain integration, resulted in competitively priced fertilizer. This, in turn, allowed the project to secure the 15-year offtake contract with Yara, thereby addressing offtake risk. Importantly, matching the full duration of the power supply and fertilizer offtake contracts made the project bankable, a critical step for managing liquidity risk and attracting Hy24 equity and EIB financing. CAPEX support from the Green Climate Fund bridged the remaining funding gap.

This structural solution crucially hinges on ultra-low power costs and an integrated value-chain approach, which may not be replicable or feasible in major net-importing markets that are the focus of this report.

Table 9: Match of risks, sectors and instruments

TOP 10 instruments	shipping (methanol)	shipping (ammonia)	aviation	rail/road	process heat	power generation	steel DRI	chemicals (captive)	refinery (captive)	fertilizer (captive)	chemicals (merchant)	refinery (merchant)	fertilizer (merchant)
quotas, mandates, bans and phase outs	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended
carbon pricing	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended
public procurement and green lead markets	recommended	recommended	good-to-have	good-to-have	recommended	strongly recommended	strongly recommended	good-to-have	recommended	good-to-have	good-to-have	recommended	good-to-have
Double-sided auctions, Contracts for difference	recommended	recommended	recommended	strongly recommended	strongly recommended	strongly recommended	strongly recommended	recommended	strongly recommended	recommended	strongly recommended	strongly recommended	strongly recommended
special economic zones and hubs	good-to-have	good-to-have	good-to-have	strongly recommended	strongly recommended	strongly recommended	strongly recommended	recommended	strongly recommended	recommended	strongly recommended	strongly recommended	strongly recommended
demand aggregation	recommended	recommended	recommended	strongly recommended	strongly recommended	good-to-have	recommended	good-to-have	good-to-have	good-to-have	strongly recommended	strongly recommended	strongly recommended
ecolabeling and chain of custody instruments	recommended	recommended	recommended	recommended	recommended	recommended	strongly recommended	recommended	strongly recommended	recommended	recommended	strongly recommended	recommended
loan guarantees	recommended	recommended	good-to-have	good-to-have	good-to-have	good-to-have	strongly recommended	recommended	strongly recommended	recommended	good-to-have	strongly recommended	good-to-have

Legend
- strongly recommended instruments
- recommended instruments
- good-to-have instruments

IMAGE CREDIT: ADOBE STOCK / VADIM.NEFEDOV

Contracts-for-difference (CfDs) have less impact on supply security but offer greater liquidity and technology risk mitigation. Additionally, establishing hubs or Special Economic Zones can be an effective alternative to project-specific instruments, especially where targeted industries are geographically concentrated.

The cost of demand support tools

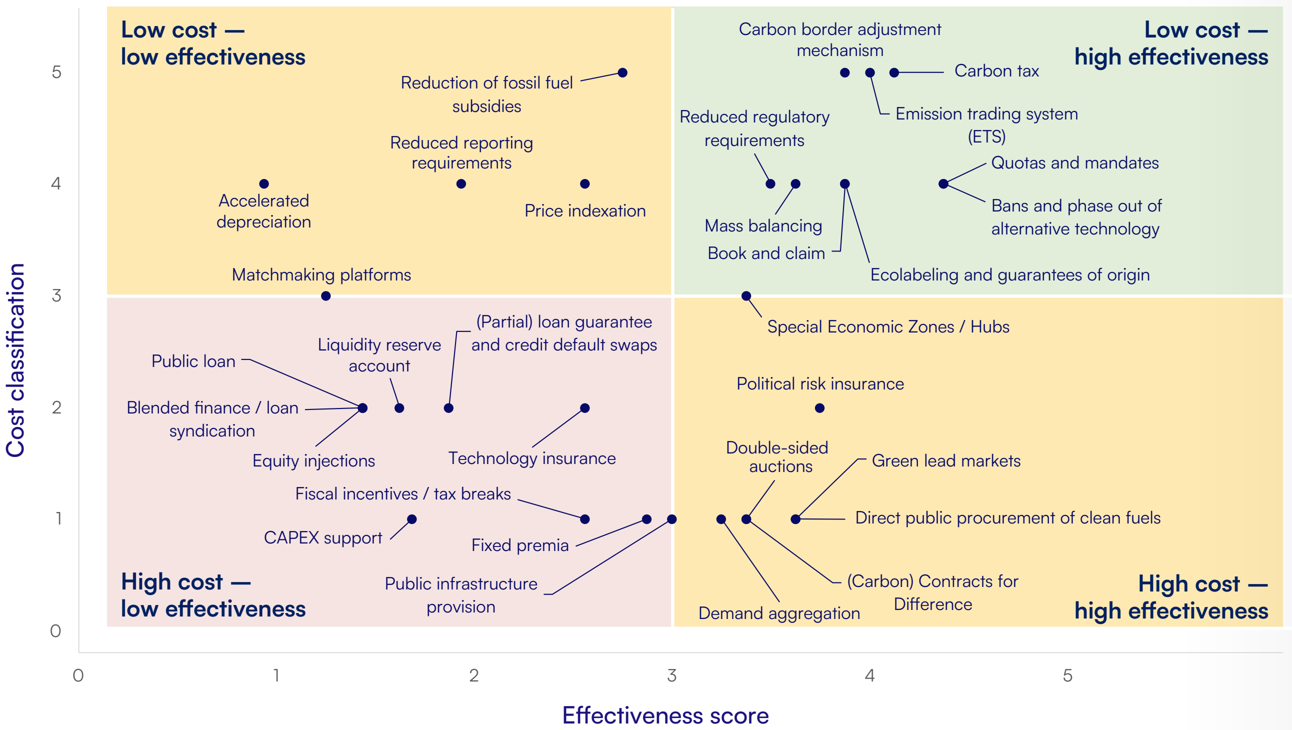
Beyond effectiveness, governments must also consider the cost of each instrument. To determine the costs associated with the policies assessed, demand support instruments were graded on a scale from 1-5 based on whether they:

1. definitively lead to payments to companies,
2. have the potential to cause payments to companies,
3. entail significant administrative costs,
4. produce only negligible costs, or
5. generate revenue for the government.

Figure 6 below maps these cost scores against the effectiveness scores from the previous sections.

The outcome of this preliminary analysis shows that carbon pricing instruments and regulatory measures, as well as tools for certification and trade, such as book-and-claim systems, are highly preferable. These instruments are effective while having a low or even positive fiscal impact

Figure 6: Efficiency of support instruments from a government perspective



Legend	
Cost classification	**Effectiveness score**
5 revenue	Highly effective
4 negligible cost	More effective
3 administrative cost	Effective
2 potential payment to companies	Less effective
1 definitive payment to companies	Least effective

for governments, making them the most cost-efficient policy choices. Policymakers thus have an incentive to prioritize the deployment of these instruments before considering those in the other quadrants.

Despite their clear benefits, carbon pricing and other regulatory interventions have not been widely adopted. Policymakers are often reluctant to implement them due to political and/or industry resistance, concerns over competitiveness, and the burden they may place on consumers, which can lead to popular discontent.

Despite their clear benefits, carbon pricing and other regulatory interventions have not been widely adopted.

In comparison, instruments such as double-sided auctions entail a direct fiscal cost to governments but offer a highly effective means of mitigating price and offtake risks. They guarantee a long-term purchase price to producers and a short-term, subsidized sales price to consumers, thus de-risking both sides of the market simultaneously.

The deployment of many instruments, however, has preconditions. Tools such as book-and-claim systems, while highly cost-effective, rely on the existence of both a producer with a product to "book" and a consumer with the willingness-to-pay (WtP) the premium to "claim" its environmental attributes. Without actual production and financial commitments from buyers, these systems lack the foundations to function effectively. This makes them better suited for market flexibility and scaling than for market creation. Similarly, while a CBAM requires an existing carbon pricing system, other instruments such as hubs and Special Economic Zones require public infrastructure investments and administrative support in locations where hydrogen-reliant industries are geographically concentrated.

The complexities and preconditions discussed here highlight the need for a targeted and pragmatic approach to policy design. The following section builds on these insights to provide specific recommendations for policymakers seeking to develop a thriving clean hydrogen sector.

IMAGE CREDIT: ADOBE STOCK / ARIP

IMAGE CREDIT: ADOBE STOCK / LUBO IVANKO

7

Recommendations

This section provides a set of recommendations for policymakers by synthesizing the findings of the report. The analysis covered twelve risks linked to the adoption of clean hydrogen and its derivatives as decarbonization pathways across nine sectors and assessed 31 demand-support instruments that can help mitigate these barriers. Based on this analysis, the section outlines primary risks, evaluates the effectiveness of various policies, and provides tailored recommendations from case studies of major hydrogen offtake markets—Germany, Japan, and the U.S.—aiming to help unlock committed hydrogen demand.

IMAGE CREDIT: ADOBE STOCK / NASSORN

Key findings on risks and policy effectiveness

The analysis highlights that while governments should be mindful of the specific risk profiles of targeted industries, price risk—particularly the cost-of-difference associated with the green premium—remains the most significant barrier for clean hydrogen offtakers.

For clean hydrogen users in industry and transport, supply and offtake risks are closely connected to price risks and diverging preferences for contract duration. The lag in infrastructure deployment presents another major source of uncertainty. In industries such as steel and refining, the scale of required investment combined with distinct contract durations introduces a specific risk: liquidity risk. Regulatory and political risks also vary across sectors and jurisdictions, tending to be lower where international institutions define the framework.

The choice of business model when pursuing decarbonization also creates differing risk profiles. For industries that already use fossil fuel-based hydrogen—such as refining, and chemical and fertilizer plants—a merchant model requires the decommissioning of existing production capacity and the construction of new supply chains, which comes with higher supply and price risks. In contrast, a captive business model that uses carbon capture, utilization, and storage (CCUS) technologies for carbon abatement faces higher risks in terms of political and social acceptance.

Among the instruments assessed in this report, regulatory tools such as quotas, mandates, bans, and phase-outs are the most effective and efficient for mitigating key risks associated with the adoption of clean hydrogen and its derivatives. By managing long-term expectations and increasing offtakers' willingness-to-pay (WtP), these tools create market certainty that incentivizes investment in supply and infrastructure. However, uncertain policy commitment often pushes industry executives toward a "wait-and-see" approach, hindering the development of long-lasting strategies. Therefore, unambiguous, long-term commitment to these regulatory tools is essential, providing the long-term fiscal guidance necessary for industry to undertake a green transformation.

Carbon pricing mechanisms are similarly effective and efficient tools for mitigating key risks faced by offtakers of clean hydrogen and its derivatives. They increase WtP and are typically implemented through long-standing institutions that provide continuity and political buy-in. These mechanisms also generate revenue that can be used for complementary instruments addressing remaining risks for offtakers. However, their full effect depends on careful design that avoids weak penalties or insufficient carbon prices, which can lead to carbon leakage and necessitate additional measures to maintain effectiveness.

Effective guarantees of origin and certification schemes, as well as flexible value-chain custody systems, provide companies with essential flexibility to reduce supply, price, and liquidity risks. These tools can thereby increase the effectiveness of regulatory and carbon pricing instruments where sectors require additional leverage.

Recommendations for a strong policy mix

Governments aiming to accelerate the decarbonization of key industries should be mindful of sector-specific risk profiles and tailor their policy instruments accordingly. A successful clean hydrogen demand-support strategy requires a complementary set of instruments. Where governments prefer to avoid strong regulatory interventions or carbon pricing—or where additional support is needed to address specific risks and maintain a competitive level playing field—a combination of tools from different categories is recommended.

Economic instruments:

— **Double-sided auctions** are highly effective in mitigating price risks and supporting supply chain development by bridging the cost-of-difference.

- **Contracts-for-difference** (CfDs) offer offtakers flexibility in selecting suppliers, alleviating liquidity pressures while still covering price risks.

De-risking and finance instruments:

- For sectors facing specific liquidity risks, **(partial) loan guarantees** are a well-suited instrument with limited budgetary impact. They are a key lever for de-risking projects and improving direct access to finance.

Enabling conditions:

- **Green lead markets** and direct public procurement can provide crucial leverage for addressing offtake risks, indirectly increasing WtP.

- Governments can support the **creation of hydrogen hubs** in regions where industries are geographically concentrated. This approach leverages synergies from co-location, reduces infrastructure needs, and can be facilitated through a combination of regulatory support (e.g., streamlined permitting) and financial grants.

- Effective **guarantees of origin and certification schemes**, along with **flexible systems of value-chain custody**, provide companies with essential flexibility to reduce supply and price risks.

Tailored recommendations for case study countries

Drawing on the lessons learned from each case study, the following recommendations are tailored to address the specific policy gaps and contextual challenges of Germany, Japan, and the United States.

- **Germany**: Germany's framework is already advanced, leveraging the EU ETS and quotas to create a solid regulatory foundation, complemented by double-sided auctions (H2Global) and CCfDs. However, since strict regulatory interventions are politically less favored, policymakers are encouraged to enhance financial support. This involves enhancing investments in infrastructure, lead markets, and project-specific support instruments such as H2Global and *Klimaschutzverträge*. The recent approval of the *Sondervermögen* provides a clear budgetary opportunity to advance these measures. Additionally, as the strategic steelmaking sector faces a highly competitive international environment and specific liquidity and price risks, deploying partial loan guarantees and targeted sector auctions is recommended.

- **Japan**: Japan has articulated a clear strategic vision for its hydrogen economy, but its policy toolkit remains fragmented and heavily focused on the power sector. The country would benefit from consolidating its support instruments and scaling up through a nationwide carbon pricing system—such as a sufficiently high carbon tax or an ETS. The voluntary GX-ETS, which is set to become mandatory in 2026, represents a key step in this direction. However, ensuring sufficiently high carbon prices and broad sectoral coverage will be essential to effectively drive decarbonization. A fully operational, nationwide system would provide greater policy coherence, moving Japan beyond its current patchwork of regional and sectoral initiatives toward a unified national strategy.

- **United States**: The U.S. currently faces high political uncertainty and a fragmented federal-state policy landscape. Given the current administration's stance, the political viability of introducing new, broad-based federal measures to support clean hydrogen market creation is very low. Nevertheless, if the U.S. decides to reengage in advancing clean hydrogen, it should prioritize market-based instruments such as a nationwide emissions trading system (ETS) and a complementary U.S. CBAM. A nationwide ETS would provide clear, consistent signals and align with international standards, while generating revenues that can support complementary policies. Such a system would also exempt U.S. producers from CBAM allowances when exporting clean hydrogen-based products to the EU. To further aid the economy, introducing a U.S. CBAM could boost revenue from imports and ensure a level playing field for U.S. companies.

In conclusion, building a successful clean hydrogen demand support strategy requires a holistic and pragmatic approach that directly addresses the key risks hindering market development. While price risk remains the most significant barrier, policies must also effectively mitigate supply and offtake risks, liquidity risk, and regulatory and political uncertainty. A successful support strategy combines "stick-and-carrot" elements. Carbon pricing and regulatory instruments can be highly effective, but their widespread implementation remains challenging due to political and social hurdles of broad adoption. However, these challenges can be overcome by leveraging tools such as auctions, which can de-risk projects and directly bridge the gap between production costs and an offtaker's WtP.

A key takeaway from the case studies of Germany, Japan, and the U.S. is that political uncertainty and fragmented policy landscapes can create conflicting signals and challenges, underscoring the need for a coherent national long-term framework. Ultimately, all policy instruments depend on sound design decisions to achieve their full effect, making careful and consistent policymaking a prerequisite for a dynamic clean hydrogen sector.

Annex I

Explanation of risks.

Risk group	Risk	Definition	Criteria for assessment (all dimensions are assessed compared to the conventional production technology)
Strategic risks	Market risk	The risk pertaining to overall market development, where the company assesses the probability of competitors moving in the same direction.	• General sectoral preference for clean hydrogen solutions • General decarbonization pressure in the sector (push factors) • Scope of the business opportunity in the sector (pull factors)
	Technology risk	The risk derived from an uncertain outlook on technology readiness levels and availability of alternative decarbonization technologies (such as direct electrification or CCUS)	• Technology readiness levels for clean hydrogen end-use technologies (i.e., fuel cells, blast furnaces, DRI units, turbines, etc.) • Business case for hydrogen compared to alternative technologies
	Regulatory risk	The risk derived from currently unclear or non-existing regulation, including sustainability certification.	• Progress of technical and political-economic regulation • Robustness (long-term safeguards) of regulatory frameworks
	Political risks	The risk derived from unclear political willingness to support the establishment of clean hydrogen projects.	• Extent of political consensus for climate change and clean hydrogen policies among relevant institutions • Political priority of clean hydrogen in major offtake markets • Foreseeable midterm development of fiscal constraints for support of clean hydrogen policies
	SLO risks	The risk associated with the societal acceptance (social license to operate, SLO) of the hydrogen project due to safety or environmental concerns, socio-economic or cultural impacts on communities or individuals.	• Change of risk profiles for fuels/feedstocks compared to unabated fossil fuels (e.g., increased toxicity or flammability) • Extent of changes associated with the introduction of clean hydrogen (derivatives) in terms of jobs, land use, public revenue, etc.

Risk group	Risk	Definition	Criteria for assessment (all dimensions are assessed compared to the conventional production technology)
Supply chain risks	Supply risk	The risk of the project pertaining to its ability to procure sufficient volumes of clean hydrogen (derivatives) to run its processes economically.	• Fuel/feedstock volumes required for continuous operations • Availability of infrastructure for clean hydrogen (derivatives) transport • Technical ability to fuel-switch with relative ease if clean hydrogen (derivatives) is not available
	Offtake risk	The risk of the project pertaining to its ability to find customers for those products developed under the use of clean hydrogen (derivatives).	• Visibility of the value-chain segment and the corresponding value or decarbonization to end users • Ability of the company to place a green premium with customers (downstream price elasticity)
	Counterparty risk	The risk of the project developer that its project partners default.	• Sector-typical size and liquidity of fuel/feedstock suppliers • Fuel/feedstock volumes required for continuous operations
Economics	Price risk	The risk posed by the green premium, future price developments, and the ability to hand price increases down the value chain.	• Increase of production cost compared to conventional technology • Volatility of market prices in the sector • Ability of the company to place a green premium with customers (downstream price elasticity)
	Credit and liquidity risk	The risk the decarbonization project poses to the company's financial liquidity and ability to service its loans.	• Sector-typical share of CAPEX for clean hydrogen solutions in relation to financial operations • Duration of fuel/feedstock supply contracts compared to sector-typical duration of offtake contracts
	Currency risk	The risk associated with the fluctuation of exchange rates between currencies pertaining to trade with clean hydrogen (derivatives).	• Dependence on and experience with international fuel/feedstock supply chains • Change of supply geographies compared to conventional production
Asset operation	Technical risks	The operational risk associated with the safe handling of the new fuel or feedstock and potential interruption of the production process.	• Existing experience in the sector with handling hydrogen (derivatives) • Technology readiness level of assets using hydrogen (derivatives)
	Quality risk	The operational risk associated with fluctuations in the quality of products like contaminations and residue.	• Purity requirements for clean hydrogen assets in the sector • Degree of control over purity levels (lower for merchant business models or pipeline-systems with third-party access)

Annex II

Studies considered in the LCOH meta-study.

Region	Year	Renewable Hydrogen	Low-Carbon Hydrogen
Latin America	2023-2025	CELA 2023; Benalcazar & Komorowska 2024	N.A.
	2030	Benalcazar & Komorowska 2024	N.A.
United States	2023-2025	U.S. DOE 2024; Lazard 2024; Joungho et al. 2024; U.S. DOE 2024	U.S. DOE 2024
	2030	U.S. DOE 2024; Joungho et al. 2024;	U.S. DOE 2024
Europe	2023-2025	European Hydrogen Observatory 2024; Agora Industry 2024; European Commission 2024; Hydrogen Europe 2024	European Hydrogen Observatory 2024; Hydrogen Europe 2024
	2030	Agora Industry 2024; International Energy Agency 2024	Export and Investment Fund of Denmark 2024
Middle East	2023-2025	Abdellatif et al. 2025; Argus Hydrogen and Future Fuels 2025;	S&P Global Commodity 2025; Argus Hydrogen and Future Fuels 2025; World Economic Forum 2023
	2030	Fraunhofer CINES 2023; Abdellatif et al. 2025; KAPSARC 2024	Hanaa, Hatim & Bandar 2024
China	2023-2025	Fan, Zhang, Sun & Pan 2025; Joungho et al. 2024;	Fan, Zhang, Sun & Pan 2025
	2030	Fan, Zhang, Sun & Pan 2025; Xiang et al. 2023; Joungho et al. 2024;	Fan, Zhang, Sun & Pan 2025
South Korea and Japan	2023-2025	Joungho et al. 2024; Argus Hydrogen and Future Fuels 2025	Argus Hydrogen and Future Fuels 2025
	2030	Joungho et al. 2024; Argus Hydrogen and Future Fuels 2025; Jiang et al. 2025	N.A

Annex III

References and assumptions of the studies providing the highest and lowest estimations for WtP across sectors and regions.

Sectors	Ranges	Value (USD/kg)	Assumptions	Reference
Europe				
Ammonia	Min	1.9	Includes carbon price of 50 EUR/t.	McKinsey & Company[150]
	Max	6.1	Includes carbon price of 100 EUR/t and penalty for RED III non-compliance of 400 EUR/t.	
Refining	Min	1.9	Includes carbon price of 50 EUR/t.	
	Max	6.1	Includes carbon price of 100 EUR/t and penalty for RED III non-compliance of 400 EUR/t.	
Maritime	Min	0.7	Includes carbon price of 50 EUR/t.	
	Max	4.9	Includes carbon price of 100 EUR/t and penalty for RED III and FuelEU non-compliance of 400 EUR/t.	
Aviation	Min	0.5	Includes carbon price of 50 EUR/t.	
	Max	3.1	Includes carbon price of 100 EUR/t; and penalty for ReFuelEU non-compliance of 400 EUR/t	
Steel	Min	2.5	Includes carbon price of 50 EUR/t.	
	Max	4.6	Includes carbon price of 100 EUR/t.	
United States				
Ammonia	Min	0.9	Based on reference natural gas price for fossil-based ammonia production.	U.S. Department of Energy[151]
	Max	1.2	Based on reference natural gas price for fossil-based ammonia production.	
Refining	Min	0.8	Based on regional industrial natural gas prices.	
	Max	1.2	Based on regional industrial natural gas prices.	
Maritime	Min	0.8	Based on fuel oil prices.	
	Max	1.6	Based on fuel oil prices.	
Aviation	Min	1.0	Based on reference oil for Jet A.	
	Max	3.3	Based on reference oil price for Jet A, assuming a CA LCFS credit up to 140 USD/credit through 2032.	
Steel	Value	<1.2	Value represents the green premium required for green steel to breakeven with traditional BF-BOF steel.	
South Korea and Japan				
Refining	Value	N.A	Based on CoD of 1.3 USD/kg.	Hydrogen Council & McKinsey and Company[152]
Maritime	Value	N.A	Based on CoD of 1.3 USD/kg under full implementation of MEPC 80.	

Annex IV

List of instruments.

Support type	Instrument	Description
De-risking instrument	**(Partial) loan guarantee and credit default swaps**	When a guarantor agrees to cover a portion of a borrower's debt if they default. CDS is a kind of insurance against credit.
De-risking instrument	**Liquidity reserve account**	A dedicated fund to cover short-term obligations during periods of low revenue, ensuring lenders are repaid even during cash-flow gaps.
De-risking instrument	**Mass balancing**	A method that uses a chain of custody to produce chemical products with consistent quality and properties from different feedstock sources in the same production process.
De-risking instrument	**Book and claim**	Allows clean fuel or materials producers to "book" the emissions savings of a good they've produced in one place, and customers to "claim" the emissions benefit from these goods for climate disclosures in a different place.
De-risking instrument	**Political risk insurance**	Protects equity investors against financial losses caused by political events, such as expropriation, currency inconvertibility, or political violence. It ensures a portion of their losses will be paid out if project repayments are disrupted.[153]
De-risking instrument	**Technology insurance**	Covers losses due to technical underperformance or failure in new/complex technologies
Economic instrument	**Accelerated depreciation**	Occurs when the book value of a capital asset is reduced at an accelerated rate compared to the "straight-line depreciation" method when the value of the asset is depreciated evenly over its lifetime. It records larger depreciation expenses during the earlier years of an asset's useful life and smaller ones in later years.[154]
Economic instrument	**Carbon border adjustment**	A Carbon Border Adjustment Mechanism (CBAM) is a policy that charges a fee on imported goods based on the carbon emissions produced during their manufacturing. It is always paired with a domestic carbon price, ensuring imported and domestic products face similar carbon costs.[155]
Economic instrument	**Carbon pricing: Carbon tax**	Carbon tax is a carbon pricing tool used to internalize the costs of carbon emissions and is a government-imposed fee on emission-generating activities.[156]
Economic instrument	**Carbon pricing: Emissions trading system (ETS)**	An emissions trading schemes (ETS) is a type of carbon market which works by placing a quantitative limit (a cap) on the amount of greenhouse gas (GHG) emissions in one or more sectors of the economy, while allowing allowances (or permits) trading. Each allowance represents each unit of emissions.[157]
Economic instrument	**(Carbon-) Contracts-for-difference**	A contract-for-difference (CfD) is a subsidy model to pay out the supplier of a low-carbon product based on the difference between the market price and an agreed strike price.[158]
Economic instrument	**Demand aggregation**	A process that consolidates individual demand from multiple buyers into a single, larger demand signal.[159]
Economic instrument	**Double-sided auctions**	A mechanism based on competitive bidding for the supply and demand of low-carbon products or electricity in which price differences between the market participants are compensated if needed.[160]

Support type	Instrument	Description
Economic instrument	**Fiscal incentives / tax breaks**	Incentives that lead to reduction or exemption of taxes.
Economic instrument	**Fixed premia**	Additional constant premium payment above a baseline price, regardless of fluctuations in the market price.
Economic instrument	**Price indexation**	Adjusting wages, prices, contracts, or other economic values based on the changes in a specific price index.
Economic instrument	**Reduction of fossil fuel subsidies**	Removal or reduction of government subsidies to the production or consumption of fossil fuels.
Finance instrument	**Blended finance and loan syndication**	The use of public and/or philanthropic capital to increase private-sector investment. Loan syndication is when a group of lenders provide a single loan to one borrower.
Finance instrument	**CAPEX support**	Funding that is provided to cover part of the upfront investment cost of infrastructure or equipment for a project.
Finance instrument	**Equity injections**	Equity financing is a type of financing where public or private investors acquire an ownership stake in a business. The raised capital can be used for the business to run and grow its operations.[161]
Finance instrument	**Public loan**	Financing provided directly by a public institution to a project or company.
Enabling conditions	**Quotas and mandates**	Government-enforced percentage to reach specific goal.
Enabling conditions	**Bans and phase-out of alternative technology**	Measure that prohibits the creation, sale, or use of specific technologies.
Enabling conditions	**Direct public procurement**	Process where public authorities purchase work, goods, or services from companies.[162]
Enabling conditions	**Ecolabeling and guarantees of origin**	Certification that, respectively, verify the sustainability of a product / service and prove its origin.
Enabling conditions	**Green lead markets**	Tool to create demand for climate-neutral products.
Enabling conditions	**Matchmaking platforms**	Tools or services designed to connect individuals to organizations based on specific criteria.
Enabling conditions	**Public infrastructure provision**	Delivery of essential services and facilities by government entities.
Enabling conditions	**Reduced regulatory requirements**	Easy rules, laws, and reducing regulations that a business must follow.
Enabling conditions	**Reduced reporting requirements**	Decreasing administrative tasks on businesses by eliminating reporting obligations.
Enabling conditions	**Special Economic Zones / Hubs**	Designated geographical areas within a country that operates under unique, favorable economic policies.

Annex V

For each support instrument, this scoring system:

1. defines the quality of the effect of the instrument on a risk in the categories "no effect", "weak effect", "medium effect", or "strong effect"
2. quantifies the assigned quality into a value from 0 (no effect) to 3 (strong effect) to establish a base score
3. adds 0.5 points to the base score for every (other) TOP 1-4 risk on which the instrument has an effect (value >0) to recognize major synergies
4. adds 0.5 points to the base score if the instrument has an effect on at least two of the (other) TOP 5—8 risks to recognize minor synergies
5. calculates a total score based on the average values for the TOP 8 risks.
6. The maximum value for each risk and the total score is 5.0, respectively. The base value for each risk score was assigned by the H2Global team and submitted to review by 32 experts.

TOP 1-4 risks

	Price risk		Regulatory risk		Supply risk		Offtake risk	
Instrument	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
Quotas and mandates	4	3	5	1	5	1	4	2
Bans and phase-out of alternative technology	4	3	5	1	5	1	4	2
Carbon tax	5	1	5	1	3	4	4	2
Emissions trading system (ETS)	4	3	5	1	3	4	4	2
Carbon border adjustment mechanism	5	1	4	2	3	4	5	1
Ecolabeling and guarantees of origin	4	3	5	1	4	3	4	2
Book and claim	4	3	3	4	5	1	5	1
Political risk insurance	3	5	5	1	3	4	4	2
Mass balancing	4	3	3	4	4	3	5	1
Direct public procurement of clean fuels	4	3	3	4	5	1	3	3
Green lead markets	4	3	3	4	3	4	5	1
Reduced regulatory requirements	4	3	4	2	3	4	3	3
Double-sided auctions	5	1	3	4	5	1	4	2
(Carbon) Contracts-for-difference	5	1	3	4	3	4	4	2

TOP 1-4 risks (continued)

	Price risk		Regulatory risk		Supply risk		Offtake risk	
Instrument	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Special Economic Zones / Hubs	4	3	3	4	5	1	4	2
Demand aggregation	4	3	3	4	5	1	4	2
Public infrastructure provision	2	7	2.5	5	4.5	2	2.5	4
Fixed premia	3	5	1.5	7	1.5	7	3	3
Reduction of fossil fuel subsidies	3.5	4	2	6	2.5	5	2.5	4
Technology insurance	2.5	6	3.5	3	2	6	2.5	4
Fiscal incentives / tax breaks	4	3	1.5	7	1.5	7	3	3
Price indexation	4.5	2	2	6	2.5	5	2.5	4
Reduced reporting requirements	2	7	3	4	1.5	7	1.5	5
(Partial) loan guarantee and credit default swaps	1.5	8	2	6	2	6	1.5	5
CAPEX support	3.5	4	1	8	1	8	1	6
Liquidity reserve account	2.5	6	1	8	1.5	7	1	6
Equity injections	2.5	6	1	8	1	8	1	6
Blended finance / loan syndication	2.5	6	1	8	1	8	1	6
Public loan	2.5	6	1	8	1	8	1	6
Matchmaking platforms	1	9	1	8	1.5	7	1.5	5
Accelerated depreciation	2	7	0.5	9	0.5	9	0.5	7

TOP 5-8 risks

	Market risk		Technology risk		Political risk		Liquidity risk	
Instrument	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Bans and phase-out of alternative technology	5	2	5	1	5	2	2	7
Quotas and mandates	5	2	5	1	5	2	2	7
Carbon tax	5.5	1	4.5	2	5.5	1	2.5	6
Carbon border adjustment mechanism	3.5	5	4.5	2	2.5	7	5.5	1
Ecolabeling and guarantees of origin	5	2	4	3	5	2	2	7
Book and claim	4.5	3	3.5	4	5.5	1	3.5	4
Double-sided auctions	5	2	3	5	4	4	2	7
Emissions trading system (ETS)	4	4	3	5	3	6	4	3
Mass balancing	3.5	5	4.5	2	2.5	7	4.5	2
(Carbon-) Contracts-for-difference	3.5	5	3.5	4	3.5	5	4.5	2
Special Economic Zones / Hubs	4.5	3	4.5	2	4.5	3	2.5	6
Demand aggregation	4.5	3	4.5	2	4.5	3	2.5	6
Political risk insurance	4.5	3	4.5	2	4.5	3	2.5	6
Direct public procurement of clean fuels	3.5	5	2.5	6	3.5	5	2.5	6
Green lead markets	3.5	5	3.5	4	3.5	5	2.5	6
Reduced regulatory requirements	3.5	5	2.5	6	3.5	5	2.5	6
Public infrastructure provision	3.5	5	3.5	4	3.5	5	1.5	8
Price indexation	3	6	4	3	4	4	2	7
Reduction of fossil fuel subsidies	4.5	3	3.5	4	2.5	7	3.5	4
Technology insurance	2	8	5	1	2	8	3	5
Fiscal incentives / tax breaks	3	6	2	7	2	8	4	3
Fixed premia	4.5	3	3.5	4	1.5	9	2.5	6
Reduced reporting requirements	2.5	7	2.5	6	2.5	7	1.5	8
Liquidity reserve account	1.5	9	1.5	8	2.5	7	4.5	2

TOP 5-8 risks (continued)

	Market risk		Technology risk		Political risk		Liquidity risk	
Instrument	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
(Partial) loan guarantee and credit default swaps	1	10	3	5	1	10	4	3
Matchmaking platforms	1	10	1	9	2	8	4	3
CAPEX support	1	10	1	9	2	8	4	3
Equity injections	1	10	1	9	2	8	4	3
Public loan	1	10	1	9	1	10	4	3
Blended finance / loan syndication	2	8	1	9	1	10	1	9
Accelerated depreciation	0.5	11	0.5	10	0.5	11	2.5	6

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