INTERNATIONAL SOLAR ALLIANCE | GHIC Green Hydrogen Innovation Center

World Green Hydrogen Outlook

GHIC Annual Flagship Report

Consultation draft

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Acknowledgements

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GHIC, hosted by the ISA, serves as a global platform dedicated to accelerating the transition to green hydrogen. As a central component of ISA's global knowledge repository aimed at advancing green hydrogen deployment, GHIC provides a nexus for expertise, innovation, and capacity building. Developed in collaboration with the Asian Development Bank (ADB) and the Ministry of New and Renewable Energy (MNRE), Government of India, the Centre connects specialists, supports emerging enterprises, and offers state-of-the-art resources, training programmes, and real-time engagement tools. GHIC was inaugurated in 2023 during India's Presidency of the G20.

This report has been prepared with the support of the ADB under its Knowledge and Support Technical Assistance for the ISA in advancing the Solar for Hydrogen Programme.

Table of Contents

List of Figures

List of Tables

Abbreviations

ACEF	Asia Clean Energy Forum
ADB	Asian Development Bank
AEM	Anion Exchange Membrane
AI	Artificial Intelligence
AWE	Alkaline Water Electrolyser
B2B	Business to Business
BoP	Balance of Plant
CBAM	Carbon Border Adjustment Mechanism
CCER	Chinese Certified Emissions Reduction
CCUS	Carbon Capture, Utilisation and Storage
CFE	Capillary Fed Electrolyser
CSP	Concentrated Solar Power
CfD	Contracts for Difference
DNI	Direct Normal Irradiation
DRI	Direct Reduced Iron
E-TAC	Electrochemical–Thermally Activated Chemical
EHB	European Hydrogen Backbone
EMDEs	Emerging Nations and Developing Economies
EMEC	European Marine Energy Centre
EU	European Union
EUR	Euro
EoDB	Ease of Doing Business
FCEV	Fuel Cell Electric Vehicle
FEED	Front End Engineering and Design
FID	Final Investment Decision
G2B	Government to Business
G2G	Government to Government
GH	Green Hydrogen
GHI	Global Horizontal Irradiation
GHIC	Green Hydrogen Innovation Centre
GII	Global Innovation Index
GW	Gigawatt
GWh	Gigawatt-hour
H2Global	Germany's H2Global mechanism
H2HUBS	US Hydrogen Hubs programme
HSPA	Hydrogen Society Promotion Act
HT-PEM	High Temperature Proton Exchange Membrane
IEA	International Energy Agency
IRA	Inflation Reduction Act
ISA	International Solar Alliance
JPY	Japanese Yen
KRW	South Korean Won
LCOH	Levelised Cost of Hydrogen
LNG	Liquefied Natural Gas
MFAT	Ministry of Foreign Affairs and Trade, Government of New Zealand
MMTPA	Million Metric Tons per annum
MW	Megawatt
NEOM	Portmanteau of the Greek word “Neo” meaning New and M for the Arabic word “Mustaqbal” meaning future
NZE	Net Zero Emissions
OECD	Organisation for Economic Co-operation and Development
PACER	Pacific Agreement on Closer Economic Relations
PEM	Proton Exchange Membrane
PFAS	Per- or poly-fluoroalkyl substances
PLI	Production Linked Incentive
PPP	Public-Private Partnership
QC	Quality Control
R2R	Research to Research
RE	Renewable Energy
RFT	Right First Time
RTC	Round-the-Clock (power)
SAF	Sustainable Aviation Fuel
SIGHT	Strategic Interventions for Green Hydrogen Transition
SOEC	Solid Oxide Electrolyser
TW	Terawatt
TWh	Terawatt-hour
USD	United States Dollar
VGF	Viability Gap Funding
WIPO	World Intellectual Property Organisation

Context of the study

The global energy landscape is undergoing a profound shift as nations work to reduce greenhouse gas emissions and address climate change. Renewable energy has become central to this transition, offering sustainable, emission free power. Green Hydrogen (GH), produced through the electrolysis of water using renewable energy, is emerging as a practical route to decarbonise "hard-to-abate" sectors such as transport, industry, and heating.

As green hydrogen strategies advance, international cooperation has become essential for knowledge exchange, policy alignment, and coordinated investment. ISA plays a central role by helping member nations leverage solar energy, which is an important input for cost effective green hydrogen. Headquartered in Gurugram, ISA comprises 126 UN recognised member countries (as of January 2026) and provides a platform for collaboration across governments, industry, and global institutions to support the safe, affordable, and sustainable expansion of solar energy.

ISA's 'Solar for Green Hydrogen' programme supports members in adopting solar based green hydrogen through analytics, capacity building, and readiness assessments[1]. Key outcomes include:

1. Blueprint for Ecosystem Readiness Assessment for Green Hydrogen, supported by Asian Development Bank (ADB)[2].
2. A Roadmap for Developing and Scaling the Green Hydrogen Ecosystem, supported by New Energy and Industrial Technology Development Organization (NEDO), Japan[3].
3. A joint initiative by European Investment Bank (EIB), ISA, and the African Union to harness Africa's solar potential for 50 MMTPA of green hydrogen by 2035, showcased at COP27[(4)].
4. Green Hydrogen Policy Accelerator Training Handbook, supported by Green Hydrogen Organisation (GH2)[5].
5. Green Hydrogen readiness assessments in African countries, supported by the Embassy of Denmark, presented at the ISA Assembly in 2024[(6)].
6. Ecosystem readiness studies for Green Hydrogen production and use across 10 ISA member countries (Argentina, Peru, Trinidad and Tobago, Tunisia, Ghana, Bhutan, Nepal, Sri Lanka, Fiji, Papua New Guinea), supported by ADB, showcased at Asia Clean Energy Forum (ACEF) 2025[(7)].
7. A framework for Green Hydrogen Hub development, supported by ADB, also presented at ACEF 2025[(8)].

To accelerate green hydrogen uptake, ISA in partnership with Ministry of New and Renewable Energy, Government of India (MNRE) and ADB, under the **G20** 2023 India Presidency has created a virtual '**Green Hydrogen Innovation Centre**' (GHIC) platform. GHIC is a global knowledge repository supported by ADB that links experts, supports startups, and provides advanced training, tools, and decision support capabilities. These tools cover green hydrogen cost estimation, project risk analysis, emissions assessment, and policy/infrastructure readiness. The tools were developed with ADB's support and were unveiled at ACEF 2025. The tools developed by ISA are as follows:

1 ISA – Programme 09 – Solar for Green Hydrogen. Accessed on 15 September 2025
2 Blueprint for Ecosystem Readiness Assessment for Green Hydrogen, ISA, November 2022 (ISA Blueprint Report 09 November 2022.cdr). Accessed on 23 January 2026
3 A Roadmap for Developing and Scaling the Green Hydrogen Ecosystem ISA, November 2023 (Untitled). Accessed on 23 January 2026
4 Africa's extraordinary green hydrogen potential, ISA, EIB, African Union (ISA_Report_ASHyP_2024.pdf). Accessed on 15 September 2025
5 2024 Handbook of the Green Hydrogen Policy Accelerator Training Course, ISA, GH2, August 2024 (1732691125GHPAT_Report.pdf)
6 Readiness assessment of green hydrogen in African Countries, ISA, 2024 (Link). Accessed on 24 March 2025
7 Green Hydrogen Readiness Assessment for 10 countries, ISA, ACEF 2025, Manila, June 2025 (International Solar Alliance). Accessed on 30 September 2025
8 Framework for the Development of Green Hydrogen Hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 10 July 2025

1. Country readiness tool
2. Green hydrogen cost assessment tool
3. Green hydrogen project risk assessment tool
4. Hydrogen carbon accounting tool

Scaling up green hydrogen continues to be a significant challenge, primarily due to the high cost of green hydrogen, which constrains offtake and slows market adoption. Nevertheless, declining renewable electricity and storage costs as well as falling electrolyser prices are improving project economics.

Despite this progress, several structural challenges persist. These include shortages of specialised and skilled manpower, limited infrastructure, knowledge and technology gaps, high operational costs, and difficulties in accessing affordable finance. In many countries, the absence of clear and dedicated green hydrogen policies further exacerbates investment uncertainty and hinders large-scale deployment.

Addressing these barriers will require enhanced public and private investment, targeted government incentives and policy support, continued engineering and technological improvements to reduce costs, and focused workforce development initiatives. Together, these measures are essential to facilitate a smooth and timely transition towards a sustainable green hydrogen based economy.

This study, "*ISA World Green Hydrogen Outlook: GHIC Annual Flagship Report*", developed under the GHIC initiative, aims to provide a strategic blueprint for advancing green hydrogen deployment by closing the gap between ambition and implementation. It offers insights on market creation, cost competitiveness, and infrastructure, while examining challenges such as high capital costs, fragmented demand, and technology constraints. It guides policymakers, investors, and industry leaders in building resilient ecosystems through integrated hubs, innovative financing, and manufacturing localisation. It also highlights the importance of digital enablers such as Artificial Intelligence (AI) and advanced materials in improving efficiency and reducing costs. Ultimately, the report seeks to support green hydrogen's transition from a promising concept to a commercially scalable solution capable of underpinning sustainable growth and competitiveness in a net-zero economy.

Executive summary

Global hydrogen demand is entering a decisive growth phase, yet execution continues to lag ambitions. The report projects a 50 per cent rise in total demand from ~100 Million Metric Tons Per Annum (MMTPA) in 2024 to 150 MMTPA by 2030, with clean (low-emissions) hydrogen expected to contribute nearly 45 per cent of supply in the International Energy Agency (IEA)'s Net-Zero Emission (NZE) pathway. However, GH still accounts for less than 1 per cent as of 2024. Further, only 9 per cent of announced projects have reached final investment decision (FID), with progress particularly weak across emerging markets (excluding China). Offtake fragility, high costs of capital and infrastructure gaps are constraining the momentum. The core message is therefore as follows: although the opportunity is large and urgent, the near-term pathway requires disciplined prioritisation of "drop-in" uses (refining, ammonia, methanol), availability of low-cost renewables with round-the-clock characteristics, and bankable demand creation mechanisms to convert announcements into assets. The key messages from the report are summarised below:

Cost remains the pivotal barrier

Electricity accounts for 60–70 per cent of the levelised cost of hydrogen (LCOH), making continuous low cost renewable availability, along with grid connection certainty and minimised network charges, essential for competitiveness. ISA's multi country deep dives show a strong inverse correlation between renewable availability and LCOH, emphasising that higher electrolyser utilisation driven by greater renewable energy supply is as important as cost efficiency. High availability can be achieved through hybridising technologies such as solar, wind and storage, as well as through baseload renewable sources including hydro and geothermal. Additional cost reductions can be realised by co-locating renewable energy generation with green hydrogen production facilities to reduce network charges, while concessional financing can further lower LCOH by approximately 10–20 per cent in high cost markets. China's multi-pronged advantages such as vertically integrated manufacturing, high-quality renewables, competitive financing (5–6.5 per cent borrowing costs), and supportive instruments like China Certified Emission Reduction (CCER) and Contracts for Difference (CfDs) illustrate how simultaneous action on electricity, capex and finance can plausibly deliver USD2–3/kg by 2030.

Multi-party strategic collaborations and GH hubs are necessary to align supply and demand and forge alternative clean commodity supply chains

To break the "no demand, no scale, no cost decline" loop, countries are turning to GH hubs integrated ecosystems that pool infrastructure (pipelines, storage, ports), de-risk logistics, and aggregate offtake across sectors. These can be domestic, export or imported oriented or a hybrid of these. The United States' H2HUBS model, Europe's "hydrogen valleys" and export/import gateway hubs (e.g., Rotterdam in Netherlands, NEOM in Saudi Arabia, SalalaH2 in Salalah, Oman) offer reproducible blueprints. These couple diversified production pathways with shared assets, transparent governance, robust standards, and early anchor customers. Hubs reduce unit costs through economies of scale, improve ease of doing business, and create investable clusters that can mobilise long-tenor capital. The storyline is clear: hubs are not merely projects, but market-making platforms that convert resource advantage into tradeable molecules and bankable revenue streams.

Vertically integrated and indigenous manufacturing plans are being put to action; many geographies are complementing such plans with greater visibility on offtakes

Vertically integrated manufacturing and innovation emerge as essential enablers for building a globally competitive green hydrogen ecosystem. The projected five-fold increase in annual electrolyser manufacturing to 200–220 GW by 2030 carries significant risk without secure offtake, strong localisation policies, green commodity consumption mandates, and fully integrated supply chains. Strategic action is therefore required to strengthen domestic capabilities across the value chain, expand advanced component manufacturing (such as electrodes, membranes), and deploy infrastructure such as hydrogen hubs and backbone pipelines that can reduce system wide costs by more than half.

Countries need a holistic strategy to focus on innovation to help promote GH equipment manufacturing

Innovation will ultimately define future competitiveness in the green hydrogen economy. Countries that lead the Global Innovation Index (GII) already host most of the world's electrolyser, fuel cell, and storage tank manufacturing, underscoring the strong link between sustained R&D and industrial capability. Key innovation priorities include scaling stack sizes, reducing precious metal loading, improving efficiency and durability, and integrating AI driven optimisation through digital twins and advanced quality systems. To anchor utilisation and accelerate innovation, governments and industry must adopt performance based incentives, forge global partnerships, ensure long term policy stability, and stimulate early demand. Nations that pair integrated manufacturing with bold innovation strategies will shape the global cost curve, strengthen supply chain resilience, and secure leadership in the emerging green hydrogen market.

Digitalisation as a force multiplier

AI may not merely stay as an add-on but might evolve as a backbone of GH projects in applications such as plant-level optimisation (forecast-to-dispatch, electrolyser control, predictive maintenance), digital twins for virtual proving (3–5 per cent Balance of Plant (BoP) efficiency gains cited), and advanced materials discovery (rapid catalyst/membrane screening) can compress timelines and lower LCOH. Embedding AI "ab initio" into hub operations, certification (Guarantees of Origin) and due diligence is recommended to raise bankability, achieve operational efficiencies and resilience.

Finance as the silent barrier and the biggest lever

With borrowing costs often 8–15 per cent in Emerging Market and Developing Economies (EMDEs) vs 5–6.5 per cent in advanced economies, financial interventions like blended finance, proportionate risk sharing, CfDs, Viability Gap Funding, tax credits and guaranteed offtake are essential to bridge the cost gap and crowd in private capital. Non-financial enablers like single window clearance, preferential allocation of resources like land and freshwater, building supporting infrastructure like power grid, water pipelines, ports and jetties are also crucial for GH projects. The message to policymakers is pragmatic: combine financial instruments with non-financial enablers (single-window clearances, land/water/power access, shared infrastructure) to turn comparative advantages into competitive projects.

Policy coherence and standards

This report emphasizes that policy support aligned with standards and certifications will ultimately determine the pace of hydrogen scale-up. More than 65 national strategies/roadmaps exist, but only a subset are holistic and backed by binding instruments. The recommended six-point policy framework which includes market creation (targets/mandates), aligned regulations and certification, generous but disciplined financial support, infrastructure build-out, innovation (including AI) and non-financial enablers, offers a practical checklist to move from ambition to execution. For governments and investors alike, the takeaways are concrete:

1. Enable the availability of low-cost, round the clock renewable energy resources
2. Build supporting infrastructure like power grid, water supply, desalination plants, dedicated hydrogen pipelines, port infrastructure as applicable
3. Promote hydrogen use first in demand-ready sectors
4. Design hubs as integrated trade and industrial platforms
5. Localise critical manufacturing where viable
6. Digitise and implement AI, wherever possible, from day one
7. Structure finance to lower LCOH and de-risk offtake.

In conclusion, this report offers clear, actionable strategies to unlock scale and restore confidence in GH by driving demand, reducing costs, leveraging technology and AI, mobilising finance, and ensuring policy coherence putting the sector on a credible path to global competitiveness. Collectively, these enablers can position countries to transition from scattered pilots to a globally competitive green hydrogen economy.

I. Green Hydrogen status and outlook: Growing ambition, lacking sufficient execution

Key takeaways:

1. The demand for hydrogen as a whole is also expected to increase by 50 per cent to 150 MMTPA by 2030, as per IEA's estimates.
2. As per IEA's NZE scenario, almost 45 per cent of the 150 MMTPA hydrogen demand by 2030 is expected to be contributed by clean hydrogen by 2030 (vis-à-vis 1 per cent today).
3. However, despite the strong projections of future demand, execution is lagging as is evident from the projects progressing to FID stage. Only 9 per cent of the announced projects have progressed to FID stage globally. The challenge is even more significant for EMDEs which exhibit only 0.5 per cent progress rate.
4. Over-reliance on green commodity exports in a market with limited number of importers along with high commodity and financing costs are some of the main reasons behind the slow execution of GH projects, especially in EMDE countries.

The global appetite for hydrogen is witnessing a steady rise, propelled by both traditional industrial applications and an expanding spectrum of novel, low-carbon use cases. As of 2024, an overwhelming proportion approximately 100 MMTPA is derived from fossil-fuel-based processes. Conversely, low-carbon or "clean" hydrogen (which also includes GH produced via electrolysis powered by renewable energy) constitutes less than 1 MMTPA, representing barely 1 per cent of the global hydrogen supply, as per IEA estimates[9].

Global hydrogen demand is projected to surge by 50 per cent, rising from 100 MMTPA to 150 MMTPA between 2024 and 2030[(10)]. It is anticipated that this growth will be predominantly underpinned by clean hydrogen, which is expected to comprise nearly 45 per cent of global supply by 2030[(11)]. Nevertheless, despite these forecasts, the realisation of GH projects remains sluggish. According to the IEA's report "Global Hydrogen Review 2025", only about 9 per cent of the announced GH projects had advanced to the FID stage as of 2024[(12)]. The proportion of project announcements reaching the FID stage and beyond is significantly lower in EMDEs, with the exception of China. In EMDEs, only 0.5 per cent of projects have progressed to the FID stage or further[13].

The underperformance of GH project announcements in EMDEs may be attributed to several factors but more particularly centred around offtake with a limited number of buyers of GH. Table 1 shown below illustrates some of the causes of limited progress of projects to FID stage, mainly in EMDE countries (except China).

9 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
10 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
11 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
12 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
13 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025

Table 1: Probable reasons behind limited progress on GH projects, especially in EMDE nations

SN	Probable cause	Remarks
1	**Over-reliance on export markets, despite the absence of firm offtake commitments**	• Memoranda of Understanding (MoUs) do not necessarily mean firm offtake. • 80 per cent of projects in EMDEs (except China) do not have firm offtakers[14]. • Offtake agreements are in 6-to-15-year range, with shorter timeframes fuelling investment uncertainties[15,16,17].
2	**Increased bargaining powers of clean energy importers**	• Limited number of prospective clean hydrogen / ammonia importers exist (European Union (EU), Japan, South Korea, Singapore) against a vast majority of renewable energy rich geographies. • Puts a downward price pressure on prospective clean hydrogen/ ammonia exporters from such RE-rich geographies.
3	**Lack of readiness of necessary infrastructure**	• Most of the EMDEs lack necessary infrastructure for GH ecosystem like power evacuation, large-scale RE projects, dedicated ports and jetties, hydrogen transportation pipelines.
4	**Significantly high cost of capital**	• Several EMDEs have significantly higher cost of capital in the range of 8 – 14.5 per cent or above, as compared to advanced economies at 5 to 6.5 per cent[18].

14 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
15 HINTCO article (Lot 1: Renewable ammonia - Hintco), Accessed on 15 September 2025
16 Press Information Bureau press release, 25 June 2025 (Press Release: Press Information Bureau). Accessed on 15 September 2025
17 TotalEnergies press release, 12 March 2025 (germany-totalenergies-and-rwe-join-forces-on-green-hydrogen-to-decarbonize-the-leuna-refinery_2025_en.pdf). Accessed on 15 September 2025
18 IEA article, 01 August 2025 (Cost of capital expectations for 2025 diverge amid rising uncertainty – Analysis - IEA). Accessed on 25 September 2025

It is therefore imperative for nations, especially EMDEs, to identify and address prevailing bottlenecks and to implement targeted interventions, drawing upon global best practices and demonstrable successes to expedite the transition towards GH. Countries may wish to consider the following pathways to foster the adoption of GH within their jurisdictions and to enhance progress towards the FID stage (refer to Figure 1[19]).

Develop domestic markets and leverage existing trade relationships for exports

- Develop a robust domestic GH market through market enabling mechanisms (e.g., demand aggregation, incentives, etc.)
- Prioritise sectors consuming hydrogen as "drop-in" commodity (eg. refineries, fertilisers, steel (annealing) etc. *[Covered in Chapter II]*
- Leverage extant energy trade relationships, where feasible, with energy-importing nations to convert them into secure, long-term exports of clean commodities.
- Market enabling mechanisms for demand aggregations, for eg., EU's Sustainable Aviation Fuel (SAF) mandate.

Develop differentiated advantages for export competitiveness

- Develop bespoke and tailored "differentiators" for green commodity exports, focusing either on cost advantages such as harnessing low-cost renewable energy and competitive financing *[Covered in Chapter III]* or on strategic geographical positioning (for example, proximity to demand centres like the EU for North African nations, or ASEAN / Pacific countries for South Korean and Japanese markets).

Focus on building complementary infrastructure

- Focus on building "infrastructure development roadmaps" to enable large-scale GH projects – like hydrogen pipelines, power grids, water desalination and recycling systems, dedicated ports and jetties, which might be integrated together to create GH hubs for additional scale benefits.

Introduce measures to reduce financing cost

- Implement schemes dedicated towards lowering the cost of financing GH projects, eg, seek blended/ concessional finance, target inflation reduction, allow production-linked or generation-based incentives, tax credits, examine clean commodity supply chain collaborations, vertical integration etc. *[Covered in Chapter III, IV]*

Figure 1: Key recommendations to increase GH adoption in countries and increase progress towards FID stage

The measures recommended in Figure 1, will necessitate further analysis and development of nuanced strategies. The ISA, through its studies and specialised tools on GH, can provide solutions to assist member countries in analysis and decision support, for example, such as risk profile analysis, hub identification, and country readiness assessment. A selection of these studies and tools is discussed in greater detail in Chapter IX.

19 Analysis for this report, 2025

II. Sectoral readiness may need to be prioritised to drive the first wave of adoption for low carbon hydrogen

Key takeaways:

1. Of the current global demand of hydrogen is driven by “drop-in” applications in oil refining, ammonia-based fertiliser production, and chemical manufacturing (such as methanol). Almost one-third of the demand by 2030 is expected to stem from emerging use cases. These include transport (road, shipping, and aviation), steelmaking via direct reduction, power generation, and other industrial applications.
2. Commodity cost, infrastructural readiness, technical maturity for clean hydrogen are expected to play a significant part in unlocking demand. Drop-in sectors may need to be prioritised for early adoption.
3. Although nearly one-third of global hydrogen supply in 2030 is expected to originate from clean or low-carbon sources, the limited progress towards the FID stage, particularly GH projects, poses a significant challenge to achieving these demand and supply targets.
4. Nearly 29 per cent of the global hydrogen demand is driven by China as of 2024, significant growth is observed from Middle East and India, primarily driven by increased demand from oil refining, chemicals and steelmaking (annealing) sectors.
5. Out of 100 MMTPA hydrogen produced globally in 2024 as per IEA estimates, less than 1 MMT came from clean sources. Out of this, nearly 620 KTPA of hydrogen was generated using water electrolysis and another 20 KTPA was generated from biomass.
6. Biomass-to-GH production may offer a low-cost alternative pathway to GH, which is useful for agriculture-export or agriculture industry dependent countries like Ghana, Fiji, Argentina and others. Countries can consider prioritising this pathway wherever applicable.

Hydrogen demand, driven today by refineries, fertilisers and methanol, is set to expand into Direct Reduction of Iron or DRI steelmaking, clean fuels, heavy transport and power led by low carbon hydrogen

Currently, hydrogen demand is concentrated in oil refining, ammonia-based fertiliser production, chemical manufacturing (such as methanol), and steel annealing, according to IEA estimates. Of this, oil refining, ammonia, and chemical sectors collectively account for over 95 per cent of total demand[20]. However, under the IEA’s NZE scenario, approximately one-third of global hydrogen demand is expected to originate from new and emerging applications. These include DRI steelmaking, shipping, green chemicals such as SAF, road transport, and power generation. Figure 2 illustrates the sectoral distribution of hydrogen demand at present and as projected for 2030, based on IEA estimates[21].

20 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
21 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025

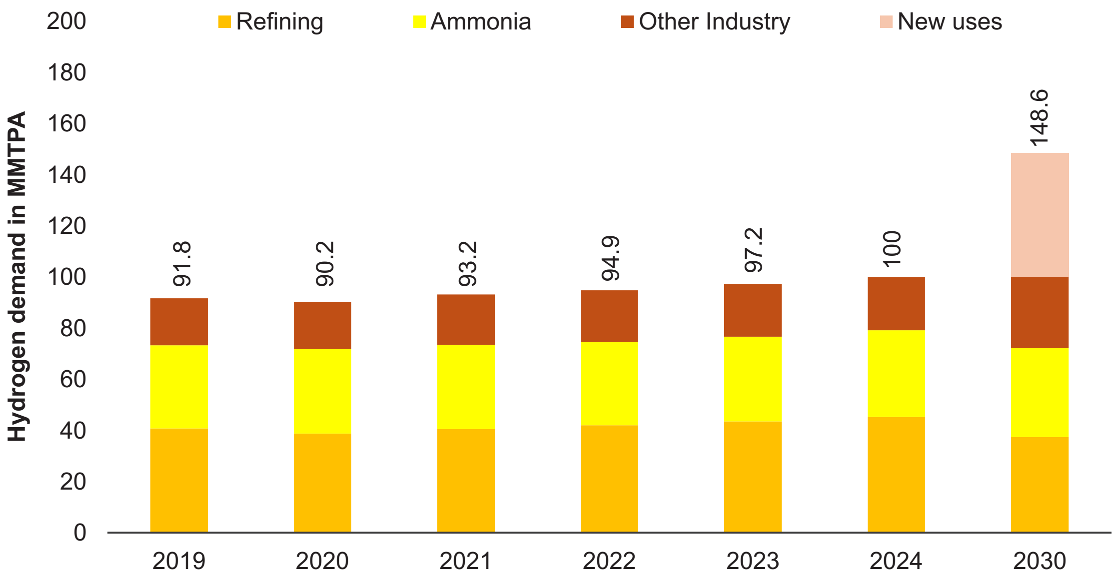

Figure 2: Estimate of sectoral demand of hydrogen as per IEA's NZE scenario

Refinery, ammonia (fertiliser), chemicals (methanol) and steel (annealing process) present "drop-in" (i.e., use of hydrogen as is) demand for low carbon hydrogen and are likely to be first adopters[22]. Table 2 outlines current and anticipated hydrogen uses, either as a "drop-in" fuel via existing infrastructure or through technical modifications, as elaborated in ISA's report "Framework for the development of GH hubs"[23].

Table 2: List of current and emerging end-use applications of hydrogen

SN	Sector	Indicative use of hydrogen	Drop-in / Technical modifications
1	Refining	Desulphurisation, hydrotreatment, hydrocracking	Drop-in
2	Fertilisers (ammonia)	Ammonia production via Haber-Bosch process	Drop-in
3	Methanol	Methanol production via Fischer-Tropsch process	Drop-in
4	Semiconductor Fabrication	Cleaning, etching, annealing, carrier-gas for doping	Drop-in
5	Steel (annealing)	Annealing (heat treatment) in conventional steelmaking	Drop-in
6	Steel (DRI)	Reducing agent for crude iron extraction in steelmaking	Technical modification

22 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
23 Framework for the development of GH hubs, ISA, ACEF 2025, Manila, June 2025 (ISA_ADB_GH Hub.pdf). Accessed on 10 July 2025

SN	Sector	Indicative use of hydrogen	Drop-in / Technical modifications
7	Blending with natural gas	Applications involving heating, combustion (like natural gas powered vehicles, domestic use etc)[24]	Technical modification
8	Power generation/ LDES	Energy storage to cater to seasonal RE fluctuations	Technical modification
9	Road transportation	Clean vehicles Powered by Fuel Cell Electric Vehicle (FCEVs), Hydrogen Internal Combustion Engine (H2-ICEs)	Technical modification
10	Shipping	Ammonia/ methanol fuel for clean ships	Technical modification
11	Glass	Clean and uniform heat source for glassmaking	Technical modification
12	Beverages (distilleries)	Clean and uniform heat source for alcohol distilleries	Technical modification
13	Mining	Clean fuel for FCEV or H2-ICE based mining machinery	Technical modification

Global hydrogen demand is led by China, with the fastest growth now coming from India and the Middle East, driven primarily by refining, chemicals and steel annealing.

As per IEA, global hydrogen demand is presently dominated by China, accounting for approximately 29 MMT or 29 per cent of global consumption, followed by North America with around 16 per cent[25]. India and the Middle East also make notable contributions to overall demand. Figure 3 depicts the region-wise distribution of hydrogen demand as of 2024, based on IEA estimates[26].

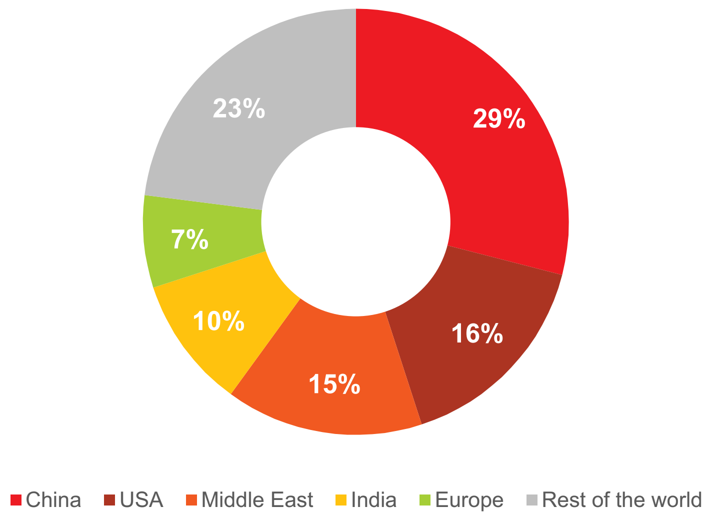

Figure 3: Regional global demand of hydrogen, as on 2024, as per IEA estimates

24 It may be noted that blending hydrogen with natural gas upto 15 - 18 per cent by volume may not entail technical modifications in the pipeline infrastructure. Beyond this, technical modification in pipelines and distribution infrastructure may be necessary to accommodate increased volume of hydrogen

25 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025

26 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025

Compared to 2023, the Middle East and India recorded the highest year-on-year (YoY) growth in hydrogen consumption, at 6 per cent and 4 per cent respectively. In contrast, China and the USA registered growth rates of 2 per cent and 0.5 per cent over the same period[27]. The surge in demand across the Middle East and India was primarily driven by existing end-use sectors such as oil refining and chemicals.

Low-carbon hydrogen supply which was expected to scale rapidly by 2030 on the back of ambitious national targets, now risks falling short due to slow progress of projects toward FID.

As per IEA estimates, the supply of low-carbon hydrogen in 2030 is anticipated to reach nearly 67.5 MMTPA, representing approximately 45 per cent of global hydrogen supply[28]. However, this projection may be revised downward owing to the limited progress of projects towards the FID stage. Among the announced clean hydrogen production targets, the USA and the EU have set the most ambitious goals, each aiming for around 10 MMT per annum. India and Canada have declared targets of approximately 4–5 MMT, while others including Japan and several Middle Eastern nations have outlined smaller yet significant commitments. Collectively, these targets underscore a global shift towards cleaner hydrogen production to meet rising demand. Figure 4 illustrates the country-wise announced targets for low-carbon hydrogen by 2030, based on published hydrogen strategies and roadmap[29].

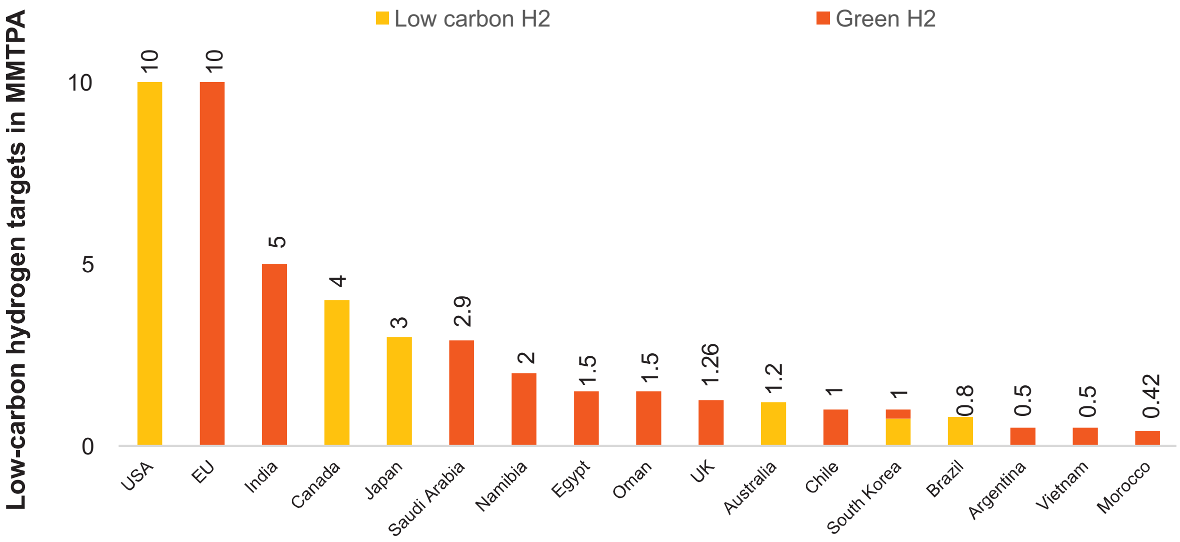

Figure 4: Low carbon hydrogen targets of key countries by 2030

It should be noted that the data presented in Figure 4 relate to the production targets of low carbon hydrogen of individual countries by 2030. Several countries in this list do not provide a strict bifurcation of production targets among blue hydrogen (produced via steam methane reforming of fossil fuels such as natural gas, followed by carbon capture, utilisation, or storage), pink hydrogen (produced through water electrolysis powered by nuclear energy), and GH. Consequently, the term "low-carbon hydrogen" encompasses all these low-emission production pathways. However, for countries where clear bifurcations are available, the GH component has been delineated separately from the overall low-carbon hydrogen data.

27 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025
28 Global Hydrogen Review 2024, IEA, September 2024 (Global Hydrogen Review 2024). Accessed on 15 September 2025
29 Analysis for this report, 2025 basis of published hydrogen strategies and roadmaps of key countries

Clean hydrogen development is increasingly constrained, with most projects still in early stages and unlikely to meet 2030 capacity targets

1. Approximately 620 KTPA of electrolysis based GH projects (equivalent to approximately 3.9 GW of electrolyser capacity) and about 20 KTPA of biomass-based GH projects (equivalent to approximately 120-130 MW of electrolyser capacity) have been installed as of September 2025 as per IEA estimates, which brings the total clean hydrogen production capacity to approximately 1 per cent of the total hydrogen production capacity.
2. However, according to IEA estimates, nearly 96 per cent of projects slated for completion by 2030 remain at early conceptual stages, creating significant market, demand, and financial uncertainties.

Although nearly one-third of global hydrogen supply in 2030 is expected to originate from clean or low-carbon sources, the limited progress towards the FID stage particularly for GH projects poses a significant challenge to achieving these demand and supply targets.

According to the IEA database, approximately 284 hydrogen projects (≥1 MW) have been announced since 2015, employing various electrolyser technologies[30]. The majority of these projects, around 251, fall within the 1–20 MW capacity range. Of the projects tracked between 2015 and 2025, nearly 179 are operational, 68 have reached the FID or are under construction, and 36 are at the demonstration stage, aggregating to a cumulative electrolyser capacity of roughly 3.9 GW or 620 KTPA of GH production, which is depicted in Figure 5[(31)]. For electrolyser based projects, alkaline electrolysers account for nearly 55 to 60 per cent of the installations at present.

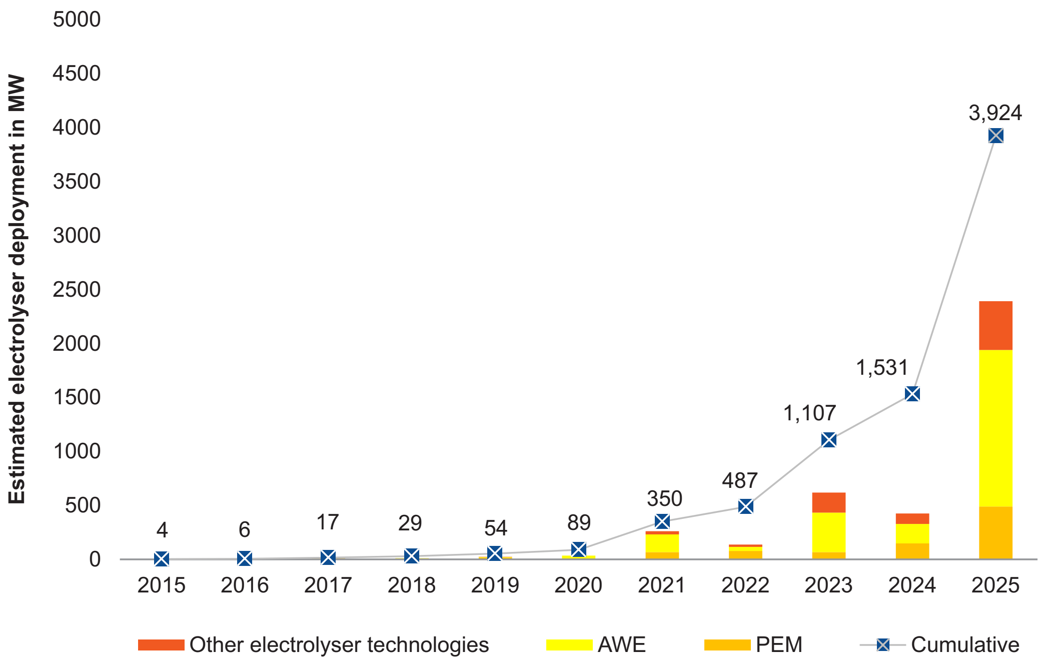

Figure 5: Trends in electrolyser deployment and key technologies

30 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 19 September 2025

31 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 19 September 2025

Out of the total capacity of 3.9 GW, approximately 2.7 GW is currently online, either operational or at the demonstration stage, while around 1.2 GW is at the FID stage or under construction (refer Figure 6)[32].

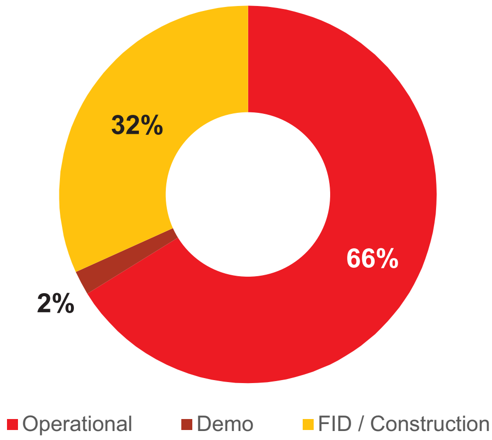

Figure 6: Breakdown of electrolyser capacity installed / under construction from 2015 - 2025

In addition to the electrolyser-based GH initiatives, there has been substantial progress in biomass-derived GH projects. Hydrogen produced through biomass or waste processing is considered as green or carbon-neutral in several regions, including India, Japan, and China. Within the EU, biomass-based hydrogen is classified as renewable only if it achieves a minimum 70 per cent reduction in life-cycle Green House Gas (GHG) emissions[33].

These projects are gaining momentum owing to the relative maturity of technologies such as gasification, steam methane reforming (SMR), and pyrolysis methods rooted in established hydrocarbon industry practices. Beyond producing GH, such projects offer the potential to generate value-added co-products.

32 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 19 September 2025

33 European Commission article (Renewable hydrogen - European Commission). Accessed on 23 September 2025

Figure 7 presents an estimate of biomass-based GH projects announced since 2015[(34)]. Technologies such as SMR, pyrolysis, and the processing of biogas, bioethanol, and biomethane have been considered valid pathways for GH production. Only projects with a hydrogen output of at least 202 Nm^3/h, equivalent to an electrolyser capacity of 1 MW or more, as previously outlined, have been included. The total estimated capacity from these projects stands at 24,769 Nm^3/h, corresponding to approximately 120-130 MW of electrolyser-equivalent capacity or approximately 18-20 KTPA of GH production capacity[35].

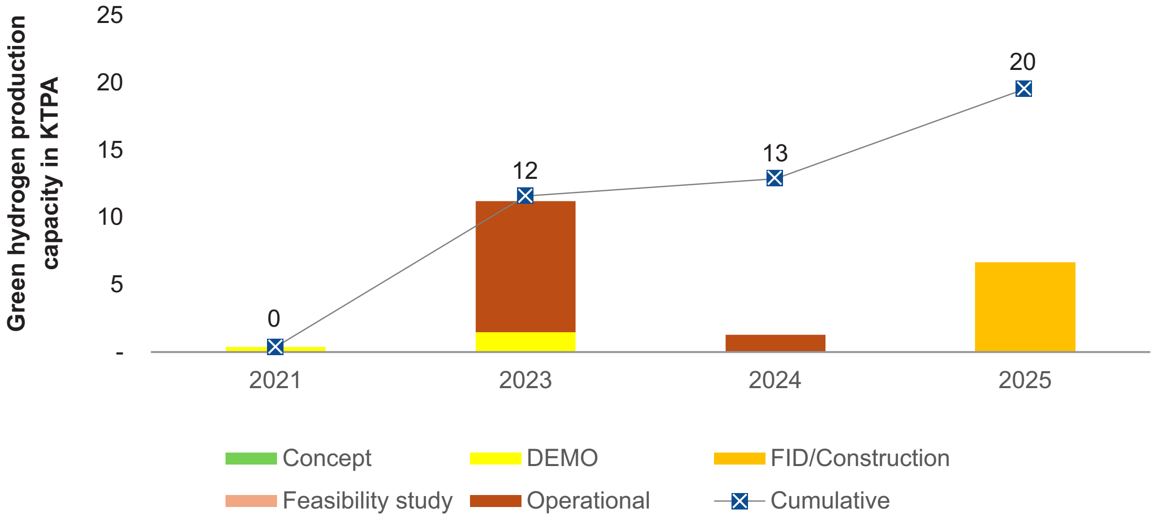

Figure 7: Trends in biomass waste to GH project deployments till 2025

Out of the total capacity, approximately 11–14 KTPA is currently online, either operational or at the demonstration stage, while around 6–9 KTPA is at FID stage or under construction (see Figure 8)[36].

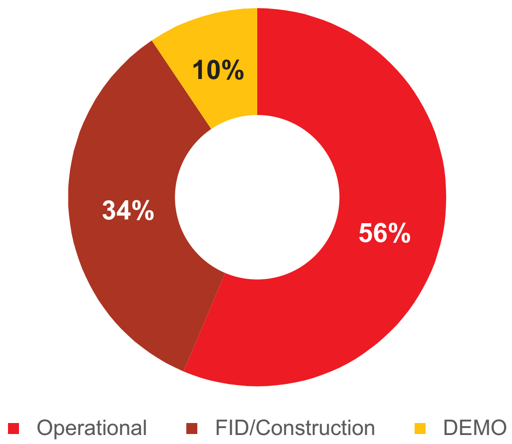

Figure 8: Breakdown of biomass waste to hydrogen production capacity installed / under construction from 2015 - 2025

According to IEA estimates, a cumulative 550–600 KTPA of biomass waste-based GH projects (equivalent to an electrolyser capacity of 3–4 GW) are expected to be available by 2030 across various stages of implementation. However, there is limited visibility on the specific projects anticipated to come online by that time.

34 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 19 September 2025

35 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 23 September 2025

36 Global Hydrogen Review 2025, IEA, October 2025 (Global Hydrogen Review 2025). Accessed on 15 October 2025

The trends and estimate of biomass waste based GH projects are provided below in Figure 9[(37)]. It may be noted that a vast majority (about 96 per cent) of projects are still envisaged to remain in preliminary stages only (concept or feasibility study stage) and only 2-3 per cent of projects are expected to graduate into FID, construction phase or operational phase by 2030[38].

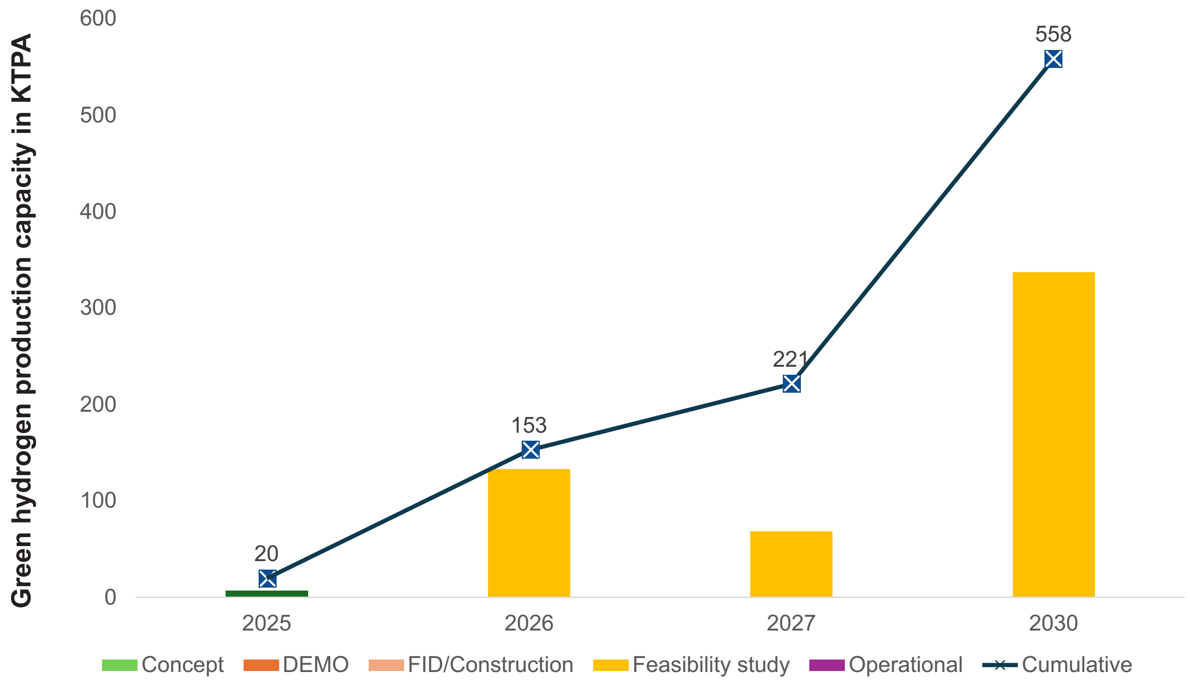

Figure 9: Envisaged breakup of biomass waste based GH projects in various stages of implementation from 2025 to 2030

While biomass-to-GH projects might face challenges with biomass availability and sorting at a global level, it can still offer niche country-specific advantages with additional avenues of byproduct valorisation

1. GH derived from biomass waste offers significant potential for nations reliant on agricultural industries or exports such as Ghana (cocoa), Argentina (soybeans and maize), and Fiji (sugarcane).
2. Production from biomass waste is substantially more economical compared to hydrogen generated via water electrolysis.
3. Valuable co-products such as organic fertilisers, biochar, liquid fertilisers, tar, and ash can be commercialised, creating additional income streams.
4. Governments may consider prioritising biomass-to-GH initiatives, particularly in agriculture-dependent economies, to enhance sustainability and economic resilience.

GH derived from biomass is a well-established technology that offers considerable advantages, particularly for countries with agriculture-based economies and persistent challenges in waste disposal and management. According to deep-dive studies on GH ecosystem readiness conducted by ISA,

37 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 23 September 2025

38 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 23 September 2025

agricultural sectors reliant on cash and food crops such as cocoa, soybean, wheat, sugarcane and maize, common in nations like Ghana, Argentina and Fiji, can generate substantial biomass[39,40,41]. This, in turn, creates a compelling opportunity for low-cost GH production tailored to these regions.

Research by IEA Bioenergy estimates the cost of producing GH from biomass to range between EUR2.2-7.4 per kg (approximately USD2.58–USD8.66 per kg)[42]. However, this cost is influenced by several critical factors, including biomass availability and pricing, tipping fees, technology selection, and feedstock characteristics such as type, quality, yield and gas composition. Consequently, biomass-based hydrogen represents a viable alternative pathway for agriculture-dependent economies to access affordable GH while addressing biomass waste challenges.

Moreover, the biomass-to-hydrogen process can yield valuable by-products such as organic fertilisers, biochar, liquid fertilisers, tar and ash depending on the chosen technology and feedstock. Many of these can be monetised, creating additional revenue streams. Notably, countries like India have already announced financial incentives to promote GH production from biomass waste, signalling a growing policy interest in this pathway[43].

In summary, biomass-based GH presents a cost-effective and sustainable solution for agriculture-driven economies, addressing waste management challenges while unlocking new revenue streams through valuable by-products. With supportive policies and incentives, this pathway can accelerate the transition to clean energy in regions where biomass resources are abundant.

Overall, given the challenges facing the sector and the slow pace of adoption, it is critical that green hydrogen deployment is initially led by sectors that represent low-risk, “drop-in” demand. In these sectors, green hydrogen can directly replace fossil-fuel–based hydrogen without requiring significant modifications to existing technologies or industrial processes, thereby addressing a key demand-side constraint.

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39 Consultation document, - Green Hydrogen Readiness Assessment for Ghana, ISA, ACEF 2025, Manila, June 2025 (1749638566ISA_ADB_GH_ACEF_2025_06_June_Ghana.pdf). Accessed on 30 September 2025

40 Consultation document, - Green Hydrogen Readiness Assessment for Fiji, ISA, ACEF 2025, Manila, June 2025 (1749638566ISA_ADB_GH_ACEF_2025_06_June_Fiji.pdf). Accessed on 30 September 2025

41 Consultation document, - Green Hydrogen Readiness Assessment for Argentina, ISA, ACEF 2025, Manila, June 2025 (1749638566ISA_ADB_GH_ACEF_2025_06_June_Argentina.pdf). Accessed on 30 September 2025

42 Biomass gasification for hydrogen production, IEA Bioenergy, February 2025 (https://www.ieabioenergy.com/wp-content/uploads/2025/03/IEA-Bioenergy_T33_Bio-H2_Final_v2.pdf). Accessed on 20 December 2025

43 Fuel Cell Works article, 19 March 2025 (Reliance, L&T, Waaree Lead in SECI’s Green Hydrogen Auction). Accessed on 20 December 2025

III. High levelised cost of green hydrogen may impact offtake

Key takeaways:

1. Reducing GH production costs will entail a multi-pronged approach to address costs at all levels of the GH value chain. The suggested strategies are as follows:
   a. **Leveraging low cost RE resources:** At LCOH of USD4–6/kWh, power cost alone can contribute USD2–3/kg which is over 60 per cent of the production cost of GH.
   b. **Using round-the-clock (RTC) RE (with higher availability) to maximise electrolyser utilisation:** May help reduce LCOH by up to 50 per cent (depending upon the Capacity Utilisation Factor (CUF) of standalone RE vs RTC RE).
   c. **Planning hydrogen hubs or cluster development to bring scale and shared infra benefits:** Shared infrastructure can reduce total infrastructure spending by more than 50 per cent.
   d. **Optimising network and regulatory costs:** A 10 per cent rise in power costs owing to such cost levies can push LCOH up by 6–7 per cent.
   e. **Bringing down financing costs by addressing risks:** 10 to 20 per cent LCOH reduction may be possible for high financing cost regimes
   f. **Optimising electrolyser efficiency and costs through innovations and scale benefits** can help reduce overall LCOH by reducing equipment CAPEX and electricity consumption.
2. It is worth noting that China is aiming for leadership in GH costs through a comprehensive approach targeting several of the strategies simultaneously, providing a pathway for other regions to contextualise and emulate.

High levelised cost of GH as an impediment to progress and offtake

High LCOH remains the most significant barrier to its scale-up, widening the gap with unabated fossil-based hydrogen and stalling investment momentum. After a brief period in 2022 when soaring gas prices temporarily improved competitiveness, the sharp decline in natural gas prices since then has pushed renewable hydrogen costs back above fossil routes in most regions. High financing costs, renewable electricity costs (in regions having lack of sufficient high quality RE-resources) have also contributed to high LCOH figures, combined with low efficiency of electrolysers. This cost disadvantage has triggered a cascade of consequences like weak demand signals, fewer bankable FIDs, and a shrinking project pipeline.

The underlying causes of high costs are structural. Electricity remains the dominant cost driver for electrolysis, and RE power prices are still elevated or volatile in many markets. Even where renewables are cheap, grid connection delays, variability management, and storage requirements add complexity and expense. Electrolysers and balance-of-plant components also carry high capital cost implications. Additionally, current electrolyser technologies operate not only with low efficiency but also limited conversion output due to intermittent RE, which decreases the amount of GH produced, thereby inflating overall LCOH figures. Financing costs are another critical factor: in emerging markets, they often reach

18 per cent, compared with upto 6.5 per cent in advanced economies, inflating levelised costs and delaying FIDs[44].

Cost of RE and utilisation of electrolysers are major factors affecting GH costs, underscoring the need for high quality, high availability and low-cost RE-resources, as highlighted from ISA studies

The economics of GH remain a formidable challenge, with it emerging as a key impediment to widespread adoption and market offtake. At the heart of this issue lies the overwhelming influence of electricity costs, which account for 60–70 per cent of total production expenses. In mature markets, it is possible to lower the LCOH by managing renewable-energy availability through a portfolio approach that balances production with power-market dynamics. In contrast, emerging economies often need to rely on hybridised renewable-energy assets to achieve higher levels of availability. This dependency makes the availability of low-cost, round-the-clock renewable energy and optimised network charges indispensable for achieving cost competitiveness. LCOH is shaped by multiple interdependent factors: the intermittency of renewable power, which constrains electrolyser utilisation; the prevailing cost of stable renewable power; financing conditions; and the capital intensity and efficiency of electrolyser systems.

ISA's deep-dive analysis of GH ecosystem readiness across 14 countries underscores a strong inverse correlation between renewable energy availability and LCOH up to approximately 70–80 per cent availability, beyond which incremental gains deliver only marginal cost reductions[45]. This finding highlights that achieving low-cost and high availability RE resources is critical to lowering LCOH. Figure 10 illustrates the relation between LCOH and RE-availability as per ISA's country deep dive studies so far on GH[46].

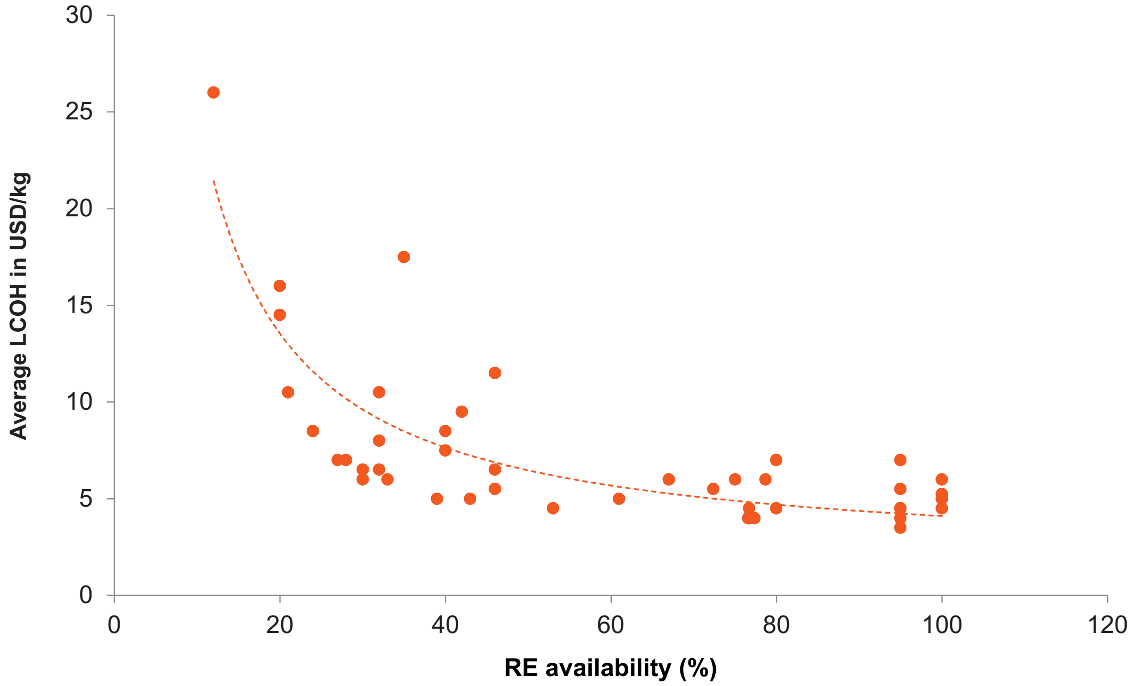

Figure 10: Scatter diagram of LCOH (USD/kg) from ISA's GH ecosystem readiness deep dive studies of 14 countries

44 IEA article, 01 August 2025 (Cost of capital expectations for 2025 diverge amid rising uncertainty – Analysis - IEA). Accessed on 25 September 2025

45 Analysis for this report, 2025, based on 41 data sets from country deep dive analyses conducted by ISA on 14 countries to examine green hydrogen ecosystem readiness in the member countries. The countries examined are Bhutan, Nepal, Sri Lanka, Egypt, Morocco, Ethiopia, Namibia, Tunisia, Ghana, Argentina, Peru, Trinidad & Tobago, Fiji, Papua New Guinea

46 Analysis for this report, 2025, based on 41 data sets from country deep dive analyses conducted by ISA on 14 countries to examine green hydrogen ecosystem readiness in the member countries. The countries examined are Bhutan, Nepal, Sri Lanka, Egypt, Morocco, Ethiopia, Namibia, Tunisia, Ghana, Argentina, Peru, Trinidad & Tobago, Fiji, Papua New Guinea

The findings above provide a reason why GH projects usually **prefer round-the-clock or baseload renewable power** or try to maximise the availability. There are several means to achieve this objective. Table 3 highlights some of the key suggestions in this regard.

Table 3: Suggested methods of increasing availability of RE resources to enable RE and GH cost reduction

SN	Method	Description	Examples of countries
1	Hybridisation	Combination of renewable resources like solar and wind, or any such resource supported by storage, to complement the intermittencies in each resource and boost overall RE-availability	Saudi Arabia, Oman, China, India
2	High quality RE resources	High quality of RE resources usually provide high availability of intermittent RE resources, due to several factors. For solar, high quality Concentrated Solar Power (CSP) grade solar means limited seasonality and high Direct Normal Irradiation (DNI) profiles, offering near baseload CSP projects. For onshore and offshore wind, high power densities (in terms of several kWh/m^2) can offer high RE availabilities. Such factors could also help reduce LCOH by offering near baseload RE.	Chile, Namibia, Argentina, Peru, Morocco, Egypt, Tunisia
3	Baseload RE resources	Few RE resources like geothermal and hydro are baseload or near baseload RE resources, offering minimal variability, thereby enabling maximum equipment utilisation and contribute to lowering LCOH.	Nepal, Bhutan, Ethiopia, Papua New Guinea use hydro or geothermal, as applicable. Other countries like Peru, Chile, Argentina, China also have significant geothermal potential and are evaluating ways to harness this.

Table 4 shows some examples of countries which have achieved record renewable power tariffs in the recent past. Some countries like Saudi Arabia and UAE have even achieved record low tariffs in the range of USD0.01/kWh.

Table 4: Examples of very low RE tariffs for various RE resources discovered in key regions of the world

SN	Country	Resource	Discovered tariff
1	Saudi Arabia	Solar PV	SAR0.039-0.118/kWh[47] (approximately USD0.010-0.030/ kWh)
2	Saudi Arabia	Onshore wind	USD0.0133/kWh[48]
3	UAE	Solar PV	USD0.0132/kWh[49]
4	UAE	CSP + Solar PV hybrid	USD0.073/kWh[50]
5	Egypt	Solar PV	USD0.025/kWh[51]
6	Chile	Solar PV	USD0.013-0.028/kWh[52]
7	UK	Offshore wind (fixed bottom) – strike price	GBP81/MWh[53] (approximately USD0.108/kWh)
8	UK	Offshore wind (floating) – strike price	GBP194/MWh[54] (approximately USD0.26/kWh)
9	New Zealand / Kenya	Geothermal	USD0.06/kWh[55]
10	Bhutan / Nepal	Hydro	USD0.040-0.050/kWh[56,57,58,59]

These are examples of some countries, and there may be opportunities for others to similarly leverage abundant, low-cost renewable energy, creating a strong case for setting up GH projects.

In addition to obtaining cheaper near round the clock RE resources for GH production, collocating renewable generation facilities with hydrogen production facilities further mitigates network and regulatory charges, as even a modest 10 per cent increase in power costs can inflate LCOH by 6–7 per cent.

47 Renewables now article, 15 July 2025 (Saudi Arabia more than doubles solar capacity to 6.1 GW in 2024 | Renewable Energy News | Renewables Now). Accessed on 25 September 2025

48 Ministry of Energy, Government of Saudi Arabia press release, 27 October 2025 (Principal Buyer Awards Five Renewable Energy Projects with a Total Capacity of 4,500 Megawatts, Al-Dawadmi Sets a New Global Record in Wind Energy, and Najran Ranks Second Worldwide in Solar Energy). Accessed on 20 November 2025

49 Energy Institute Knowledge article, 22 November 2023 (World's largest single-site solar power plant inaugurated | Article Page). Accessed on 25 September 2025

50 ACWA power article (ACWA POWER | Noor Energy 1). Accessed on 25 September 2025

51 ACWA power article (ACWA POWER | Kom Ombo PV). Accessed on 25 September 2025

52 Mercom India article, 02 September 2021 (Chile Announces the Lowest Bid of $0.01332/kWh in its Renewable Energy Auction). Accessed on 18 December 2025

53 TGS 4C article, 24 July 2025 (UK boosts offshore wind guarantees ahead of upcoming auction TGS 4C | 4C Offshore News). Accessed on 18 December 2025

54 TGS 4C article, 24 July 2025 (UK boosts offshore wind guarantees ahead of upcoming auction TGS 4C | 4C Offshore News). Accessed on 18 December 2025

55 Renewable power generation costs in 2024, IRENA, Abu Dhabi, 2025 (Renewable power generation costs in 2024 - Executive summary). Accessed on 18 December 2025

56 Green Hydrogen Readiness Assessment for Nepal (1749638566ISA_ADB_GH_ACEF_2025_06_June_Nepal.pdf), ISA, ACEF 2025, Manila, June 2025. Accessed on 18 December 2025

57 Green Hydrogen Readiness Assessment for Bhutan (1749638566ISA_ADB_GH_ACEF_2025_06_June_Bhutan.pdf), ISA, ACEF 2025, Manila, June 2025. Accessed on 18 December 2025

58 Green Hydrogen Readiness Assessment for Bhutan (1749638566ISA_ADB_GH_ACEF_2025_06_June_Bhutan.pdf), ISA, ACEF 2025, Manila, June 2025. Accessed on 18 December 2025

59 It may be noted that for some months of the year, especially the monsoon season in Nepal and Bhutan, there might be excess hydropower generation in the country, leading to very low-cost of hydropower generation. Green hydrogen might be generated during such periods to help lower the commodity cost.

Vertically integrated manufacturing can help reduce cost of equipment such as electrolysers; China has achieved this and other regions like USA and EU attempt to replicate this strategy

Electrolyser costs, while secondary to electricity, remain a significant lever for cost optimisation. Technological innovation and economies of scale through vertically integrated manufacturing can deliver meaningful cost reductions. China exemplifies this approach, leveraging its integrated supply chains and cost leadership to produce electrolysers at prices 50–55 per cent below global averages.

Hydrogen hubs/clusters can enable scale and reduce total infrastructure via shared infrastructure

Large-scale hydrogen hubs also offer a pathway to cost efficiency by enabling shared infrastructure, reducing total infrastructure expenditure by more than 50 per cent[60]. These hubs, already operational or planned in regions such as the United States, Europe, and the Middle East, represent a blueprint for systemic cost reduction through collaboration and scale.

Financing cost has a significant effect on overall LCOH; EMDEs need bold policy overhauls to bring this cost down to levels comparable to advanced economies and China

Financing costs exert a similarly profound impact: in high-cost regimes, targeted interventions such as inflation-reduction measures, risk-sharing frameworks, and incentive schemes can lower LCOH by 10–20 per cent. Advanced economies have already deployed such mechanisms, including CfDs and clean supply chain collaborations, to de-risk investments and accelerate project bankability.

Some of the measures used by various countries to reduce financing costs are elaborated in Table 5.

Table 5: Examples of measures to reduce financial costs for GH projects

SN	Method	Description	Examples of countries
1	Inflation reduction	Bold policy reforms undertaken to reduce hyperinflation in countries by attracting high-value investment, offering legal and policy certainty, accelerated depreciation and other such measures.	Argentina, through the passage of Régimen de Incentivos para-Grandes Inversiones (RIGI) Law attempts to promote large-scale infrastructure projects (including GH), combat inflation and reduce commodity costs. As per ISA's deep dive study, RIGI Law might help achieve LCOH reduction in turn of approximately 30 per cent[61].
2	Incentives such as Generation Based Incentives (GBI) / Production Linked Incentives (PLI) / direct Capex subsidies	Offering direct financial incentives for every unit of GH produced, or, for every equipment manufactured, or Capex / Opex subsidies, in an attempt to reduce commodity costs in nascent industries.	Countries like USA, EU, Japan, South Korea, India etc offer incentives through various schemes to boost manufacturing and promote GH production and offtake.

60 Steelonthenet article, 11 August 2025 (Trillion Dollar Hydrogen Infrastructure for Steel Industry Investment Costs), Accessed on 15 September 2025. It may be noted that such an estimate can widely vary depending on the hub-to-hub and country-to-country

61 Green Hydrogen Readiness Assessment for Argentina (1749638566ISA_ADB_GH_ACEF_2025_06_June_Argentina.pdf), ISA, ACEF 2025, Manila, June 2025. Accessed on 18 December 2025

SN	Method	Description	Examples of countries
3	Clean supply chain collaborations	Collaborations between a low-cost RE / GH producer and a clean energy importer to ensure the establishment of alternative clean energy supply chain and reduction of costs.	Collaboration between Oman (GH producer) and Japan (clean energy importer)

China aims to achieve cost competitiveness in GH, banking on scaled up and vertically integrated manufacturing, high-quality RE and low-financing costs

China's cost competitiveness in GH stems from a unique blend of structural and policy advantages. It has built a vertically integrated manufacturing ecosystem for renewable energy and hydrogen technologies, enabling economies of scale and streamlined supply chains. This integration, has resulted in manufacturing cost leadership, where solar modules are 20–80 per cent cheaper and electrolyser stacks, 50–55 per cent cheaper than global averages. China also benefits from abundant, high-quality renewable resources, including CSP-grade solar, vast wind potential, hydropower, and emerging geothermal capacity, which lower electricity costs - the largest component of hydrogen production. Financing conditions further strengthen its position: interest rates for clean energy projects are typically 5–6.5 per cent, comparable to advanced economies and far below those in most emerging markets. Supportive government policies, such as generous funding, CCER credits, and CfDs for renewable pricing, provide stability and incentives across the value chain. These combined factors are expected to bring China's LCOH down to USD2–3/kg by 2030, making it one of the most competitive markets globally for GH production.

The key measures undertaken by China in reducing RE and GH costs can be summarised in Table 6 shown below.

Table 6: Key strategies resulting in China's multi-faceted competitive advantages in the GH ecosystem

<table>
<tr><th>Strategy undertaken</th><th>Key impacts</th></tr>
<tr><td>Vertically integrated manufacturing</td><td>China has vertically integrated its RE supply chains and is seeking to replicate this success in the GH value chain, as reflected in global manufacturing capacities below[62,63,64]. The figures in the table below represent the approximate proportion of global manufacturing capacity for each item that is based in China.
<table><tr><td>Polysilicon:
75-80 per cent</td><td>Wafers:
>95 per cent</td><td>Solar cell:
80-85 per cent</td></tr><tr><td>Modules:
70-75 per cent</td><td>Battery cell:
80-85 per cent</td><td>Electrolyser:
50-55 per cent</td></tr></table></td></tr>
<tr><td>High quality renewable resources</td><td>China has abundant RE potential including CSP grade solar, wind, hydro and geothermal resources, which can aid in providing near base load type/higher availability of RE resource for GH production. China also has plans to expand the generation capacity of all forms of renewable energy sources available within the country, to meet its climate goals and promote GH production.
Solar: As per Global Solar Atlas figures, China experiences Global Horizontal Irradiation (GHI) between 2.64-5.93 kWh/m^2 and Direct Normal Irradiation (DNI) of 0.98 – 7.58 kWh/m^2 [(65)]. Regions like Inner Mongolia, Gansu, Anhui, Shanxi, Xinjiang and Qinghai offer good locations for setting up large-scale solar PV and CSP projects.
Ambient temperature: The moderate to low average temperature of the country (average monthly temperatures ranging from -13.05^{O}C to 25.65^{O}C observed from 1991-2020) provides ideal conditions for the operation of solar panels by avoiding efficiency losses due to high seasonal temperatures[66].
<i>Onshore wind:</i> As per Global Wind Atlas, the wind power density of the top 10 per cent windiest areas in China is approximately 717 W/m^2, with wind speeds reaching about 9-10 m/s at 100 m hub height from the ground[67]. Regions like Inner Mongolia, Xinjiang, Liaoning and Hebei offer high wind power densities in the country for wind power projects with some areas in Xinjiang offering wind power densities as high as 2,000 W/m^2.
Offshore wind: As per the World Bank Group, the technical potential of offshore wind power in China is approximately 2.98 TW, which is almost equally distributed between fixed-bottom and floating wind projects[68].</td></tr>
</table>

62 Solar PV Global Supply Chains, IEA, Paris, 2022 (Executive summary – Solar PV Global Supply Chains – Analysis - IEA). Accessed on 26 October 2025
63 Batteries and Secure Energy Transitions, IEA, Paris, 2024 (Status of battery demand and supply – Batteries and Secure Energy Transitions – Analysis - IEA). Accessed on 26 October 2025
64 Analysis for this report, 2025
65 Global Solar Atlas, The World Bank Group, 2025 (Global Solar Atlas), accessed on 13 October 2025
66 Climate Change Knowledge Portal, The World Bank Group, 2025 (ChinaCHN - Country Overview | Climate Change Knowledge Portal), accessed on 13 October 2025
67 Global Wind Atlas, The World Bank Group, 2025 (Global Wind Atlas), accessed on 13 October 2025
68 Offshore wind technical potential in China, ESMAP, The World Bank Group (World Bank Document). Accessed on 13 October 2025

<table>
<tr><th>Strategy undertaken</th><th>Key impacts</th></tr>
<tr><td></td><td>

- ***Hydro:*** As per International Hydropower Association (IHA), China has the largest installed base of hydropower projects at 400 GW, with additional 200 GW under construction[69]. The overall potential however is not clear. China also hosts the "**World's Largest Hydropower Project**", the Three Gorges Dam, capable of generating 22.5 GW power. Additionally, the country also launched Fengning Pumped Storage Power Station the "**World's Largest Pumped Hydro Storage Project**" having a capacity of 3.6 GW[70].
- ***Geothermal:*** China hosts a significant portion of the Himalayan Mountain Range and Tibetan Plateau, both of which are characterised by intense seismicity caused due to the ongoing subduction of the Indian tectonic plate beneath the Eurasian plate, resulting in Himalayan mountain and Tibetan plateau orogenesis. The Kunlun Mountain ranges, a part of the Western Tibetan Plateau near Xinjiang, are also known for active volcanoes like Ashi volcano. As per Chinese Academy of Geological Sciences, China had nearly 51 MW of geothermal power generation capacity in 2021, but has plans to establish 200 MW of geothermal power capacity by 2030 and 1 GW by 2050 [(71)]. A part of China's geothermal potential is used directly for heating and cooling. This corresponds to about 32 GW of thermal capacity as of 2020[(72)]. Geothermal energy's baseload characteristics and possibility of utilising high efficiency SOECs can help drive down costs of GH production.

</td></tr>
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Manufacturing cost leadership

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China's vertically integrated manufacturing ecosystem coupled with generous government support has enabled the country to achieve manufacturing cost leadership. For example, solar modules manufactured in China are 20-80 per cent cheaper and electrolysers 50-55 per cent cheaper as compared to the global counterparts[73,74]. Figure 11 illustrates cost competitiveness of key GH and RE components compared to select geographies.

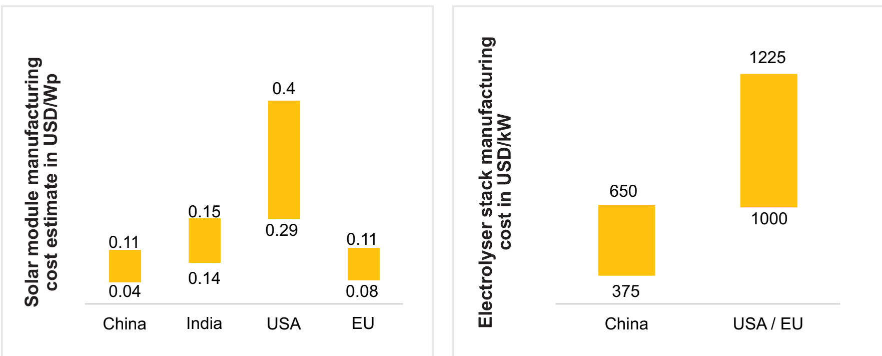


Figure 11: Manufacturing cost competitiveness in China for different components of the GH value chain

</td></tr>
</table>

69 International Hydropower Association article, 30 July 2025 (#IHA30 - 30 countries where hydropower is the backbone of the energy mix), accessed on 13 October 2025
70 International Hydropower Association article, 30 July 2025 (#IHA30 - 30 countries where hydropower is the backbone of the energy mix), accessed on 13 October 2025
71 Geothermal Resources For the 21st Century - Insights from China's Geothermal Resources Exploration and Development, Wang Guiling Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, 23 October 2024, United Nations Geospatial Knowledge and Innovation Week 2024 (GeoNow 2024) Deqing, China (Link), accessed on 13 October 2025
72 Geothermal Resources For the 21st Century - Insights from China's Geothermal Resources Exploration and Development, Wang Guiling Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, 23 October 2024, United Nations Geospatial Knowledge and Innovation Week 2024 (GeoNow 2024) Deqing, China (Link), accessed on 13 October 2025
73 Infolink website (PV spot price). Accessed on 26 October 2025
74 Global Hydrogen Review 2024, IEA, 2024 (Global Hydrogen Review 2024 – Analysis - IEA). Accessed on 26 October 2025

Strategy undertaken	Key impacts
Competitive cost of capital	China offers competitive cost of capital, which is almost at par with advanced economies. The usual loan interest rates for clean energy projects in China are in the range of 5 to 6.5 per cent, against 8 to 15 per cent in most of the EMDEs[75].
Supportive government policies	China offers generous funding and policy support for clean energy projects, including RE and GH projects. China is offering funding support and incentives for GH value chain projects, including end-use sectors like mobility, chemicals, etc. For RE projects, support is available in the form of conducive policies like CCER credits and CfDs for market oriented RE pricing[76,77].

The above findings clearly illustrate China's competitive advantage in the emerging GH ecosystem and the rapid progress the country is making in this direction. This also can offer some key learnings for countries which aim to achieve leadership in GH, or help increase the proportion of projects progressing to the FID stage.

Key strategic takeaways and recommendations

Driving GH competitiveness demands simultaneous action on five levers: electricity cost reduction, improving equipment availability and utilisation, building shared and integrated infrastructure, financing cost reduction and vertically integrated scaled up manufacturing. Electricity remains the dominant cost driver which is about 60–70 per cent of LCOH, so policymakers must unlock ultra-low tariffs of higher availability RE resources through hybrid solar-wind-storage tenders, baseload hydro/geothermal, and collocation to neutralise grid surcharges. Financing costs in EMDEs, often 8–15 per cent, must be reduced via CfDs, Viability Gap Funding (VGF), sovereign guarantees, and blended finance to achieve parity with advanced economies. Investors should prioritise hub-centric models with shared pipelines, storage, and port assets to cut midstream capex by 50 per cent, while anchoring projects with multi-sector Sales and Purchase Agreement (SPAs) in refining, fertilisers, and methanol to de-risk revenue. Technology localisation and electrolyser cost-downs via vertical integration, larger stacks, and reduced Platinum Group Metals (PGMs) are critical to compress engineering, procurement, and construction (EPC) contingencies. Nations that synchronise these actions will break the "no demand, no scale, no cost decline" loop and position themselves as leaders in GH production ecosystems as summarised below (Table 7).

Table 7: Key strategic recommendations to help reduce GH costs

SN	Major lever	Strategic actions	Typical examples
1	**Reduce the cost of electricity**	**Leveraging low cost RE resources:** Focus on setting up projects in areas offering low-cost RE resources	Saudi Arabia, Oman, China, Nepal, Bhutan, Egypt, Ethiopia, Namibia, Morocco, etc
		Optimise network and regulatory costs: Reduce or waive off network charges to reduce overall electricity cost	Countries like Oman, Saudi Arabia, Chile, Egypt etc are opting for collocation of RE and GH plants

75 Cost of capital expectations for 2025 diverge amid rising uncertainty, IEA, Paris, 2025 (Cost of capital expectations for 2025 diverge amid rising uncertainty – Analysis - IEA). Accessed on 26 October 2025

76 S&P global article, 06 March 2025 (China completes first issuance of domestic voluntary carbon credit CCERs | S&P Global). Accessed on 03 November 2025

77 Taiyang News article, 17 March 2025 (World's Biggest Solar Market China Moving Towards CfD Mechanism). Accessed on 03 November 2025

SN	Major lever	Strategic actions	Typical examples
2	**Use RTC RE (with higher availability) to maximise electrolyser utilisation**	**Hybridisation:** Combine complementing RE-resources with battery storage or other energy storage systems to increase electrolyser utilisation	Saudi Arabia, Oman, China, India
		High quality RE-resources: Utilise CSP-grade solar and high energy density wind resources, wherever possible	Chile, Namibia, Argentina, Peru, Morocco, Egypt, Tunisia
		Baseload RE-resources: Utilise baseload RE-resources like geothermal and hydro, subject to availability, for continuous operation	Nepal, Bhutan, Ethiopia, Papua New Guinea use hydro or geothermal, as applicable. Other countries like Peru, Chile, Argentina, China also have significant geothermal potential and are developing ways to harness this
3	**Plan hydrogen hubs or cluster development to bring scale and shared infra benefits**	**Shared infrastructure:** Prioritise shared infrastructure development as that can reduce total infrastructure spending by more than 50 per cent	Large-scale hydrogen hubs in USA, Netherlands, Germany, Oman, Saudi Arabia, Japan, South Korea
4	**Lower financing costs by addressing risks**	**Inflation reduction:** Introduce policy reforms to tackle inflationary pressures, attract high-value investments	Argentina (passage of RIGI Law)
		Incentives like GBI / PLI: Provide direct incentives to boost low-cost commodity production and equipment manufacturing	USA, EU, Japan, South Korea, China, India
		Clean Supply Chain Collaborations: Collaborations between a low-cost RE / GH producer and a clean energy importer	Collaboration between Oman (GH producer) and Japan (clean energy importer)
5	**Bring down equipment cost through scale and innovation**	**Vertically integrated manufacturing:** End-to-end manufacturing of GH value chain equipment, even for subcomponents	Existing in China, though USA, EU, Japan, South Korea have extensive plans to promote vertically integrated manufacturing
		Innovation: Addressing key concerns of equipment related to efficiency, BoP optimisation to help reduce cost	USA, EU, Japan, South Korea, China

IV. Strategic domestic and global collaborations are pivotal to shaping a resilient and integrated green hydrogen ecosystem

Key takeaways:

1. Formation of large hydrogen hubs across the world has emerged as a critical strategy for achieving cost leadership through scale benefits and bringing socio-economic benefits to the region. US, through its H2HUBS programme offers a stellar example of inter-industry and region-wide collaborative efforts for GH projects. Other countries like Japan, EU, South Korea are also adopting such collaborative models
2. Clean energy importers like Japan, South Korea, EU are developing multi-investor GH hubs in select RE-rich countries akin to Liquefied Natural Gas (LNG) projects, to develop multiple, alternate, GH / green ammonia supply chains.
3. Countries lacking sufficient local resources can learn from global best practices and explore partnerships with low-cost GH producers that also offer other favourable characteristics.
4. Active involvement of stakeholders with a high degree of influence is essential to ensure project success and long-term sustainability.

Integrated infrastructure is essential to aid in GH cost reduction through extensive use of shared infrastructure connecting producers and consumers

Robust infrastructure and large-scale deployment are fundamental to reducing costs and ensuring efficiency in GH production. Shared facilities, integrated transport networks, and storage systems enable economies of scale, making hydrogen more accessible and affordable.

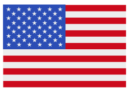
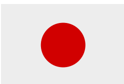
GH hubs present a transformative approach to scaling up the production and utilisation of GH by creating integrated ecosystems that bring together producers, consumers, and shared infrastructure within a defined geography. Their primary advantage lies in enabling economies of scale, which significantly reduces production costs and accelerates market adoption. By clustering multiple projects and stakeholders, hubs allow for pooled infrastructure such as pipelines, storage facilities, and port terminals, which would otherwise be prohibitively expensive for individual projects. This shared infrastructure not only optimises resource utilisation but also improves ease of doing business, attracting investment and fostering innovation. Furthermore, hubs create concentrated demand centres, ensuring steady offtake and financial viability, while supporting ancillary industries such as equipment manufacturing and renewable energy development. They also generate socio-economic benefits through job creation, skill development, and local community engagement, making them a catalyst for regional economic growth and sustainable industrialisation.

Clean hydrogen hubs: Providing templates for domestic and global collaboration

Countries are increasingly looking to establish hydrogen hubs because they offer a strategic solution for meeting ambitious decarbonisation targets and energy security goals. Hydrogen hubs provide the necessary infrastructure backbone to achieve scale, enabling efficient production, storage, and distribution while supporting global trade in hydrogen and its derivatives such as ammonia and methanol. For resource-rich nations, export-oriented hubs present an opportunity to monetise renewable energy potential and diversify economies, as seen in Saudi Arabia’s NEOM project and Oman’s SalalaH2 hub. Conversely, import-based hubs in regions like Japan, South Korea and Europe address domestic resource constraints by leveraging global supply chains to secure clean energy imports. Domestic hubs, such as those in the United States, focus on decarbonising local industries and transport sectors, supported by strong policy frameworks and federal funding. These models illustrate how hubs align with national priorities, whether reducing emissions, creating jobs, or positioning countries as leaders in the emerging hydrogen economy. Table 8 provides details of clean hydrogen hub programmes across key countries.

Several pioneering clean hydrogen hubs have been documented in ISA's report "Framework for the Development of Green Hydrogen Hubs" released in June 2025 in ACEF, Manila, offering valuable lessons for future projects worldwide[78]. It may also be noted that green hydrogen hubs are currently under development as of now.

Table 8: Promotion of clean hydrogen hubs across the world (list not exhaustive)

Country	Programme
	**USA: H2HUBS programme** Seven federally approved hydrogen hubs across the country announced with a funding support of USD7 billion[79]. The hubs feature Government to Government (G2G), Business to Business (B2B), Government to Business (G2B), and Research to Research (R2R) collaborations, with each partner providing dedicated services to support the overall hub network.
	**Japan: Hydrogen Society Promotion Act (HSPA)** Under the HSPA, Japan plans to provide financial subsidies for clean hydrogen hubs, allocating nearly JPY5.7 billion (approx. USD38.4 million) in FY2025–26 for Front End Engineering and Design (FEED) studies[80]. Further funding details will follow. Five priority regions including Tohoku, Kanto (including Tokyo), Chubu, Kinki, and Kyushu are earmarked for initial hub development[81].
	**EU: Hydrogen clusters/valleys/hubs** The EU is developing export, import, domestic, and hybrid GH hubs across several member states. Major hubs such as Rotterdam (Netherlands), Hamburg (Germany), Sines (Portugal), and BotH$_2$Nia (Finland/Sweden) are expected to feature extensive G2G, B2B, G2B, and R2R collaborations.
	**South Korea: Hydrogen cities** Six hydrogen cities namely Pyeongtaek, Namyangju, Dangjin, Boryeong, Gwangyang, and Pohang are planned, focusing on imports, production, infrastructure, and diversified hydrogen use. Nearly KRW240 billion (approximately USD193 million) is expected to be spent by the federal government with additional funding from respective provincial and municipal governments[82].

Cross-border collaborations: Driving alternate clean energy supply chains

While domestic hubs aim to deliver scale benefits, global collaborations are emerging as a critical lever to diversify clean energy networks and strengthen energy security. Clean energy importers such as Japan,

78 Framework for the development of GH hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 10 July 2025

79 Framework for the development of GH hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 10 July 2025

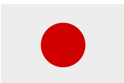
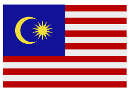
80 S&P Global article, 06 March 2025 (Japan to examine subsidy applications for hydrogen hub FEED after June 30 | S&P Global). Accessed on 26 October 2025

81 METI press release, 19 May 2025 (First Selection of Priority Regions for Promoting the Deployment of Fuel-Cell Commercial Vehicles). Accessed on 01 October 2025

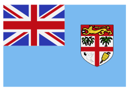
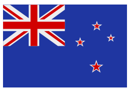
82 Hydrogen Insight article, 10 January 2023 (South Korea to create six 'hydrogen cities' that would use H2 in buildings and transport as part of daily life | Hydrogen Insight). Accessed on 01 October 2025

South Korea and the EU are spearheading multi-investor GH hubs in renewable-rich geographies, following models similar to multi-party LNG projects. These initiatives focus on creating multiple, alternate GH or green ammonia supply chains by leveraging rich renewable resources, industrial demand centres and supportive policy frameworks in partner countries. Cross-border partnerships aim to accelerate infrastructure development, enable technology transfer and reduce supply risks, thereby driving resilient and cost-competitive clean energy supply chains. Countries with limited domestic resources can adopt these best practices to forge partnerships with low-cost producers, ensuring diversified and secure energy flows. Table 9 highlights instances of such collaborations that are shaping the global clean energy landscape[83].

Table 9: Global collaborations to explore alternate GH / green ammonia supply chains (list not exhaustive)

SN	Importing country	Exporting country	Key companies	Possible characteristics for identifying exporting country
1			Samsung, Posco and others	• Rich RE resources • Presence of industrial demand centres • Strong government support, transparent auctions, infrastructural support (pipelines, jetties, land allocation) • Strong legal support (development rights for 47 yrs.)[84]
2			JAPEX, Sumitomo, Eneos and others	• Rich RE resources + Carbon Capture, Utilisation and Storage (CCUS) infrastructure • Presence of industrial demand centres • Nearshoring energy supplies
3		**North Africa**	SouthH2 corridor (multiple companies from EU, North Africa)	• Rich RE resources • Proximity to demand centres • Cheaper method of hydrogen transportation (undersea pipelines) • Part of a parallel cross-continent pipeline infrastructure, European Hydrogen Backbone (EHB)

83 Analysis for this report, 2025, based on publicly available news reports
84 S&P Global article, 22 June 2023 (Oman awards green hydrogen/ammonia project to South Korea's top steelmaker POSCO, France's Engie | S&P Global). Accessed on 30 October 2025

SN	Importing country	Exporting country	Key companies	Possible characteristics for identifying exporting country
4			Fiji Gas, Obayashi Corporation, Halcyon Power	• Rich RE resources (baseload geothermal in New Zealand) • Geographical proximity • Existing favourable trade relations, framework agreements, climate partnerships (like PACER, Fiji country plan of MFAT)[85,86,87,88]

85 Green Hydrogen Readiness Assessment for Fiji, ISA, ACEF 2025, Manila, June 2025 (1749638566ISA_ADB_GH_ACEF_2025_06_June_Fiji.pdf). Accessed on 03 November 2025

86 Globalization and Health article, 2025 (Monitoring the impact of trade agreements on national food environments: trade imports and population nutrition risks in Fiji | Globalization and Health | Full Text). Accessed on 03 November 2025

87 Fiji Country Plan, MFAT, Government of New Zealand, May 2025 (Fiji-Country-Plan.pdf). Accessed on 03 November 2025

88 Abbreviations: PACER: Pacific Agreement on Closer Economic Relations, MFAT: Ministry of Foreign Affairs and Trade, Government of New Zealand

Emerging collaborative models in GH ecosystem

The growing emphasis on cross-border collaborations for GH / ammonia supply chains is evident in the diverse collaboration models emerging globally. These frameworks, spanning governments, businesses and research institutions, are instrumental in converting strategic intent into real projects. By combining policy support, technical expertise and financial resources, such collaborations accelerate infrastructure development, reduce costs and promote innovation. Global trends in collaboration demonstrate this shift, with G2G, B2B, B2G, B2R and R2R alliances driving the creation of integrated GH ecosystems worldwide. Table 10 provides instances of such collaborative models.

Table 10: Emerging collaborative models in GH ecosystem

Type of collaboration	Countries/ Companies examples	Collaborative projects	Potential benefits/role of collaborators
G2G	Egypt and France[89]	Egypt and France have formalised a strategic cooperation agreement in April 2025 worth EUR7 billion, to jointly develop, finance, construct, and operate a project near Ras Shokair with a capacity of 1 MMTPA GH and its derivatives.	**Egypt:** Foreign investment, employment opportunities, and positioning as a GH export hub. **France:** Secures long-term GH supply, strengthens energy security, and gains access to cost-competitive imports.
	Germany, Austria and Italy[90]	Germany, Austria and Italy signed a joint declaration of intent (JDOI) for the development of SouthH2 Corridor in May 2024. The trilateral partnership aims to ensure hydrogen imports from North Africa through southern Italy and is then to be connected to important hydrogen demand clusters in Italy, Austria and Germany. This large-scale pipeline project is likely to facilitate the import of 10 MMT of renewable hydrogen by 2030.	**Germany/Austria/Italy:** Diversifies energy sources, ensures pipeline connectivity, and gains support in decarbonisation targets. **North Africa:** Gains infrastructure investment and export revenues.
	EU and Tunisia[91]	Tunisia is collaborating with EU, notably Germany, to explore potential of GH production through regulatory support, technical expertise, and financing, driven by Europe's interest in importing GH from North Africa.	**Tunisia:** Gains technical know-how, regulatory support and foreign capital. **EU:** Secures low-cost GH imports and strengthens supply chain resilience.

89 Africa Energy Portal article, April 2025 (Egypt and France Sign €7 Billion Agreement for Green Hydrogen Production | Africa Energy Portal). Accessed on 25 May 2025

90 Press Release, Federal Ministry for Economic Affairs and Energy, 2024 (BMWE - Germany, Austria and Italy sign a Joint Declaration of Intent for the Development of the SoutH2 Corridor). Accessed on 23 March 2025

91 European Commission article, July 2024 (Tunisia signs agreements to progress six GH projects with nine European companies | Hydrogen Insight), accessed on 17 March 2025

Type of collaboration	Countries/ Companies examples	Collaborative projects	Potential benefits/role of collaborators
B2B	ACWA Power and Snam[92]	In January 2025, ACWA Power, Saudi Arabia and Snam, European Union, have signed MoU for joint investment to establish an international GH supply chain from Saudi Arabia to Europe. The agreement includes assessing the development of an ammonia import terminal in Italy to support hydrogen delivery via the 3,300 km SouthH2 Corridor, linking Italy, Austria, and Germany.	**ACWA Power** to focus on production and export, gaining market access, investment and global prominence. **Snam** to handle infrastructure and import, ensuring supply security, strategic positioning and support for EU climate objectives.
	TotalEnergies and Air Products[93]	TotalEnergies and Air Products have signed a 15-year offtake agreement for the annual supply of 70,000 tonnes of GH to support the decarbonisation of TotalEnergies' refineries in Northern Europe, starting in 2030.	**TotalEnergies** to secure a long-term supply of GH to decarbonise its Northern European refineries **Air Products** is expected to benefit from assured offtake, further strengthening its position as a leading hydrogen supplier.
	ACWA Power, Air Products and NEOM[94]	The NEOM Green Hydrogen Project is a joint venture between NEOM, Air Products, and ACWA Power, aiming to produce 600 TPD of GH via electrolysis and up to 1.2 MMTPA of green by 2026.	NEOM provides strategic infrastructure and location support, ACWA Power leads renewable energy development, and Air Products acts as EPC contractor and ammonia off-taker, enabling large-scale GH production and global export.

92 Press Release, ACWA, January 2025 (ACWA Power and Snam Sign MoU for Green Hydrogen and Ammonia). Accessed on 23 March 2025

93 Press Release, Air Products, July 2024 (TotalEnergies and Air Products Green Hydrogen Deal | News Release). Accessed on 23 March 2025

94 NEOM press release, 23 May 2023 (NEOM Green Hydrogen Company completes financial close at a total investment value of USD 8.4 billion in the world's largest carbon-free GH plant). Accessed on 23 March 2025

Type of collaboration	Countries/ Companies examples	Collaborative projects	Potential benefits/role of collaborators
B2G	SalalaH2 Green Hydrogen Hub, Oman[95,96]	SalalaH2 GH hub project is led by OQ, a government-owned energy investment company, which serves as the principal equity investor. It brings together a consortium of international private sector partners, including Samsung Engineering from South Korea, Marubeni Corporation from Japan, Dutco Group from the UAE, and Linde from Germany. These companies contribute technical expertise, project development capabilities, and substantial foreign investment.	**OQ:** – Facilitates provision of land, access to shared hydrogen and ammonia pipeline infrastructure, port and jetty facilities, and power evacuation systems, leading project development. – Channels equity investment, strengthening Oman's role in global energy transition. – Acts as a partial offtaker of the GA ensuring commercial viability and long-term sustainability. **Consortium companies**: – In this project, Samsung Engineering offers EPC expertise, Marubeni brings investment and development capability, Dutco supports infrastructure, and Linde provides hydrogen technology. The project is likely to position itself as a leading integrated global green hydrogen project and secure financial closure.

95 Hydrogen Insight Article, December 2023 (Oman's latest GH deal brings country's project pipeline close to its million-tonnes-a-year target | Hydrogen Insight) Accessed on 30 April 2025
96 Zawya Article, March 2021 ($1bln project to create green ammonia export hub in Oman). Accessed on 30 April 2025

Type of collaboration	Countries/ Companies examples	Collaborative projects	Potential benefits/role of collaborators
B2R	Midwest Alliance for Clean Hydrogen (MachH2), USA[97,98,99]	Collaboration of MachH2, a US Department of Energy (DOE) funded clean hydrogen hub, with Idaho National Laboratory (INL) and Argonne National Laboratory (ANL) provides an instance for B2R collaboration.	**MachH2**: – Gains advanced technology support for hydrogen production and infrastructure. **INL and Argonne labs**: – Lead innovation in high-temperature steam electrolysis, reinforcing their research leadership. – Expand role in commercial hydrogen applications and partnerships. – Apply multidisciplinary expertise in modelling, life-cycle analysis and infrastructure planning in hydrogen production, storage and distribution systems.
R2R	Roll-to-Roll Consortium, USA[100]	This consortium is a collaborative effort among several leading national laboratories, including the National Renewable Energy Laboratory (NREL), ANL, Oak Ridge National Laboratory (ORNL), Lawrence Berkeley National Laboratory, and Sandia National Laboratories. The initiative is focused on advancing high-throughput, cost-effective manufacturing processes for hydrogen technologies,	**Research labs:** – Drive innovation in material and process technologies for scaling up hydrogen production and reducing costs. – Translate scientific breakthroughs into practical solutions via Cooperative Research and Development Agreements.

97 Midwest Alliance for Clean Hydrogen (MachH2), USA (h2hubs-midwest-factsheet-booklet-11.20.24-final.pdf). Accessed on 20 March 2025
98 Idaho National Laboratory (Idaho National Laboratory to play a key role in Midwest hydrogen hub - Idaho National Laboratory). Accessed on 25 April 2025
99 Alliance Members, MIDWEST Alliance For Clean Hydrogen (Alliance Members - Midwest Alliance for Clean Hydrogen). Accessed on 30 April 2025
100 Roll to Roll Consortium, U.S Department of Energy, 2024 (R2R: Roll-to-Roll Consortium | Department of Energy). Accessed on 30 April 2025

Type of collaboration	Countries/ Companies examples	Collaborative projects	Potential benefits/role of collaborators
		particularly fuel cells and water electrolysers. The Roll-to-Roll Consortium aims to address key challenges in material synthesis, coating, drying, and quality control, which is essential for scaling up hydrogen production and reducing costs. It also includes academic partners such as the University of New Mexico, which contributes expertise in coating process modelling[101].	**Academic partners:** – Gain opportunities for applied research in GH sector. – Provide and develop skilled talent pools through student exchange programs.

Stakeholders' buy-in is critical for the success of a major GH project or hub; continuous and transparent stakeholder engagement is thus essential ab-initio

The success of GH hubs hinges on the coordinated efforts of a diverse set of stakeholders, each playing a distinct yet interconnected role in shaping a robust and sustainable ecosystem. At the core are the value chain participants such as renewable electricity providers, power transmission operators, hydrogen producers, and storage and distribution operators. These entities ensure the seamless generation, transportation, and delivery of GH and its derivatives to end-users across sectors like refining, fertilisers, steel, and mobility. Their responsibilities extend beyond production to include maintaining quality standards, optimising operational efficiency, and ensuring reliability of supply. Complementing these are technology providers and manufacturers who supply critical components such as electrolysers, fuel cells, pipelines, and storage tanks, while EPC contractors oversee the design and commissioning of infrastructure. The layers of the stakeholders have been explained in detail in ISA's report "Framework for the Development of Green Hydrogen Hubs" released in June 2025 in ACEF, Manila[102].

Institutional enablers form the second pillar of hub development, providing the regulatory, financial, and technical scaffolding necessary for large-scale deployment. Policymakers and regulators establish clear legislation and standards to create an enabling environment, while financiers inject capital through equity, debt, and innovative instruments such as tax credits and viability gap funding. Standards and certification agencies ensure compliance with global benchmarks, facilitating international trade and investor confidence. Academia and research institutions contribute by driving innovation and developing a skilled workforce, while international collaborators bring technical expertise and market access, strengthening global partnerships. Demand aggregators play a critical role in consolidating offtake commitments, converting fragmented demand into bankable volumes that underpin project viability.

Local communities represent a vital stakeholder group whose engagement determines the social licence to operate. Their involvement ensures that projects deliver tangible socio-economic benefits such as employment generation, gender inclusion, and environmental stewardship. Transparent dialogue and participatory decision-making are essential to mitigate risks of opposition, which could derail timelines and financing. Global examples underscore this imperative: projects in regions with indigenous populations have faced resistance when community concerns were overlooked, whereas initiatives like the Western Green Energy Hub in Australia demonstrate how proactive engagement fosters trust and accelerates development[103].

101 Roll to Roll Consortium, U.S Department of Energy, 2024 (R2R: Roll-to-Roll Consortium | Department of Energy). Accessed on 30 April 2025

102 Framework for the development of GH hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 10 July 2025

103 Framework for the development of GH hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 10 July 2025

To navigate this complexity, a stakeholder matrix has been devised to categorise key actors based on two dimensions: level of influence which defines their ability to shape outcomes and degree of participation which defines their current engagement in GH initiatives, as illustrated in Figure 12 [(104)]. The figure outlines recommended strategies for different stakeholders in a GH hub or project, based on their level of influence and involvement.

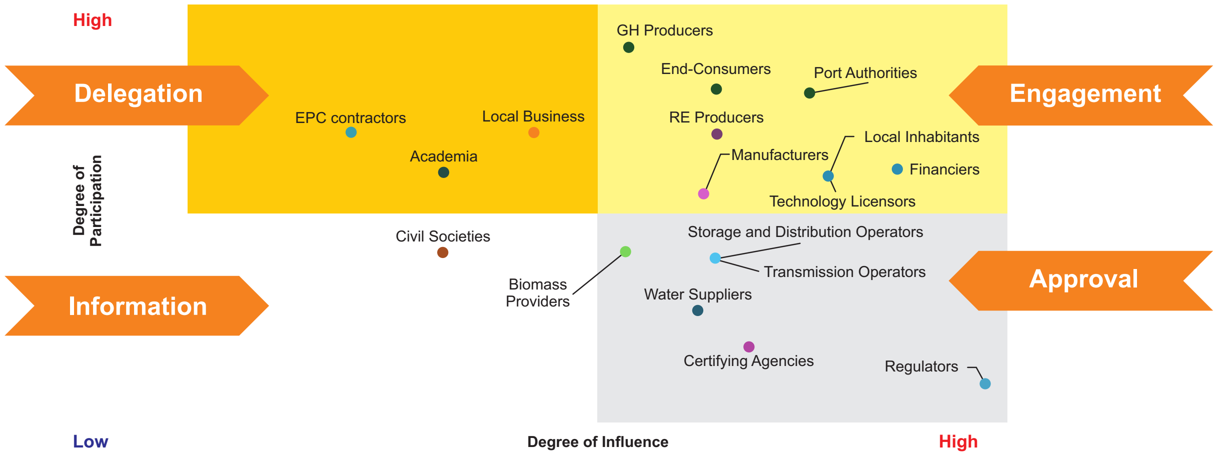


Figure 12: Suggested stakeholder engagement strategies based on degree of participation and influence (list not exhaustive)

The matrix serves as a roadmap for more inclusive and effective stakeholder engagement. It helps identify where to strengthen capacity, enhance collaboration, and elevate voices that are often overlooked but remain essential to the effective and inclusive development of the GH sector. This analysis reveals several key insights:

- Stakeholders positioned in the **upper-right quadrant**, are the ones with both high influence and high participation. They actively shape national and international policy, unlock and direct capital flows, and drive innovation through research and technology deployment. Their high engagement ensures that projects move from concept to reality. Their continued leadership is essential, but they must also collaborate with under-engaged influential actors to drive systemic progress.
- The **lower-right quadrant** highlights stakeholders with high influence but low participation. These stakeholders possess considerable authority over infrastructure, standardisation, resources, and supply chains essential for scaling GH projects. They have limited engagement, but they have the capacity to drive or hinder the progress of a GH project. The approvals of such stakeholders are essential for various aspects of the project like resource supply, adherence to standards, issuance of certificates, etc.
- Stakeholders positioned in the **upper-left quadrant**, are the ones with low influence and high participation. These stakeholders bring invaluable local insights, help build community trust, and support skill development. They lack formal decision-making authority, but their high-level participation through allocation of work or delegation ensures proper performance of the project.
- The **lower-left quadrant** comprises stakeholders with currently limited influence and participation. Despite their peripheral position, these groups can rapidly shape public discourse, particularly on sensitive issues like gender equality, social inclusion (GESI), employment opportunities, economic benefits, environmental risks, and land use. Proactively engaging these stakeholders and exchanging information not only promotes inclusivity but also helps mitigate potential resistance and ensures broader community support.

104 Analysis for this report, 2025. It may be noted that the relative positions of the indicated stakeholders can vary from country to country and project to project. A detailed stakeholder analysis needs to be performed before commencing work on any project.

Key strategic takeaways and recommendations

Hydrogen hubs are emerging as strategic enablers of the GH economy, designed to integrate production, shared infrastructure, and diversified end-use sectors under robust governance frameworks. They deliver economies of scale, reduce unit costs, and create bankable ecosystems by clustering projects and aggregating demand. Global trends point to LNG-style collaborations that pool capital, harmonise standards, and secure firm offtake, ensuring resilience and trade competitiveness. Success depends on multi-faceted stakeholder alignment: governments must legislate clear policies, mandate demand, and provide infrastructure access; industry and EPCs must localise technology and deliver cost efficiency; financiers must deploy CfDs, guarantees, and blended finance to unlock long-tenor capital; academia must accelerate innovation and skills; and local communities must be engaged early to secure social licence. In essence, hydrogen hubs are not isolated projects but integrated platforms that transform resource advantage into scalable, tradable value requiring synchronised action across policy, capital, technology, and society to convert ambition into execution and position nations for leadership in the global clean energy transition. Table 11 enlists some strategic recommendations for stakeholders associated with shared infrastructure, collaborations and hydrogen hub development.

Table 11: Strategic recommendations to promote shared infrastructure and hydrogen hub development

Stakeholder	Recommended strategic actions
Policymakers	1 **Create hub governance frameworks:** Establish clear roles, transparent decision-making, and risk-sharing models to align government, industry, and financiers. 2 **Mandate standards & certification:** Harmonise Guarantees of Origin and carbon accounting to enable global trade and compliance with **Carbon Border Adjustment Mechanism (CBAM)**. 3 **Anchor domestic demand:** Enforce GH mandates in "drop-in" sectors like refining, fertilisers, and steel to secure predictable offtake, in addition to creating opportunities for emerging use cases in close proximity to the hydrogen hub. 4 **Enablers and infrastructure:** Provide enabling legislation, incentives, and infrastructure access (land, water, power). 5 **Collaborations:** Leverage existing energy trade collaborations to transition into green commodity supply chain establishment and draw long-term investments, akin to LNG projects.
Investors or developers	1 **Prioritise hub-centric investments:** Back integrated clusters with diversified end-use portfolios and firm offtake agreements to de-risk revenue streams. 2 **Leverage policy incentives:** Target geographies offering CfDs, tax credits, and blended finance for superior risk-adjusted returns. 3 **Shared infrastructure:** Draw advantages from shared infrastructure of hubs to reduce costs and reconfigure risk categories.
Common	1 **Local Communities:** Engage early to secure social licence and deliver socio-economic benefits.

V. Integrated manufacturing and innovation are central to technology leadership

Key takeaways:

1 Global momentum is building in domestic GH equipment manufacturing, covering electrolysers, storage tanks, and fuel cells. While China still accounts for around 50–55 per cent of electrolyser production, regions such as the EU, USA, Japan, and South Korea are working to establish domestic manufacturing ecosystems

2 Global electrolyser manufacturing is expected to rise 5-times the current capacity to about 200-220 GW/yr by 2030, basis announcements.

3 China's share of electrolyser manufacturing is expected to fall globally from 50-55 per cent in 2024 to about 20 per cent by 2030, although manufacturing within China is expected to grow.

4 AWE and PEM technologies currently account for 90-95 per cent share in existing capacity as of 2024, emerging technologies are expected to occupy nearly 25-30 per cent of the manufacturing capacity by 2030.

5 Leading industrial regions are increasingly announcing projects for high-tech GH components such as fuel cells, electrodes, membranes and Type-IV storage tanks, signalling a strong push to localise advance manufacturing, achieve vertical integration and maintain technological leadership.

6 Localised, vertically integrated supply chains are becoming a global priority to enhance resilience, secure technological leadership, and generate employment.

7 Infrastructure is equally critical for effective storage and distribution. Strategic infrastructure planning can unlock scalable Gigawatt-hour (GWh) to Terawatt-hour (TWh) energy storage solutions, addressing seasonal intermittency in renewable energy.

8 Fuel cell manufacturing is set to nearly double from the current 10–12 GW/yr, driven by growing power and mobility demand and strong policy support. South Korea is leading with Hyundai Mobis building the world's largest fuel cell manufacturing plant. Japan, EU, United States and China are also expected to add substantial capacity.

Despite announcements, lack of progress towards FID stage indicates that electrolyser installations for GH production may fall short of IEA Net Zero targets of 2030

Electrolysers are the critical technology component used for generation of GH from water using renewable power. According to IEA, the installed capacity could reach 230–520 GW by 2030; however, most projects remain at early development stages[105]. This trajectory still falls short of the Net Zero Emissions by 2050 pathway, which calls for about 560 GW of installed electrolysis capacity by 2030, underscoring the need for rapid scale-up and supportive policy frameworks[106].

Progress is geographically diverse with China leading in total installed capacity, European Union advancing in enabling policies, and regions such as India and the Middle East are moving ahead with a handful of large-scale projects. From a technology standpoint, four major electrolyser technologies

105 Electrolysers-Energy System, IEA, 2024 (Electrolysers - Energy System - IEA). Accessed on 15 April 2025
106 Electrolysers-Energy System, IEA, 2024 (Electrolysers - Energy System - IEA). Accessed on 15 April 2025

exist in the market i.e. AWE, PEM, SOEC and AEM electrolyser (Annexure–1). Additionally, several new and emerging technologies are developing in the market. Annexure–2 examines the advanced and emerging electrolyser technologies, offering insights into their functionalities and development progress.

Despite progress in conventional alkaline and PEM electrolyser technologies, several technical gaps remain that must be addressed to enable large-scale deployment for GH production. Innovations in existing technologies like AWE and PEM and emerging technologies are attempting to solve some of the pain points related to existing electrolyser families, mainly cost, efficiency, durability, etc. Table 12 outlines some of the important research areas.

Table 12: Direction of research and innovation in electrolysers

SN	Parameter	Direction of research
1	Turndown ratio	▼
2	Platinum Group Metals (PGMs) loading	▼
3	Pressurised hydogen output	▲
4	Module size / stack size	▲
5	Efficiency	▲
6	Durability	▲
7	PFAS loading[107]	▼

Ongoing research is also focused on developing next-generation technologies capable of overcoming existing barriers comprehensively. The key emerging electrolysis technologies have been discussed in detail in Annexure-2 in this report.

China dominates existing manufacturing facilities. AWE technology comprises more than 60 per cent market share globally with PEM gaining fast traction

Electrolyser manufacturing is expanding rapidly, driven by the global push for low-emission hydrogen. Capacity growth has outpaced actual deployment, creating regional imbalances and overcapacity in some markets. While costs remain a barrier, economies of scale, innovation, and supportive policies are expected to make GH more competitive by 2030 encouraging uptake of electrolysers.

As of September 2025, the global electrolyser manufacturing capacity stands at 35–40 GW per annum[108]. China is the leading manufacturer, accounting for an estimated 50–55 per cent of existing capacity, followed by Germany (10–12 per cent) and the USA (8–9 per cent)[109]. Manufacturing facilities are also located in countries such as Australia, the UK, and India.

Figure 13 below summarises the bifurcation of existing electrolyser manufacturing facilities based on country and technology[110]. Some of the electrolyser gigafactories which are expected to commence operations, as per announcements, are shown in Table 13 below.

107 PFAS: Per-fluoro alkyl substance or Ploy-fluoro alkyl substance. These are toxic substances, often labelled as “forever chemicals” due to their low-degradation abilities. PEM electrolyser membranes usually contain PFAS
108 Analysis for this report, 2025
109 Analysis for this report, 2025
110 Analysis for this report, 2025

Table 13: Electrolyser gigafactories expected to commence operations by 2026

Manufacturer	Manufacturing location	Proposed Gigafactory Capacity (GW/yr)	Technology
EvolOH[111]	Massachusetts, USA	3.75	AEM
John Cockerill[112]	France	1.00	AWE
John Cockerill[113]	Belgium	1.00	AWE

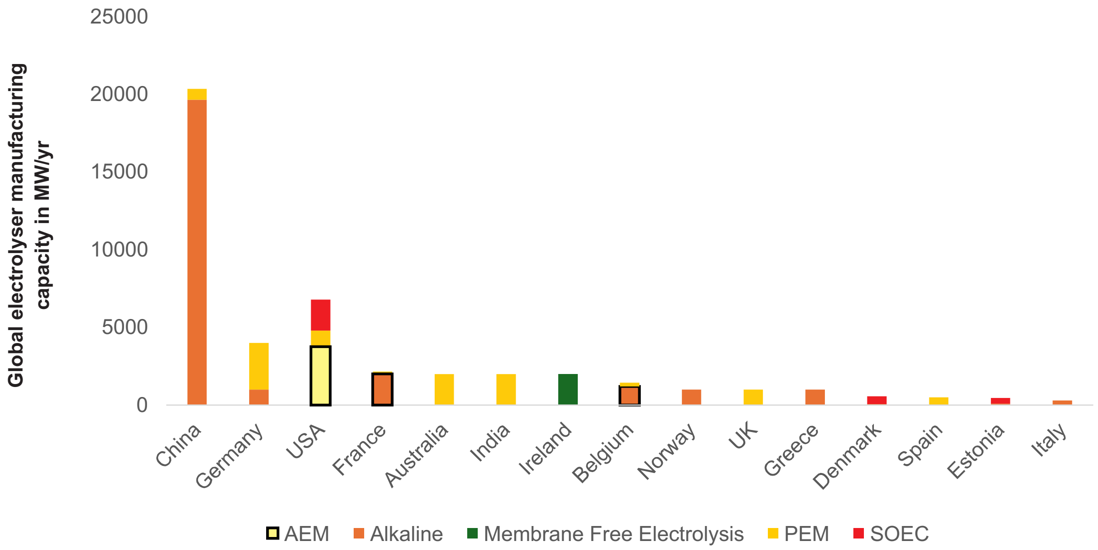


Figure 13: Global electrolyser manufacturing capacities based on country and technology. The data points shown in BOLD OUTLINE mean that the corresponding capacities are expected to begin operations in 2026

With regards to technology, alkaline electrolysers currently dominate the existing manufacturing setup, contributing to almost 60-65 per cent of the market share[114]. PEM technology is also gaining traction, accounting for approximately 30 per cent of the market[115]. Newer technologies like SOEC are emerging and hold around 6-7 per cent market share[116]. There may be a few more capacity additions in 2026, which may expand the global existing manufacturing base by 6-7 GW/yr[117]. If the slated plans fructify (optimistic case in Figure 13) by the end-of 2026, the additional capacity might include significant additions in new technologies, like AEM and MFE[118].

111 Hydrogen Insight article, 02 March 2023 (EXCLUSIVE | 'World's biggest hydrogen electrolyser factory will be a quarter the cost and size of a comparable PEM or alkaline plant' | Hydrogen Insight). Accessed on 10 October 2025
112 Recharge article, 04 May 2022 (EXCLUSIVE | John Cockerill to expand hydrogen electrolyser production to 8GW by 2025 | Recharge). Accessed on 10 October 2025
113 Recharge article, 04 May 2022 (EXCLUSIVE | John Cockerill to expand hydrogen electrolyser production to 8GW by 2025 | Recharge). Accessed on 10 October 2025
114 Analysis for this report, 2025
115 Analysis for this report, 2025
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117 Analysis for this report, 2025
118 Analysis for this report, 2025

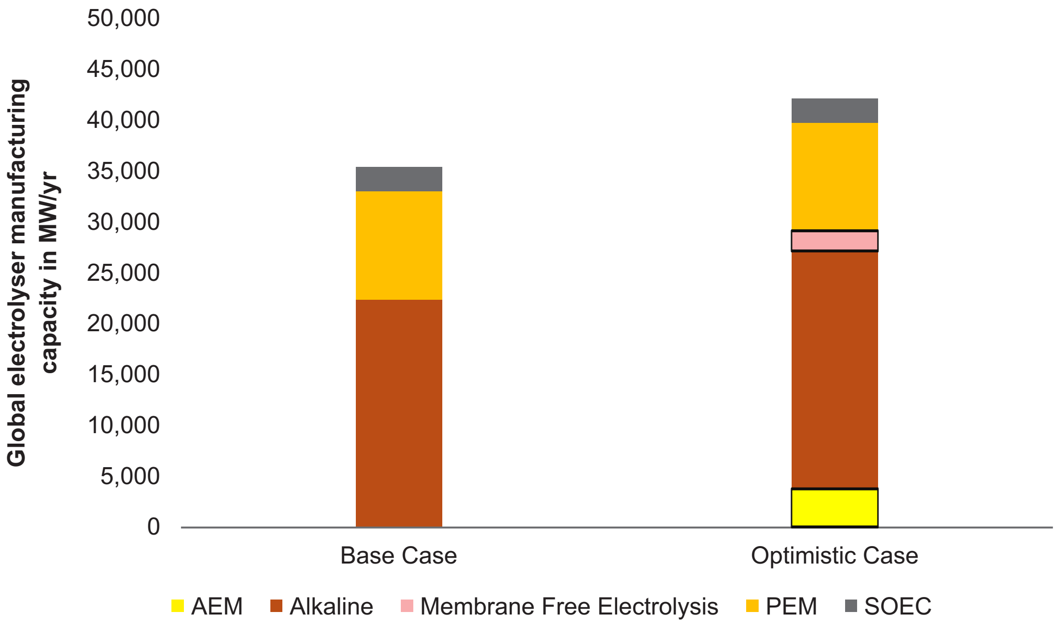


Figure 14: Global manufacturing capacity by 2026 in base and optimistic scenarios. The data points shown in BOLD OUTLINE mean that the corresponding capacities are expected to begin operations in 2026

It may be noted that mere existence of manufacturing lines does not necessarily guarantee production or sales. For instance, recent reports have indicated potential closure and layoffs of some large electrolyser factories owing to lack of product offtake amid market uncertainties.

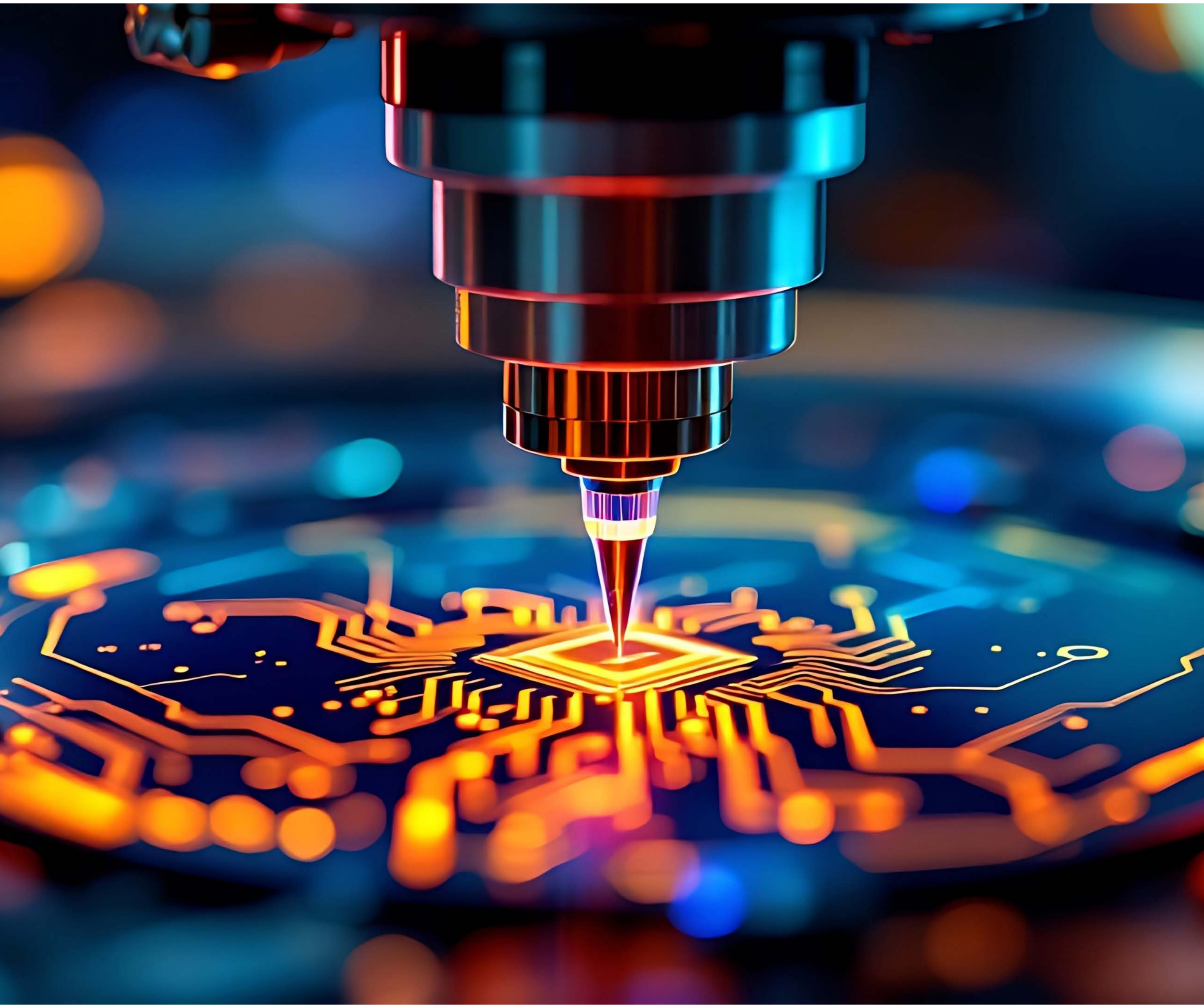
Some of the global electrolyser manufacturing companies have also filed for bankruptcy in the recent past, leading to significant changes in ownership and operational plans[119,120]. These developments highlight the financial challenges within the electrolyser manufacturing sector, despite growing global demand for hydrogen technologies.

Global electrolyser manufacturing capacity is expected to quintuple to 200-220 GW/yr annually basis announcements, with supply chain expected to diversify from China

1. China and the United States are projected to lead with around 19 per cent of market share each, though US growth in electroyser manufacturing capacity may slow due to paused Inflation Reduction Act (IRA) and Infrastructure Investment and Jobs Act (IIJA) incentives. APAC is forecast to hold 36 per cent of the market, followed by the EU at 28 per cent.
2. Emerging regions like Africa, Middle East and North Africa (MENA), Australia and India are also advancing significant plans for electrolyser manufacturing, which could collectively contribute several gigawatts of capacity by 2030.
3. PEM technology is likely to dominate with a 41 per cent share by 2030, while PEM and AWE together could account for 75-80 per cent of total manufacturing capacity. Other technologies such as AEM, SOEC, and membrane-less systems are also gaining traction and expected to secure a notable manufacturing capacity by 2030.

119 Fuel Cell Works article, 08 July 2025 (John Cockerill Acquires McPhy Energy's Belfort Gigafactory). Accessed on 25 September 2025
120 Thyssenkrupp Nucera press release, 02 September 2025 (thyssenkrupp-nucera_Press-Release_GHS-Closing_250902.pdf). Accessed on 25 September 2025

Global electrolyser manufacturing capacity is projected to grow nearly 5-fold to 200-220 GW per annum, between 2025 and 2030[(121)]. Based on announced publicly available information, USA and China are expected to be the leading manufacturers of electrolysers, with their market shares between 15 per cent to 19 per cent[122]. However, give the geopolitical realities and the US' halting of IIJA and the IRA for most renewables and GH projects, it is less likely that the pace of manufacturing would continue as expected in USA[123]. Other top manufacturing countries include Japan, Germany, India, France, UK. The top 10 countries together are envisaged to contribute to about 85 to 90 per cent of the global electrolyser manufacturing capacity by 2030[(124)].



121 Analysis for this report, 2025
122 Analysis for this report, 2025
123 Hydrogen Insight article, 27 January 2025 (Trump puts US clean hydrogen support schemes on hold as part of plan to terminate 'Green New Deal' | Hydrogen Insight). Accessed on 25 September 2025
124 Analysis for this report, 2025

Basis announcements, APAC is expected to lead with about 36 per cent market share, followed by Europe (including UK) at 28 per cent and North America at 19 per cent. These three regions may contribute to 82 per cent of the global capacity by 2030. Refer to Figures 15 and 16 respectively for country-wise and region-wise breakup. Although a major announcement has been made regarding an electrolyser manufacturing project in Namibia, the details on the actual progress on the ground, as well as any clarity on funding, market development, or commercial planning, are awaited.

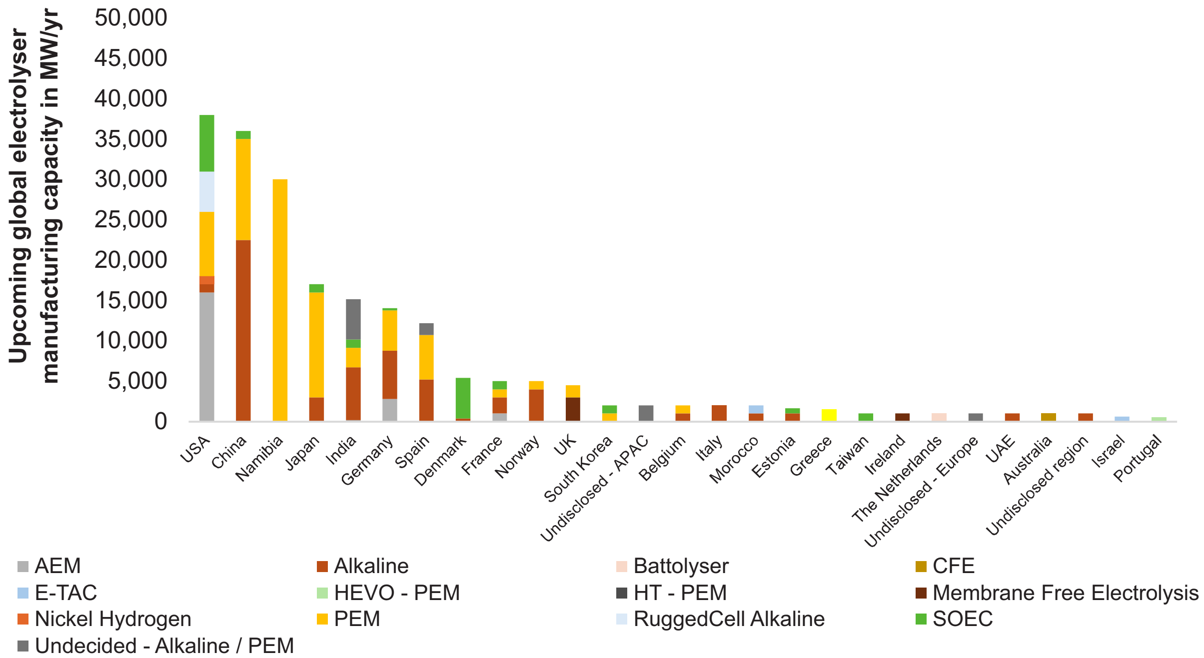


Figure 15: Upcoming global electrolyser manufacturing capacities based on countries

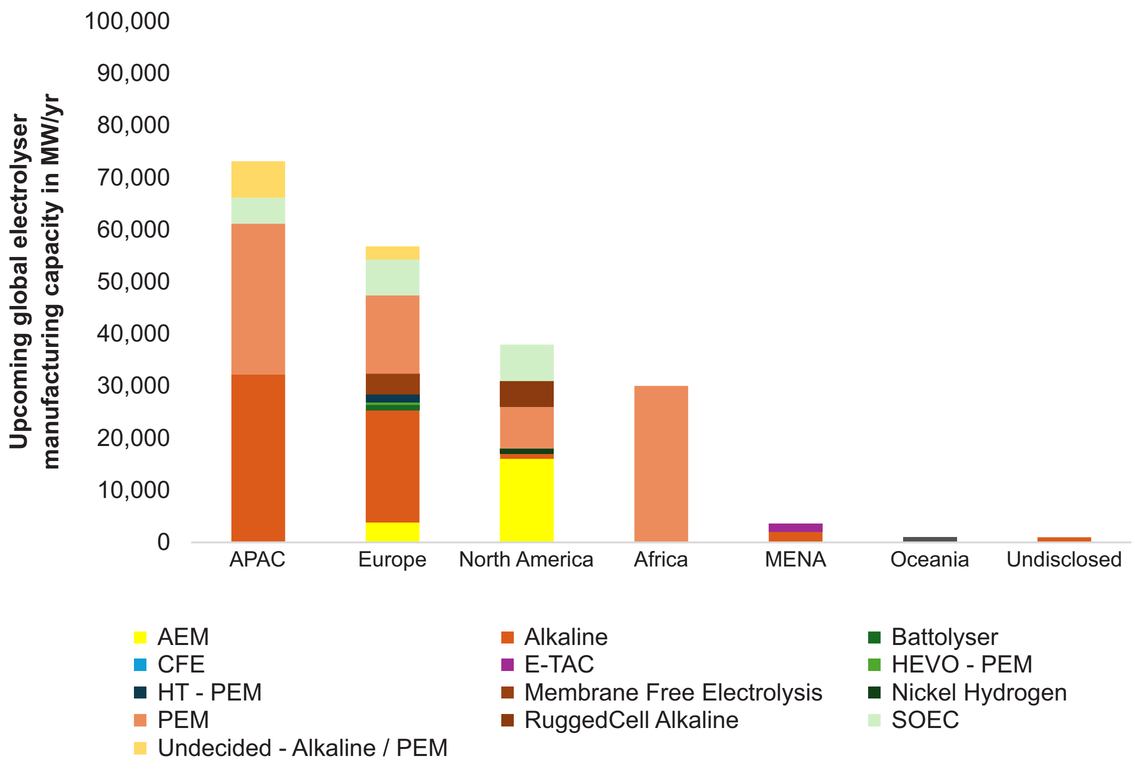


Figure 16: Upcoming global electrolyser manufacturing capacities based on regions

PEM electrolysers may dominate the future manufacturing landscape with a projected market share of nearly 40–45 per cent. This includes conventional PEM, High Temperature (HT) PEM and HEVO-PEM variants. Alkaline electrolysers (inclusive of Rugged Cell Alkaline) are expected to follow with a market share of approximately 30 per cent.

Many manufacturers have yet to commit to either AWE or PEM technologies, as they are capable of offering both. Nevertheless, these two technologies are collectively expected to contribute to nearly 75–80 per cent of the upcoming electrolyser manufacturing market by 2030[125]. Emerging technologies, such as Membrane-Free Electrolysis (MFE), Electrochemical-Thermally Activated Chemical (E-TAC), Battolyser, and Capillary-Fed Electrolysis (CFE), are expected to account for nearly 5 per cent of the market share. The detailed breakdown is provided in Figure 17 [126]. The details of individual sub-technology like HT-PEM, HEVO-PEM and Rugged Cell Alkaline are provided in Annexure-2 of this report.

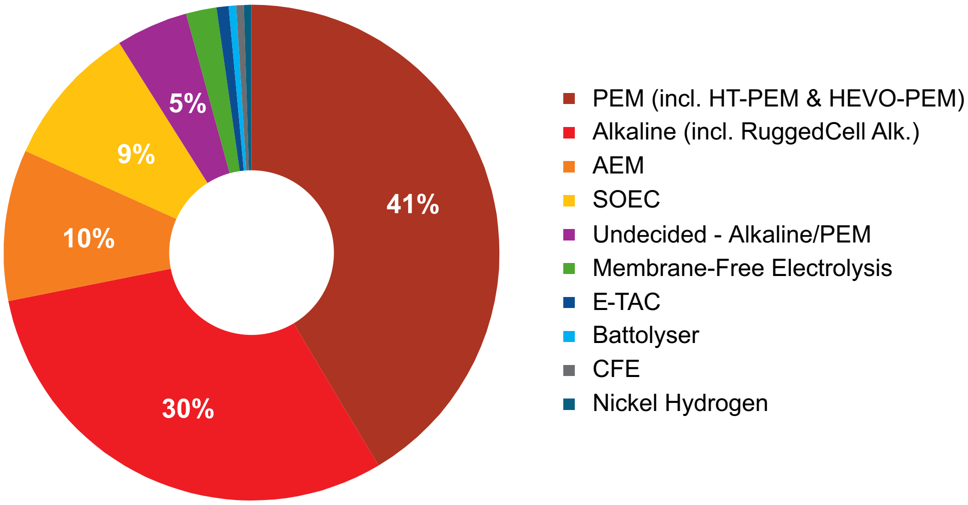


Figure 17: Upcoming global electrolyser manufacturing capacities based on technology

Key strategic recommendations

1. **There might be an oversupply of electrolysers in near future with China dominating the existing manufacturing establishment:** China aims to replicate its success in mass-producing solar PV panels and wind turbines by scaling up electrolyser manufacturing. As discussed previously in Chapter III and in the present chapter, the lack of progress of projects to FID stage might create an oversupply of electrolysers in the short term future.

   Investor caution is thus essential, particularly for projects lacking confirmed offtakers, adequate approvals, or government support especially those still at the pre-FID stage. Such projects carry heightened risks of delays, cost overruns, or cancellation, making thorough due diligence and risk mitigation strategies critical before committing capital.

2. **Countries are increasingly applying localisation laws aimed at securing the electrolyser supply chain by boosting domestic manufacturing:** The surge in electrolyser manufacturing announcements across Organisation for Economic Co-operation and Development (OECD) nations, the Middle East, and other regions underscores a strong policy push to localise supply chains and

125 Analysis for this report, 2025
126 Analysis for this report, 2025

avoid ceding manufacturing dominance to China, India, and others. This sentiment is echoed by industry players; leading European manufacturers recently appealed to European Commission to safeguard domestic manufacturing, warning against EU subsidies indirectly benefiting Chinese firms already supported by their government[127]. Similar localisation measures such as Saudi Arabia's In-Kingdom Total Value Add (IKTVA), UAE's In Country Value (ICV), Oman's Omanisation policy, and the IRA's Section 45V, are reinforcing domestic production mandates. These trends could erode the low-cost manufacturing advantage of China and India, severely limiting export opportunities. In response, some Chinese firms, like CSIC Peric, are partnering with European companies (for example Sweden's Metacon AB) to establish local manufacturing, including a planned electrolyser gigafactory in Sweden[128].

3. **Policy uncertainty in USA might create short-term opportunities for exporters such as China and India, subject to stringency of localisation laws:** Section 45V of the IRA introduced generous tax incentives for electrolyser and fuel cell manufacturers to re-establish America's leadership in high-tech equipment manufacturing and reduce reliance on Chinese imports. However, recent funding cuts and restrictions on clean energy projects particularly GH could put plans at risk[129].

> Policy uncertainty in the USA might create short-term opportunities for exporters such as China and India. However, the real impact may depend on several factors, including the stringency of local manufacturing mandates, trade barriers like tariffs, access to core technologies, and the pace of GH project development in destination markets. The viability of such export-oriented opportunities may likely vary on a case-by-case basis.

4. **Alkaline is the dominant technology at present, though this might be challenged by PEM in future; emerging technologies like SOEC, AEM expected to carve their own niche:** Alkaline electrolysers currently dominate installed capacity, but PEM technology is expected to lead future deployments, while SOEC and AEM gain traction in niche applications. Innovation is driven by factors such as reducing equipment and commodity costs, minimising precious metal use (e.g., PGMs), improving response to renewable variability, and enabling low-load operations. These efforts are fostering new technologies like MFE, CFE, and E-TAC, as well as improvements in existing AWE and PEM systems. Some notable advancements include:

   a. Thyssenkrupp Nucera's zero-gap alkaline electrolysis technology – Offers rapid response (30 seconds to ramp from 10 per cent to 100 per cent load) and a low turndown ratio of 10 per cent, outperforming conventional alkaline systems[130].

   b. Thyssenkrupp Nucera's large 20 MW stack size – Compared to the typical 5–6 MW stacks, reduces the number of modules required for large-scale projects[131].

   c. Electric Hydrogen's modular PEM systems – Skid-based, standardised plants configurable between 75–120 MW, enables faster delivery and cost optimisation[132].

   d. Toshiba's Alternating Catalyst Layer Structure (ACLS) technology – Aims to cut PGM usage in PEM electrodes from several mg/cm² to just 0.1 mg/cm² without major efficiency loss[133].

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127 Open letter to European Commission President Dr. Ursula von der Leyen by European electrolyser manufacturers, 01 July 2024 (Letter-to-President-Von-der-Leyen_Make-Made-in-Europe-a-reality.pdf). Accessed on 03 October 2025

128 Vätgas Sverige article, 28 December 2024 (Metacon has signed an agreement to build a "Gigafactory" for the manufacture of its own electrolysis plants - Vätgas Sverige). Accessed on 03 October 2025

129 Hydrogen Insight article, 27 January 2025 (Trump puts US clean hydrogen support schemes on hold as part of plan to terminate 'Green New Deal' | Hydrogen Insight). Accessed on 25 September 2025

130 Large scale Modular AWE Technology for Green Hydrogen plants, Thyssenkrupp, 2021 (PowerPoint Presentation). Accessed on 15 April 2025

131 Large scale Modular AWE Technology for Green Hydrogen plants, Thyssenkrupp, 2021 (PowerPoint Presentation). Accessed on 15 April 2025

132 Electric Hydrogen website (Electric Hydrogen's HYPRPlant). Accessed on 03 October 2025

133 Technology for Reduction of Precious Metals Used in Anode Catalyst of PEM Electrolyzers, Yoshinaga Norohiro, Nakano Yoshihiko, Mei Wu, Toshiba Review Vol. 73, No. 3, Toshiba Corporation, May 2018 (Link). Accessed on 03 October 2025

e. Advanced Ionics' low-temperature SOEC – Operates at around 100°C, significantly lower than the 500–800°C range of conventional SOECs, reducing thermal stress and energy requirements[134].

Global energy majors and climate-tech investors are increasingly backing next-generation electrolyser startups to overcome cost, efficiency and scalability barriers in hydrogen production. Prominent climate technology investment arms of existing energy companies like Shell Ventures, Toyota Ventures, Aramco Ventures, organisations like Mitsubishi Heavy Industries and venture capital firms like Breakthrough Energy Ventures are investing in advanced electrolyser startups. Some of those startups are Verdagy, Supercritical Solutions, Advanced Ionics, H2PRO, Electric Hydrogen and others. These moves signal a clear trend: investors are prioritising technology differentiation, focusing on efficiency gains, material innovation and modularity, rather than conventional scale-up. This positions these startups as critical enablers for cost-competitive GH.

A prospective investor, project developer or policymaker may consider focusing on technology optionality and innovation-driven strategies rather than relying solely on conventional scale-up. Some recommended strategies can be:

1. Capital allocation could prioritise electrolysers that demonstrate efficiency improvements, modularity, reduced reliance on scarce materials and enhanced flexibility for renewable integration.
2. Developers may think of structuring projects to accommodate evolving technologies, avoiding lock-in to legacy systems.
3. Policymakers may explore incentive frameworks that reward performance metrics and innovation outcomes, rather than only installed capacity, to encourage cost reductions and long-term resilience in the hydrogen value chain.

Effective storage is essential to unlocking the hydrogen value chain; hydrogen storage equipment manufacturing gaining pace in EU, USA and China

GH storage is vital to the hydrogen value chain. Owing to its low volumetric energy density, hydrogen must be compressed to high pressures or liquefied at cryogenic temperatures for practical storage, both demanding advanced technology and materials.

Key storage methods includes compressed gas, liquid hydrogen, and material-based solutions which are essential for balancing supply and demand, ensuring safety, and improving efficiency.

Among several GH storage technologies (explained in Annexure – 3 in this report), small and mid-sized hydrogen storage cylinders, primarily suited for mobility and limited-scale energy applications are amenable to mass manufacturing, with several facilities currently operational worldwide. These units typically store only a few kilograms of hydrogen and are not considered viable for large-scale industrial use. In contrast, large-scale storage systems, capable of handling several tonnes of hydrogen, are generally constructed on-site for specific projects.

Existing global manufacturing capacity for Type I, II, III, and IV cylinders, largely serving mobility applications, is estimated to be in the range of 170,000–180,000 units annually. However, detailed data on the distribution by cylinder type and volume remains unclear[135]. France is understood to lead current production capacity, with approximately 90,000–100,000 units per year, followed by Germany and the United States. As the hydrogen economy evolves, additional capacity in the range of 250,000–300,000 units per year may be established by 2030, potentially increasing total global output to around 340,000–400,000 units annually[136]. The United States, Germany, France, and China are expected to play prominent roles in this expansion. Major industry players including Hexagon Purus, NPROXX, Forvia, and Plastic Omnium are reported to have existing facilities and are planning significant capacity additions.

134 Advanced Ionics website (Technology | Advanced Ionics). Accessed on 03 October 2025
135 Analysis for this report, 2025
136 Analysis for this report, 2025

Storage tank manufacturing announcements and existing capacities, based on technology and country are shown in Figures 18 and 19 [137].

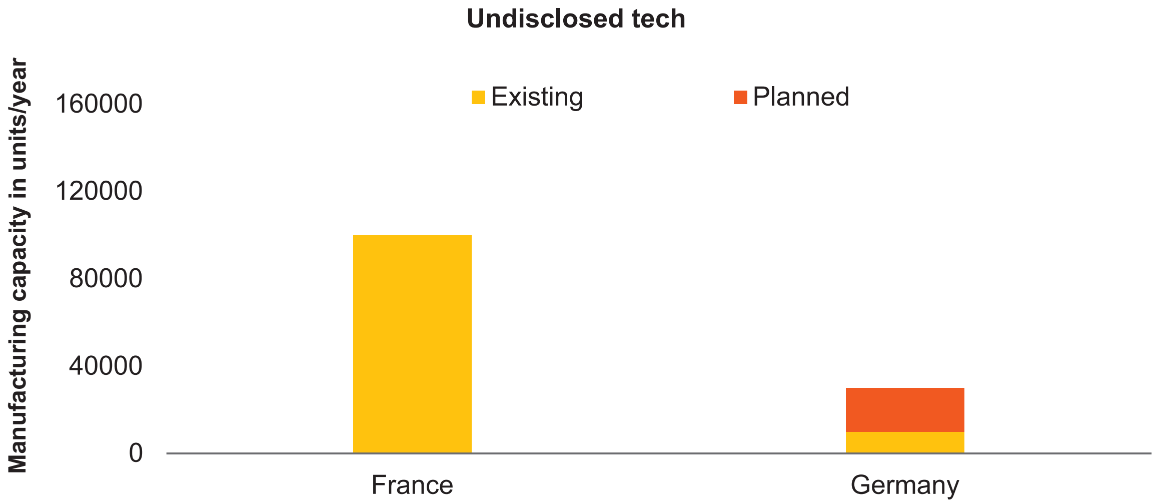


Figure 18: Existing and planned capacities of storage tanks in France and Germany

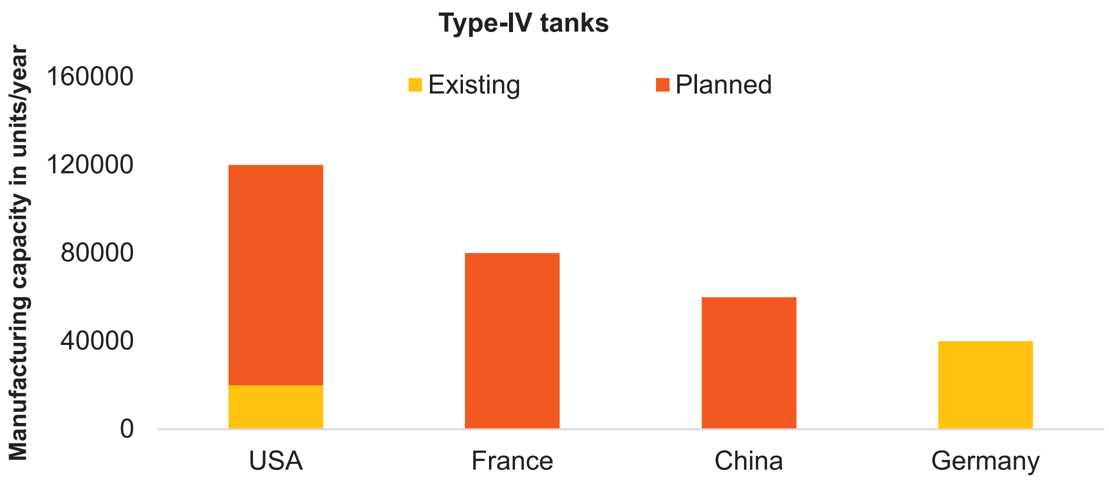


Figure 19: Existing and planned capacities of Type-IV storage tanks in key countries

By enabling seasonal energy storage at massive scale, geological hydrogen storage acts as a backbone for resilient, renewable-dominated energy systems

Geological hydrogen storage refers to the storage of hydrogen in underground geological formations such as salt caverns, depleted gas fields, or porous rock reservoirs. These geological structures provide large, secure, and long-duration storage options that complement hydrogen's role as a clean energy vector. Unlike above-ground artificial tanks, geological formations can accommodate vast volumes of hydrogen at relatively low cost per unit of energy, making them particularly suitable for seasonal or multi-week balancing of energy systems.

137 Analysis for this report, 2025

The key advantage of geological hydrogen storage lies in its ability to provide deep flexibility to power systems dominated by variable RE (VRE) sources like wind and solar. While batteries excel at short-duration balancing (minutes to hours), they become prohibitively expensive for storing energy over weeks or months. Pumped storage entails high gestation and geographical constraints. Nuclear power offers baseload generation but concerns might arise regarding the safe disposal of nuclear wastes. Other baseload RE resources like geothermal and hydro might have a limited reach due to geographical constraints. Hydrogen stored underground can be converted back to electricity via turbines or fuel cells, or used directly in industry and transport, creating a multi-sector hedge against intermittency. This capability positions geological hydrogen storage as a strategic enabler of net-zero systems, reducing reliance on fossil backup and enhancing energy security.

In essence, large-scale underground hydrogen storage could be a game changer because it combines massive capacity, long-duration storage, and cross-sector integration. It allows RE to be captured during periods of surplus and deployed when demand peaks or generation dips, effectively decoupling production from consumption over long timescales. By doing so, it offers the maximum possible hedge against renewable variability, something neither batteries nor nuclear can fully achieve on their own while supporting a resilient, low-carbon energy system.

As per ISA's report on "Development of an implementation roadmap and identification of project pipelines for scaling solar-integrated Long Duration Energy Storage (LDES) technologies in developing nations" released in ACEF 2025 in Manila, Philippines, it is estimated that hydrogen energy storage solutions have a TRL level from 4 (for example, Metal Oxide Frameworks based cryo-adsorbers and reversible borohydrides) to 9 (for example, salt caverns)[138,139]. Scalability of upto GWh-level storage can be offered by geological GH storage solutions. Details on geological hydrogen storage solutions has been provided in Annexure – 3 of this report.

GH-based energy storage solutions are increasingly being explored for large-scale use, potentially reaching GWh- or even TWh-level capacities, and may offer a viable alternative to conventional battery technologies. For context, even one of the most advanced lithium-ion prototypes, with an energy density of about 0.4 kWh/kg, would require roughly 750 KT of batteries to store 300 GWh of energy, as planned in the under-construction Advanced Clean Energy Storage (ACES) project in Utah, USA[140,141]. By contrast, only about 9 KT of hydrogen may be needed to store the same energy, an almost 83-fold reduction in material mass[142].

This illustrates the efficiency and scalability advantages of hydrogen-based storage, particularly where weight and volume matter. It is also notable that one of the world's largest operational battery storage systems offers only 3.3 GWh of capacity, which is nearly 100 times less than the hydrogen storage project in Utah, USA[143].

As per global announcements, nearly 70 – 80 TWh of geological hydrogen storage projects are under various stages of implementation[144]. This would correspond to a mass of nearly 2 – 2.5 MMT of hydrogen stored, or the production output of nearly 10-16 GW of electrolysers[145,146].

138 A review of hydrogen storage and transport technologies, Miao Yang , Ralf Hunger , Stefano Berrettoni , Bernd Sprecher , Baodong Wang, Clean Energy, Volume 7, Issue 1, February 2023 (Link). Accessed on 19 January 2026

139 Advances in Type IV Tanks for Safe Hydrogen Storage: Materials, Technologies and Challenges, Francesco Piraino, Leonardo Pagnotta, Orlando Corigliano, Matteo Genovese, and Petronilla Fragiacomo, Hydrogen 2025, 03 October 2025 (Link). Accessed on 19 January 2026

140 ACES Delta project website (Sites | ACES Delta). Accessed on 29 September 2025

141 Innovation Origins Plus article, 18 January 2025 (Chinese researchers achieved a lithium battery with an unprecedented energy density in 2023. This is where the promising technology stands now). Accessed on 29 September 2025

142 Considering the calorific value of pure hydrogen to be 33.3 kWh/kg in LHV terms

143 Energy Storage News article, 24 January 2024 (California project with world's biggest battery at 3,287MWh online). Accessed on 29 September 2025

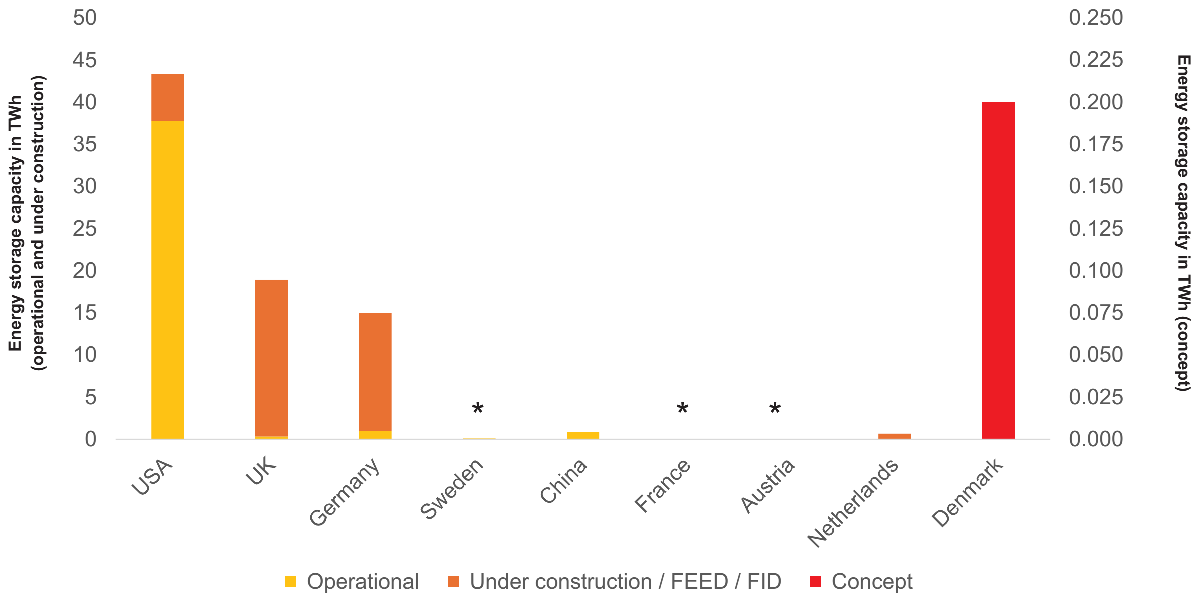
144 Analysis for this report, 2025

145 Analysis for this report, 2025 basis IEA's Hydrogen Production Projects Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 30 September 2025

146 Considering the calorific value of pure hydrogen to be 33.3 kWh/kg in LHV terms

The maturity of geological hydrogen systems is evidenced by the fact that the current operational capacity of this system is about 35–40 TWh[147]. A vast majority of this system is present in the US Gulf coast region, where a geological abundance of salt caverns provides a natural advantage for storing vast quantities of hydrogen. Air Liquide's Beaumont underground hydrogen storage system in US Gulf Coast, which is among the largest of its kind, boasts of a massive 1.5 km-deep and 70 m-diameter underground salt cavern providing storage for roughly 4.5 billion cubic feet (BCF) of hydrogen[148]. Some pilot or demonstration scale projects are also operational in European countries like UK, Sweden, Germany, France and Austria.

While the United States leads in operational and pilot projects, Europe dominates in projects under construction, including those at FEED and FID stages totalling around 30–35 TWh[149]. Several have been granted IPCEI status, ensuring partial funding from the European Commission due to their strategic role in scaling GH ecosystems. Several other countries, including China, Oman and Saudi Arabia are assessing geological formations such as salt caverns, saline aquifers, and depleted oil and gas fields to enable large-scale hydrogen storage. The summary of announced geological hydrogen storage systems at various stages of implementation in key countries is shown in Figure 20 [150].



*(Note *: Sweden, France and Austria have under construction / demonstration scale hydrogen storage projects of estimated capacity: 100 GWh, 2.46 GWh and 4.2 GWh respectively)*

Figure 20: Geological hydrogen storage announcements and existing capacities, based on country

147 Analysis for this report, 2025
148 Air Liquide article (H2 Storage & Power | Air Liquide USA). Accessed on 30 September 2025
149 Analysis for this report, 2025
150 Analysis for this report, 2025

Large-scale hydrogen storage facilities such as geological formations in rock and salt caverns, depleted oil and gas fields, and saline aquifers can significantly complement existing and planned hydrogen pipeline networks. Along the US Gulf Coast, salt cavern storage is linked to a 1,000-mile (approximately 1,600 km) hydrogen pipeline system connecting producers, consumers and storage sites[151]. This infrastructure could readily accommodate GH as a drop-in gas when GH projects scale up. In Europe, major projects are planned to connect to national hydrogen grids or to trans-continental pipelines such as EHB, providing a faster and more economical route between importing terminals, producers, consumers and geological storage units.

Quite notably, the US Gulf Coast is also a site of a major clean hydrogen hub, approved by US DOE for receiving a funding of nearly USD1 billion. The said clean hydrogen hub has been explained in detail in ISA's report "Framework for the Development of Green Hydrogen Hubs" released in ACEF 2025 in Manila, Philippines[152].

Key strategic takeaways and recommendations

1 **Geological hydrogen storage systems like salt and rock caverns are proven and mature solutions offering GWh or TWh scale energy storage with minimal contamination or leakage:** The usage of geological hydrogen storage solutions since decades, especially in USA, and some recent tests in EU confirm that geological hydrogen storage solutions like salt caverns offer the most secure and technically mature option for hydrogen storage, with minimal risk of leakage or contamination. The ecosystem for the design, engineering and utilisation of such caverns is readily available, thereby boosting the industrial acceptability and bankability of such solutions.

2 **The US leads salt cavern storage systems with proven expertise and complementary hydrogen pipelines, but policy changes might jeopardise further expansions:** The United States is embedding underground hydrogen storage within its Regional Clean Hydrogen Hubs programme, which funds production, storage, and end-use integration. Projects such as ACES Delta remain on track despite policy uncertainty, while the Gulf Coast continues to benefit from existing salt cavern infrastructure and pipeline networks. However, recent cancellations of certain hydrogen hub awards highlight the importance of stable policy frameworks for sustaining momentum[153].

3 **The EU and the UK are leveraging geological storage solutions with pragmatic policy support and complementary infrastructure buildouts:** Europe is emerging as the most proactive region in enabling underground hydrogen storage through targeted policy instruments and coordinated infrastructure planning. The EHB initiative is aligning storage nodes with pipeline corridors, while IPCEI funding and national strategies are accelerating FEED and FID decisions. The United Kingdom has introduced a Hydrogen Storage Business Model to de-risk early projects. Europe's integrated approach ensures that storage is not an afterthought but a central pillar of hydrogen system design, reducing merchant risk and enabling faster project execution.

4 **Middle East countries like Saudi Arabia and Oman are positioning themselves for integrated hydrogen systems that include storage:** Taking cues from the pragmatic approach of EU, leading hydrogen exporting countries like Saudi Arabia and Oman are focusing on large-scale GH production for export, while simultaneously assessing geological formations for future underground storage. The NEOM project in Saudi Arabia is advancing towards commissioning, and research institutions are studying salt caverns and porous formations for long-term storage potential. Oman has identified priority salt domes and is developing conceptual designs as part of its national green hydrogen strategy.

151 Reuters article, 23 May 2024 (US Gulf Coast a natural fit for clean hydrogen industry | Reuters). Accessed on 30 September 2025

152 Framework for the development of GH hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 30 September 2025

153 Hydrogen Insight article, 27 January 2025 (Trump puts US clean hydrogen support schemes on hold as part of plan to terminate 'Green New Deal' | Hydrogen Insight). Accessed on 25 September 2025

Geological hydrogen storage offers energy storage capacity which might range in TWh-level, thus providing seasonal energy storage needs to complement VREs. It is recommended that investors and project developers align themselves with the geographies developing or having geological hydrogen storage systems and providing pipeline connections to such storage facilities, to help reduce hydrogen storage and transportation costs.

Robust transport and hub infrastructure is key to scaling global hydrogen trade, integrating production, storage, and distribution across region

A. Transportation

Transporting hydrogen efficiently from production sites to points of consumption is a crucial link in the GH value chain. Depending on the scale, distance, and end-use, hydrogen can be transported via hydrogen pipelines, high pressure tanks, cryogenic tanks, insulated tanks in different forms such as gaseous, liquid, LOHC and ammonia. Some of these technologies have been discussed in detail in the above sections in terms of storage. The means of transportation varies for each of these storage technologies basis of their application and distance.

- Compressed hydrogen gas is typically transported in high-pressure cylinders in trucks or tube trailers for short distances, especially to refuelling stations or small industrial users.
- Liquid hydrogen is cooled to cryogenic temperatures and transported in insulated cryogenic tanks, preferable for long-distance and large-scale transport due to its higher volumetric energy density.
- Hydrogen carriers such as ammonia (NH_3) or LOHCs offer a promising option for storing and transporting hydrogen over large distances, as they leverage existing infrastructure and are easier to handle.

Port and hydrogen hubs infrastructure: Ports and hydrogen hubs are emerging as critical enablers for global GH trade, integrating production, storage, and distribution infrastructure to support both domestic consumption and international exports. A key trend is the clustering of hydrogen hubs around major ports to facilitate global trade, with Europe focusing on imports and the U.S. prioritising domestic hubs under its USD7 billion H2HUBS programme. Some port-led hubs in the Middle East and Latin American countries are positioning as major exporters, with Oman's SalalaH2 and Saudi Arabia's NEOM leading the charge. These hubs leverage shared infrastructure, economies of scale, and strategic port access to reduce costs and accelerate adoption. Advantages of these hubs include cost optimisation through shared infrastructure, enhanced energy security, and the creation of green maritime corridors for decarbonised shipping. By 2030, global hydrogen trade primarily in the form of ammonia is expected to grow significantly, with Europe projected to account for 75 per cent of announced import volumes and Japan and South Korea together targeting 3.7 MMTPA by 2040. Also, as per ISA's report "Framework for the development of GH hubs" released in ACEF 2025 in Manila, Philippines, it is estimated that there are about 98 hydrogen hubs in various stages of development across the globe, spread out over 36 countries and entailing an investment of nearly USD185 billion[154]. These developments underscore the role of ports as gateways for scaling hydrogen ecosystems and enabling cross-border decarbonisation.

B. Distribution

Once transported near the point of use, hydrogen needs to be distributed to various end-users including industries, mobility sectors, and residential energy systems. Various infrastructures are used for distribution of hydrogen, which includes:

Pipeline: GH produced at production sites or hubs, transports and distributes GH through a network of pipelines to the demand centres. These pipelines may be either dedicated hydrogen pipelines or repurposed natural gas pipelines with 100 per cent hydrogen or natural gas blended hydrogen. Figure 21 provides a comparison of announced pipeline infrastructure across key countries[155].

154 Framework for the development of GH hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 30 September 2025

155 Analysis for this report, 2025 basis IEA's Hydrogen Infrastructure Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 19 September 2025

- An analysis of the IEA infrastructure database indicates the announcement of a total of 38,265 km of new pipelines and 14,492 km of repurposed pipelines projected by 2050[156].
- Of this, 38 per cent of the pipelines are in conceptual stage, while 37 per cent are undergoing feasibility studies and 17 per cent are currently in the Front-End Engineering Design (FEED) stage[157].

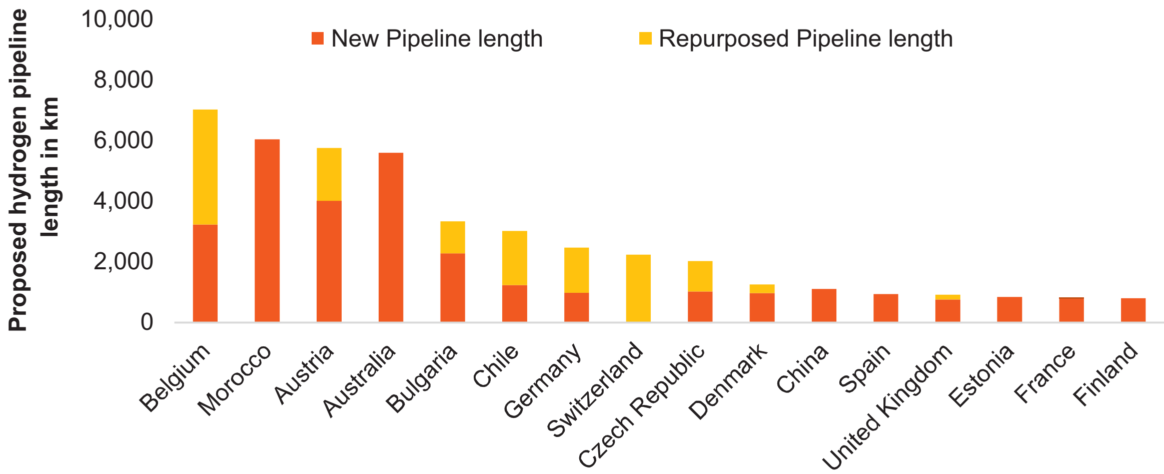


Figure 21: Country-wise announced hydrogen pipeline projects

European Hydrogen Backbone (EHB)

- The EHB is a visionary initiative aimed at creating a dedicated pan-European hydrogen transport infrastructure[158].
- It is a collaborative project of more than 30 European gas transmission system operators (TSOs). It proposes a network of over 58,000 km of hydrogen pipelines across Europe by 2040 in two phases.
- The plan involves repurposing approximately 60–70 per cent of existing natural gas pipelines and building new hydrogen-dedicated infrastructure to connect key hydrogen supply and demand regions, including industrial hubs, RE zones (like offshore wind farms), and hydrogen import terminals.
- The first phase is expected to be commissioned by 2030, connecting countries such as Germany, the Netherlands, Spain, France, and Eastern Europe. The network is envisaged to be expanded further into Southern and Northern Europe, integrating hydrogen valleys, storage facilities, and cross-border corridors.
- This network is critical to achieving the EU's decarbonisation targets, facilitating the transport of GH from renewable-rich regions such as Spain, North Sea to major consumption centres in Central and Eastern Europe.

156 Analysis for this report, 2025 basis IEA's Hydrogen Infrastructure Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 19 September 2025

157 Analysis for this report, 2025 basis IEA's Hydrogen Infrastructure Database, September 2025 (Hydrogen Production and Infrastructure Projects Database - Data product - IEA). Accessed on 19 September 2025

158 European Hydrogen Backbone, European Union, April 2022 (ehb-report-220428-17h00-interactive-1.pdf). Accessed on 15 April 2025

Key strategic takeaways and recommendations

1 **Dedicated large-scale cross country hydrogen pipeline projects are coming up in EU:** The EU, through its EHB initiative, is spearheading the development of 58,000 km of new and repurposed hydrogen pipelines for import and distribution[159]. According to the EHB report "European Hydrogen Backbone: Boosting EU Resilience and Competitiveness", underground hydrogen pipelines can transport up to four times more energy than large overhead power lines and deliver energy at two to four times lower cost[160]. Progress is also being made on "feeder corridors" designed to supply GH to the EU from neighbouring regions like North Africa, Scandinavia, the British Isles etc. via cross-border pipelines.

> Investors in hydrogen projects should consider locating production or end-use facilities near EHB nodes, particularly along corridors that are operational or in FEED/FID stages. This approach can significantly shorten project gestation periods and ensure early access to commodity and equipment offtakers, enhancing commercial viability and accelerating market integration.

2 **Initial demand might be centred around ammonia importing ports or terminals in EU or other geographies depending on ammonia imports:** Despite the EU's ambitious EHB targets and rapid progress, full backbone completion is still at least 15 years away from 2025, assuming no delays. Major green ammonia importers such as Japan and South Korea also lack clarity on large-scale hydrogen pipeline plans. In the meantime, hydrogen use in Europe is likely to concentrate around key ammonia-importing ports such as Rotterdam, Amsterdam, Wilhelmshaven and Hamburg, where industrial and mobility sectors are expected to transition first. Exporters relying on maritime routes may therefore focus on large-scale green ammonia projects. Ports and projects with cost advantages and shared infrastructure, including Oman's SalalaH2 hydrogen hub, are well positioned to benefit. ISA's report provides further detail on these hubs and their shared infrastructure[161].

> Investors may prioritise port-led hydrogen hubs, both import and export oriented, to secure first-mover advantages. The focus should be on locations with strong commodity cost competitiveness and solid government support, including clear consumption or production mandates. Shared infrastructure is also essential, such as power evacuation systems, hydrogen and ammonia transport and storage, dedicated ammonia jetties, and large nearby demand centres. These factors help reduce project risk, speed up delivery, and strengthen long-term commercial viability.

159 European Hydrogen Backbone: Boosting EU Resilience and Competitiveness, EHB, 20 November 2024 (1732103116_EHB-Boosting-EU-Resilience-and-Competitiveness-20-11-VF.pdf). Accessed on 01 October 2025

160 European Hydrogen Backbone: Boosting EU Resilience and Competitiveness, EHB, 20 November 2024 (1732103116_EHB-Boosting-EU-Resilience-and-Competitiveness-20-11-VF.pdf). Accessed on 01 October 2025

161 Framework for the development of green hydrogen hubs, ISA, ACEF 2025, Manila, June 2025 (1749638385ISA_ADB_GH_ACEF_2025_06_June_GH_Hub.pdf). Accessed on 30 September 2025

Global fuel cell manufacturing is scaling rapidly to gigawatt-level manufacturing, driven by focus on power generation and mobility applications, strong policy support, and international technology collaborations

The global hydrogen fuel cell manufacturing industry has witnessed remarkable growth and diversification between 2020 and 2025. Major automotive and industrial companies across Asia, Europe and North America have rapidly expanded their production capabilities, commissioning new facilities, pilot plants and large-scale gigafactories. Firms such as Ballard, Toyota, Doosan and Hyundai have established multiple sites in Japan, South Korea, China, USA, Canada and Europe, with annual production capacities ranging from ten thousand to over one hundred thousand fuel cell units per plant, underpinning both the transport and industrial markets. These expansions reflect both escalating hydrogen demand and the emergence of FCEVs as viable alternatives to traditional internal combustion engine vehicles.

In addition, the past five years have seen considerable developments in China. Leading manufacturers including BYD, SAIC, Yutong and Foton have launched fuel cell units or FCEV manufacturing facilities. These firms serve both the domestic bus and truck markets, as well as supporting demonstration projects in logistics and public transport. Chinese manufacturers now represent a substantial share of the global FCEV market, producing hundreds to thousands of fuel cell buses and heavy-duty trucks annually, with technology advances driven by both state policy and rapid scale-up.

Elsewhere, established and emerging firms such as Cellcentric (a Daimler and Volvo joint venture), BMW, Hino, Komatsu and others have announced fuel cell manufacturing plants, with some like Hino planning to launch mass manufacturing by October 2025. In India, Tata Motors, Ashok Leyland, Adani Group and Reliance Industries have also grown their hydrogen and fuel cell footprints or have indicated their ambition regarding the deployment of fuel cells. Their activities demonstrate a compelling commitment to both zero-emission transport and GH production, with planned and operational projects in Germany, India, Japan and North America. Technology diversification is evident, with companies investing in PEM fuel cells and solid oxide fuel cells (SOFC) for power generation, mobility and industrial uses. This dynamic landscape illustrates a transition from pilot and demonstration projects towards commercial manufacturing and deployment. Cumulative investments, strong governmental policies, and technological advancements have positioned fuel cell manufacturing as a foundational element in the transition to sustainable transport and industry worldwide. As more facilities come online and market uptake increases, the sector is set to play a keystone role in decarbonisation efforts and in the realisation of a global hydrogen economy.

At present, the estimated global fuel cell manufacturing capacity stands at approximately 10-12 GW/yr, predominantly driven by PEM fuel cells[162]. These capacities are primarily aligned with the automotive sector, serving passenger vehicles and heavy-duty mobility applications, though a portion of the output can be repurposed for rail, maritime, and stationary power generation applications. China continues to dominate the global supply base, accounting for over 5 GW/yr of installed capacity, while other advanced markets including the United States, Canada, South Korea, France and Japan, collectively contribute a further 5–6 GW/yr, with Hyundai Mobis' Chungju plant in South Korea manufacturing nearly 23,000 fuel cell units per year[163,164]. A fuel cell mega factory was also recently inaugurated by Helion (a subsidiary of Alstom) in Aix-en-Provence, France, but the exact manufacturing capacity is unknown[165]. It is important to note that beyond these headline figures, there remains limited visibility on the true aggregate capacity of already commissioned plants, particularly those operated by leading Original Equipment Manufacturers (OEMs) such as Toyota, Cellcentric, HDF Energy and Fuel Cell System Manufacturing LLC (FCSM)[166].

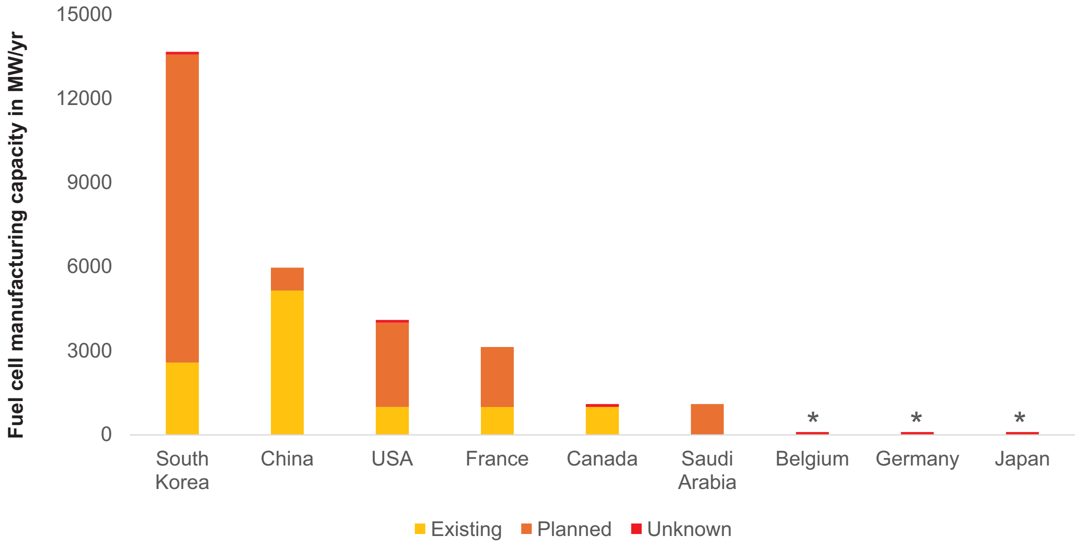
Planned manufacturing plants and facility expansions are expected to add 15–20 GW per year of capacity globally by 2030[(167)]. Among the most significant is Hyundai Mobis's fuel cell plant in Incheon, South Korea, designed to produce 100,000 units annually making it the world's largest fuel cell manufacturing facility[168]. With each unit rated at 110 kW, the plant could deliver approximately 11 GW of fuel cells per year once operational[169]. Another significant capacity addition might be from Ballard, a Canada based fuel cell manufacturing company, with its planned 3 GW/yr manufacturing capacity in Rockwall, Texas (USA)[170]. HDF Energy also announced plans to establish a 1 GW/yr fuel cell gigafactory in Bordeaux, France, to cater to domestic and export markets[171].

As part of its IKTVA programme to boost domestic manufacturing and accelerate the deployment of clean technologies such as GH, Saudi Arabia has announced plans for an FCEV manufacturing facility

162 Analysis for this report, 2025
163 Analysis for this report, 2025
164 Helion press release, 13 June 2025 (Helion Hydrogen Power | Inauguration of our new fuel cell megafactory in Aix-en-Provence). Accessed on 01 October 2025
165 Hyundai press release, 08 October 2021 (Hyundai Mobis invests $1.1 billion for 2 new hydrogen fuel cell system plants in Korea). Accessed on 01 October 2025
166 FCSM is a 50:50 JV between Honda and General Motors (GM) with its operational facility located in Michigan, USA
167 Analysis for this report, 2025
168 Hyundai press release, 08 October 2021 (Hyundai Mobis invests $1.1 billion for 2 new hydrogen fuel cell system plants in Korea). Accessed on 01 October 2025
169 Analysis for this report, 2025, basis Hyundai press release, 03 April 2025 (Hyundai Motor Unveils 'the all-new NEXO' FCEV with Bold New Design and Enhanced Technology). Accessed on 01 October 2025
170 Sustainable Bus article, 21 March 2024 (Ballard will build a new plant in Texas for manufacturing of 3 GWh of fuel cells per year). Accessed on 01 October 2025
171 HDF Energy press release, 12 December 2022 (Press release | HDF | Game-changing hydrogen power). Accessed on 01 October 2025

in partnership with RONN Inc. (USA). The plant aims to produce around 10,000 hydrogen-powered logistics trucks and 1,000 Phoenix sports cars, representing an investment of approximately USD4 billion[172].

The Figure 22 below summarises the existing and planned fuel cell manufacturing capacities worldwide[173]. The fields marked under "unknown" category in this figure denotes operational manufacturing capacity, which exists in South Korea, USA, Canada, Germany, France Japan and Belgium, but the manufacturing output is not clear.



(Note *: *Although significant fuel cell manufacturing capacity might exist at present in Belgium, Germany and Japan, the capacity is unknown at present)*

Figure 22: Existing and upcoming fuel cell manufacturing capacity based on country and operating status

Fuel cell manufacturing is currently dominated by PEM technology across both existing and planned facilities. SOFC production remains limited. Bloom Energy operates an SOFC plant in the United States with a capacity of around 1,000 MW per year[174,175]. In South Korea, Doosan, in partnership with Ceres, manufactures approximately 50 MW per year, and SK Ecoplant (in partnership with Bloom Energy, USA) has achieved cumulative SOFC installations of 560 MW[176,177]. The manufacturing capacity of SK Ecoplant is unclear at present. Planned SOFC capacities have not yet been publicly disclosed, though there has been research and trials on SOFCs performed by leading OEMs like Mitsubishi Heavy Industries and Denso among others. It is envisaged that many such organisations might develop dedicated SOFC manufacturing plants in future.

Analysis of the global fuel cell industry reveals that international collaboration has evolved from a strategic option into an operational imperative. This paradigm shift is primarily driven by the need to de-risk the prohibitive capital expenditure associated with establishing gigawatt-scale manufacturing and to accelerate go-to-market timelines for a still-nascent technology. By forming synergistic partnerships, organisations are effectively leveraging complementary core competencies.

172 Fuel Cell Works article, 07 May 2025 (RONN-Saudi Arabia JV Greenlit: Hydrogen Expansion). Accessed on 01 October 2025
173 Analysis for this report, 2025
174 Turbomachinery International article, 11 April 2024 (Bloom Energy Secures up to $75M in Federal Tax Credits for Fremont Plant). Accessed on 01 October 2025
175 It is assumed that half of the 2 GW/yr manufacturing capacity of Bloom Energy is expected to be used for SOFC manufacturing and the remaining half for SOEC manufacturing. The exact breakup, as per official sources, is unclear.
176 Doosan Fuel Cell press release, 09 September 2024 (Media Center - News). Accessed on 01 October 2025
177 SK Ecoplant website (Green Energy | Business | SK ecoplant). Accessed on 01 October 2025

Several distinct partnership archetypes have become ubiquitous across the sector, each tailored to specific strategic objectives. Some of these alliances are detailed in Table 14 below.

Table 14: Key global partnerships between companies for manufacturing fuel cells at scale

SN	Partner (Country)	Partner (Country)	Possible synergies
1	Toyota (Japan)	BMW (Germany)	1. Co-development of advanced 3rd Generation Fuel Cells for both Toyota's and BMW's FCEV models[178]. 2. Co-creation of hydrogen infrastructure, value chain and a possible hydrogen hub. 3. Toyota's proven expertise in PEM fuel cells electrolysers and hydrogen supply chain can be synergetic with BMW's expertise in premium vehicle integration, R&D and local automotive supply chain in Germany and EU. 4. Cost reduction through shared engineering, fuel efficiency improvements, standardisation of components and manufacturing expertise[179].

178 Toyota press release, 05 September 2024 (Toyota Motor Corporation and BMW Group Strengthen Collaboration Towards the Advancement of a Hydrogen Society | Corporate | Global Newsroom | Toyota Motor Corporation Official Global Website). Accessed on 01 October 2025

179 BMW Group press release, 02 September 2025 (Hydrogen high tech at the BMW Group: start of series production in 2028 is getting closer.). Accessed on 01 October 2025

SN	Partner (Country)	Partner (Country)	Possible synergies
2	Toyota (Japan) / Hino (a subsidiary of Toyota)	Isuzu (Japan)	1. Co-development of advanced Fuel Cells for J-Bus (a 50:50 JV between Isuzu and Hino focusing on bus manufacturing) with commercialisation starting in FY2027[180]. 2. Toyota's expertise in PEM fuel cells electrolysers and hydrogen supply chain can be synergetic with Isuzu's expertise in bus and commercial vehicle manufacturing. 3. Collaboration with the prefectural governments of Japan (designated by Japan's Ministry of Economy, Trade and Industry (METI) in May 2025 as priority regions for the deployment of fuel-cell commercial vehicles)[181,182].
3	Daimler (Germany)	Volvo (Sweden)	1. Established Cellcentric – a 50:50 JV between Daimler and Volvo focusing on fuel cell manufacturing for heavy haul trucking industry[183]. 2. Both Daimler and Volvo bring with themselves decades of experience in rugged and heavy duty trucks manufacturing. 3. Daimler has proven experience with fuel cell development and liquid hydrogen handling (developed in collaboration with Linde)[184]. 4. Both companies enjoy dominant positions in European heavy duty trucking industry and securing the fuel cell value chain can help boost competitive advantage for both the companies.

180 Toyota press release, 29 September 2025 (Isuzu and Toyota to Jointly Develop Next-Generation Fuel Cell Route Bus | Corporate | Global Newsroom | Toyota Motor Corporation Official Global Website). Accessed on 01 October 2025

181 METI press release, 19 May 2025 (First Selection of Priority Regions for Promoting the Deployment of Fuel-Cell Commercial Vehicles). Accessed on 01 October 2025

182 The METI-designated priority regions are: Tohuku, Kanto (Tokyo Metropolis and Kanagawa prefectures), Chubu, Kinki and Kyushu. Core local prefectural governments coordinating the progress of METI's initiatives (except Kanto region) are: Fukushima, Aichi, Hyogo and Fukuoka respectively

183 Volvo Group press release, 29 April 2024 (Volvo Group & Daimler Truck AG- Launches Cellcentric). Accessed on 01 October 2025

184 Daimler website (Partnerships | Daimler Truck). Accessed on 01 October 2025

SN	Partner (Country)	Partner (Country)	Possible synergies
4	Hyundai (South Korea)	Iveco Group (Italy)	1. Partnership established to foster innovation in light and heavy commercial vehicle segment, with the deployment of both battery EVs and FCEVs for different applications[185]. 2. Hyundai's expertise in PEM fuel cells electrolysers and hydrogen supply chain can be synergetic with Iveco Group's expertise in heavy duty vehicle integration, truck manufacturing and local automotive supply chain in Italy and EU. 3. Partnership with Iveco Group can help open the European heavy duty trucking industry for Hyundai.
5	Toyota (Japan)	1 JR East (Japan) 2 Hitachi (Japan)	1. JR East has partnered with compatriots Toyota and Hitachi to develop innovative solutions using fuel cells for railway applications[186]. 2. The project is named HYBARI (Hydrogen-Hybrid Advanced Rail vehicle for Innovation). 3. Toyota's proven expertise with fuel cells will be coupled with Hitachi's expertise with hybrid-electric drives and traction systems to create HYBARI railcars for JR East.
6	Honda (Japan)	General Motors (GM) (USA)	1. Honda and GM have established a 50:50 JV called FCSM LLC, with manufacturing facility located in Brownstown, Michigan (USA) built with an investment of USD85 million[187]. 2. FCSM's plant has been operational since 2024, but the plant output is unclear at present. 3. The JV is envisaged to draw from the expertise of both Honda and GM in the field of automobiles.

185 Iveco Group press release, 14 March 2024 (Hyundai Motor and Iveco Group expand their partnership to explore synergies for electric heavy-duty trucks in the European markets | Iveco Group). Accessed on 01 October 2025

186 Hitachi press release, 06 October 2020 (JR East, Hitachi and Toyota to Develop Hybrid (Fuel Cell) Railway Vehicles Powered by Hydrogen). Accessed on 01 October 2025

187 FCSM website (Fuel Cell System Manufacturing LLC). Accessed on 01 October 2025

SN	Partner (Country)	Partner (Country)	Possible synergies
7	1 Michelin (France) 2 Forvia (France)	Stellantis (Netherlands/ USA)	1. Forvia and Michelin formed a 50:50 JV Symbio in 2019. Stellantis joined in 2023, making Symbio an equal share JV between Forvia, Michelin and Stellantis[188]. 2. Symbio inaugurated its fuel cell gigafactory called SymphonHy in Saint-Fons, France in 2023, capable of manufacturing 16,000 cells per year[189]. 3. SymphonHy plant is planned to expand to a capacity of 50,000 cells / yr, equivalent to 3.125 GW/yr manufacturing capacity[190]. 4. However, Stellantis exited this JV in July 2025, raising concerns about the plant's order book and future expansions[191].

Key strategic takeaways and recommendations

1 **Fuel cell bus adoption is picking up at a global level:** Between 2023 and 2025, orders for fuel cell electric buses (FCEBs) have surged globally, marking a decisive shift from pilot projects to commercial deployment. EU's Joint Initiative for hydrogen Vehicles across Europe (JIVE) programmes 1 and 2 has expanded beyond demonstrations, with 156 FCEB orders across 16 cities achieved by the end of 2023[192]. Meanwhile the UK and continental markets have seen record procurement frameworks, including Wrightbus securing multi-year FCEB orders from various cities in the UK. In North America, New Flyer's large-scale orders and a 55 per cent year-on-year increase in FCEB deployments across the USA underscore the momentum of FCEBs[193,194]. Similarly, South Korea has doubled its hydrogen bus fleet within a year (from 650 to 1,000 FCEBs) with an ambition to increase this 20-fold to 20,000 FCEBs by 2030[195]. Consequently, the demand for hydrogen from the mobility sector soared 64 per cent to 9.5 KT in 2024, compared to 5.8 KT in 2023[196]. This rapid uptake is expected to create predictable hydrogen demand and anchoring service networks, which may accelerate cost reductions and operational learning curves.

188 Symbio website (Our history | Symbio). Accessed on 01 October 2025
189 Symbio press release, 05 December 2023 (Symbio inaugurates SymphonHy, Europe's largest integrated Gigafactory for hydrogen fuel cells | Symbio). Accessed on 01 October 2025
190 Analysis for this report, 2025, basis data from Symbio press release, 05 December 2023 (Symbio inaugurates SymphonHy, Europe's largest integrated Gigafactory for hydrogen fuel cells | Symbio). Accessed on 01 October 2025
191 Fuel Cell Works article, 16 July 2025 (Stellantis' Exit Threatens Symbio's Future, Michelin Sounds Alarm). Accessed on 01 October 2025
192 JIVE 2 publication, European Commission (PRD 2022 PANEL - H2 End uses - Transport). Accessed on 01 October 2025
193 Zeroing in on ZEBs, CALSTART, March 2025 (Zeroing in on Zero-Emission Buses: March 2025). Accessed on 01 October 2025
194 Ballard press release, 04 November 2024 (Ballard to supply 200 fuel cell engines for New Flyer). Accessed on 01 October 2025
195 Yonhap News Agency article, 27 December 2024 (Hydrogen demand from transportation sector up 64 pct in 2024 | Yonhap News Agency). Accessed on 01 October 2025
196 Yonhap News Agency article, 27 December 2024 (Hydrogen demand from transportation sector up 64 pct in 2024 | Yonhap News Agency). Accessed on 01 October 2025

Bus fleets' predictable duty cycles, backed by strong demand for FCEBs and aided by depot refuelling may create repeatable, bankable offtake for both GH projects and fuel cell stacks and automotive OEMs accelerating learning rates and anchoring regional service footprints ahead of heavy-truck scale-up.

2. **Manufacturing capacity is scaling rapidly with regionalisation strategies:** Global fuel cell manufacturing capacity, estimated at 7–10 GW per year, is being augmented by significant new investments. Hyundai Mobis is progressing towards 100,000-unit annual output across its South Korean plants, while Ballard is constructing a 3 GW/yr gigafactory in Texas, supported by approximately USD94 million of US federal incentives[197]. There are manufacturing facilities announcements in EU, Saudi Arabia, Japan and China. These developments reflect a deliberate "local-for-local" approach, driven by policy requirements for domestic content and the need to de-risk supply chains. The surge in bus demand is providing an immediate utilisation base for these facilities, improving economies of scale.

1 Investors might expect regional content compliance requirements, especially for USA, EU, South Korea, Japan, Middle East etc, along with unit-cost reduction due to mass manufacturing, with some relaxation offered due to public funding support for FCEB bus tenders.
2 Manufacturers may consider aligning their strategies with geographies showing concrete plans and financial incentives for producing, importing (as applicable) and consuming GH, especially for mobility applications. Japan, South Korea, EU, China, Saudi Arabia and the hydrogen hubs in USA are emerging as strong candidates to attract such large-scale manufacturing projects.

3. **Policy frameworks are increasingly favouring hydrogen mobility, particularly buses, but the key is to identify the right geographies for projects:** Governments are coupling capital grants with operational subsidies to close the total cost of ownership gap for hydrogen vehicles. The European Hydrogen Bank has allocated nearly EUR1 billion (approximately USD1.17 billion) to GH projects across EU (for producing a total of 2.2 MMT GH over 10 years), while Japan has introduced a JPY700/kg (approximately USD4.76/kg) hydrogen price support mechanism for commercial vehicles in METI-designated priority regions across the country[198,199]. South Korea has launched a clean hydrogen power bidding market and linked bus subsidies to performance metrics, with announced hydrogen fuel subsidies of KRW5000/kg (approximately USD3.55/kg) and subsidy on buses ranging from KRW210-260 million (approximately USD149.3-184.8 million)[200,201]. The United States continues to advance its H2Hub programme despite regulatory uncertainty. These measures are accelerating adoption in segments where hydrogen offers clear operational advantages, such as long-range and high-utilisation routes.

197 Ballard press release, 01 April 2024 (Ballard announces $54 million of additional funding support, bringing total U.S. federal funding to $94 million for Ballard's fuel cell Gigafactory in Texas - Ballard). Accessed on 01 October 2025
198 Reccessary article, 19 May 2025 (Japan backs hydrogen-powered commercial vehicles with major subsidies | NEWS | Reccessary). Accessed on 01 October 2025
199 European Commission press release, 20 May 2025 (Nearly €1 billion awarded to boost development of renewable hydrogen). Accessed on 01 October 2025
200 Hydrogen Insight article, 24 February 2025 (South Korea slashes fuel costs for hydrogen buses by 22% with huge subsidy increase | Hydrogen Insight). Accessed on 01 October 2025
201 Business Korea article, 02 January 2025 (Only Hydrogen Buses Passing Performance Tests to Receive Subsidies Starting This Year - Businesskorea). Accessed on 01 October 2025

1 Countries that pair CAPEX grants with per-kg price support on fuel might see the fastest FCEB uptake, greater savings on fleets and attract more project or manufacturing related investments.
2 Policymakers or investors might consider prioritising transit corridors (for example, EU cities implementing JIVE programme, priority prefectures in Japan, approved hydrogen hubs in USA etc.) for bundled FCEV offtake, hydrogen offtake and prefer destinations with shared infrastructure, to aid in rapid offtake of fuel cells.

4. **Stationary fuel cells and electrolysis are reinforcing the hydrogen ecosystem; SOFCs might pick up in near future for non-nuclear baseload clean power generation**: In some regions prioritising hydrogen for stationary power generation, fuel cell manufacturing capacity is expanding, as these applications provide more stable demand for the equipment. Bloom Energy has scaled its SOFC capacity to approximately 1 GW per year, while South Korea's clean hydrogen power market ambitious 6,500 GWh/yr hydrogen based power generation tender is creating long-term offtake for hydrogen in the power sector[202]. These developments complement mobility by improving hydrogen production economics and enabling co-location strategies, such as depot-based electrolysis. This integrated approach reduces delivered hydrogen costs and enhances the financial viability of hydrogen infrastructure.

1. It is recommended that holistic and end-to-end incentive support be provided, not only for fuel cell manufacturing OEMs but also downstream fuel cell users like power generation plants or transportation fleet operators.
2. The combination of FCEB deployments and depot refuelling (to cater to FCEB applications) with baseload hydrogen based power projects may help improve utilisation of shared infrastructure and create avenues for further cost reductions. Identifying the right geographies is the key, which support both such initiatives. However, for baseload power generation, erasure of demand to some extent may be expected if nuclear small modular reactor technologies mature and become mass manufacturable.

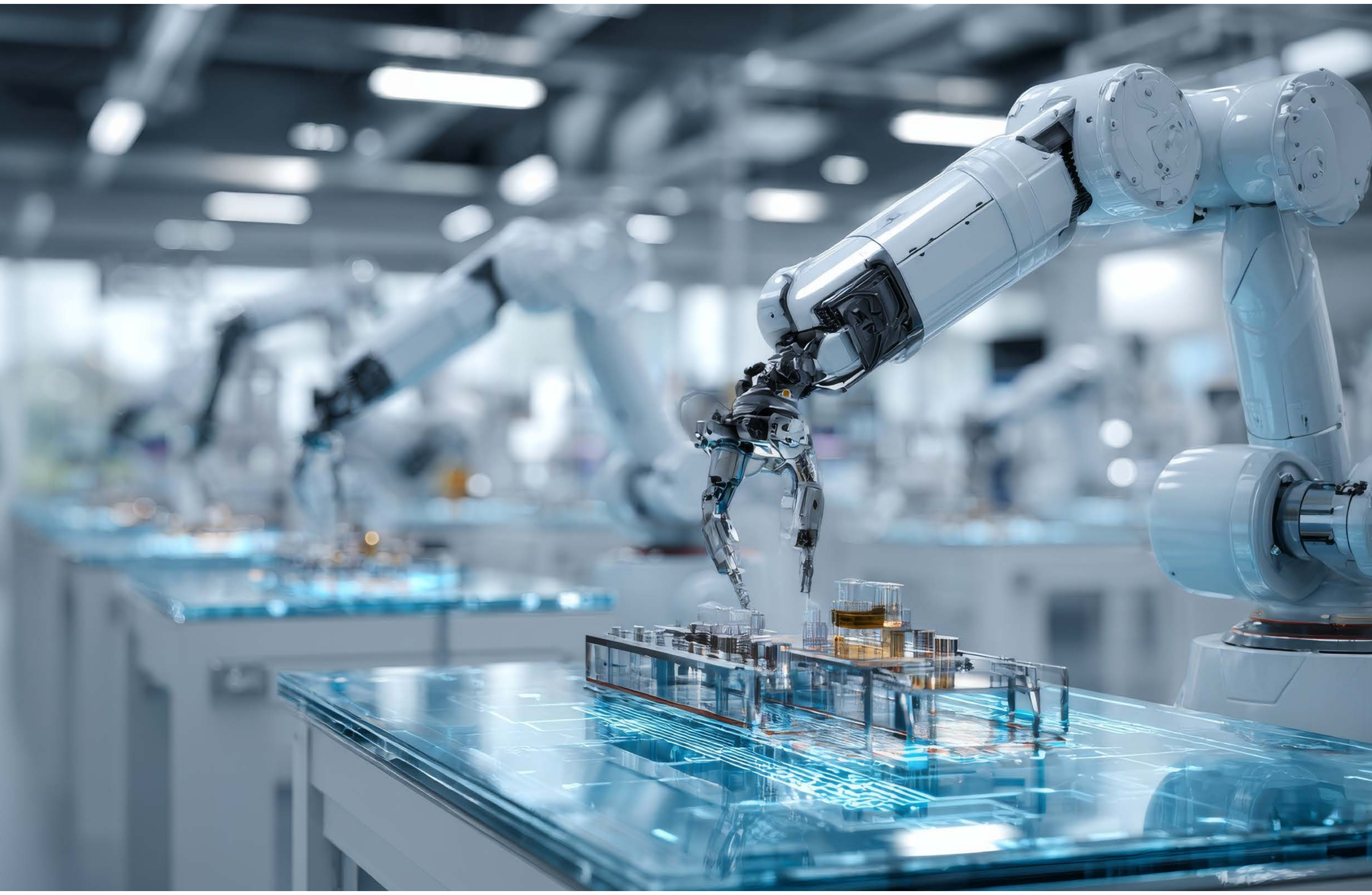
5. Project developers and policymakers might consider deploying stationary fuel cells for clean and reliable power generation needs, especially for land-constrained geographies like Small Island Developing States (SIDS), arboraceous and alpine geographies. Utility scale solar and wind projects might not be viable due to the lack of land and building large scale power transmission networks might also not be possible due to geographic spread between communities and power generation plants. As per ISA's studies on "Green Hydrogen Readiness Assessment" conducted for Fiji and Papua New Guinea, it was observed that these countries relied significantly on diesel based off-grid power generation systems to serve a part of their populations located in remote archipelagic or arboraceous locations[203,204]. GH based decentralised power generation solutions like fuel cells can be viable options to decarbonise a part of the SIDS countries' power generation operations, reduce reliance on imported fossil fuels and partly help in positioning some of these countries as "sustainable tourist destinations".

202 Hydrogen Insight article, 24 May 2024 (South Korea launches world's first auction for clean-hydrogen power generation | Hydrogen Insight). Accessed on 01 October 2025
203 Consultation document, - Green Hydrogen Readiness Assessment for Fiji, ISA, ACEF 2025, Manila, June 2025 (1749638566ISA_ADB_GH_ACEF_2025_06_June_Fiji.pdf). Accessed on 30 September 2025
204 Consultation document, - Green Hydrogen Readiness Assessment for Papua New Guinea, ISA, ACEF 2025, Manila, June 2025 (1749638566ISA_ADB_GH_ACEF_2025_06_June_PNG.pdf). Accessed on 30 September 2025

There exists a strong correlation between innovation driven countries and GH value chain manufacturing; countries need a holistic strategy to focus on innovation to help promote GH equipment manufacturing

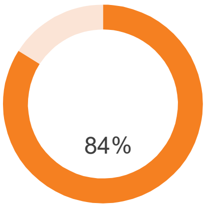
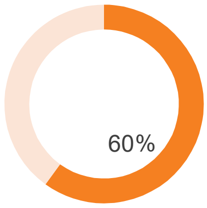
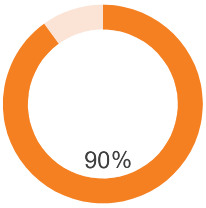
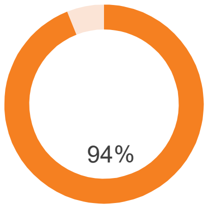
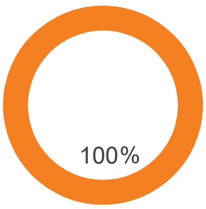
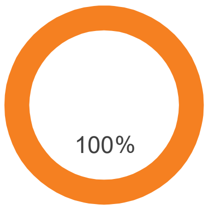
Advanced regions such as the EU, USA, and China lead not only in vertically integrated manufacturing and large-scale infrastructure plans but also in innovation. The Global Innovation Index (GII) 2025 (released by World Intellectual Property Organisation or WIPO) highlights a strong link between high-tech manufacturing and national innovation rankings underscoring push by advanced nations for localised advanced manufacturing and vertical integration to sustain technological leadership.

Technology leadership and innovation are major drivers behind the large-scale high-tech GH value chain manufacturing plans. While countries ranking high on the GII 2025 are advancing strategies for components like fuel cells, storage tanks, and electrolyser stacks as shown below in Table 15, there is significant opportunity for all nations to participate through collaboration, localised innovation, and leveraging comparative advantages in cost, resources, and talent.[205]



205 Analysis for this report, 2025 basis data from Global Innovation Index 2025: Innovation at a Crossroads, WIPO, Geneva, and publicly available announced projects. The countries in top 10 percentile range are: Switzerland, Sweden, United States, Republic of Korea, Singapore, United Kingdom, Finland, Netherlands, Denmark, China, Germany, Japan, France, Israel.

Table 15: Existing and upcoming (2030) manufacturing capacity hosted by top 10 percentile countries as per GII 2025 rankings

Type of manufacturing in GH value chain	Existing manufacturing capacity	Upcoming manufacturing capacity	Remarks
Electrolyser manufacturing			About 84 per cent and 60 per cent of existing and upcoming (2030) manufacturing capacity are hosted by top 10 percentile countries as per GII 2025 rankings[206].
Fuel cell manufacturing			Overwhelmingly, about 90 per cent and 94 per cent of existing and upcoming (2030) manufacturing capacity respectively are hosted by top 10 percentile countries as per GII 2025 rankings[207].
Storage tanks manufacturing			Near absolute majority of about 100 per cent of existing and upcoming (2030) manufacturing capacity are hosted by top 10 percentile countries as per GII 2025 rankings[208].

Strategic takeaways and recommendations regarding GH value chain equipment manufacturing and innovation

A. Countries are seeking to secure critical equipment supply chain to have a reliable and seamless GH value chain without geopolitical uncertainties.

B. Manufacturing is increasingly being looked at holistically beyond assemblies. Governments are looking at offering support to other value chain components like fuel cells, storage tanks, compressors, turbines etc. Subcomponent manufacturing like electrodes, speciality chemicals, membranes, etc. are gaining attention and dedicated funding especially in EU, Japan, South Korea, USA etc.

206 Analysis for this report, 2025 basis data from Global Innovation Index 2025: Innovation at a Crossroads, WIPO, Geneva, and publicly available announced projects
207 Analysis for this report, 2025 basis data from Global Innovation Index 2025: Innovation at a Crossroads, WIPO, Geneva, and publicly available announced projects
208 Analysis for this report, 2025 basis data from Global Innovation Index 2025: Innovation at a Crossroads, WIPO, Geneva, and publicly available announced projects

C. Countries are working on holistic innovation strategies. Innovation is no longer an aspirational word but a critical necessity in this competitive domain of GH. Countries may consider employing digital enablers like AI to accelerate innovation. Innovation strategies or projects (for example, Hy2Tech (EU), GX strategy (Japan)) supported by generous funding are therefore essential.

Table 16 highlights the recommendations for countries to achieve vertically integrated manufacturing for GH.

Table 16: Recommendations for countries to achieve domestic vertically integrated manufacturing for GH

	Recommendation	Key examples			
	Build strong decarbonisation laws (like CBAM), mandate green energy and green chemical consumption (like REFuel EU), provide generous targeted incentives to ensure the announcements cross the FID threshold *Enables clean tech equipment offtake due to market enablement through policy support*				
	Build competitive frameworks to support domestic equipment manufacturing according to ambitions *Ensures competitive frameworks are in place, including incentives frameworks and equitable conditions for domestic producers versus international competitors*				
	Focus heavily on innovation and GII rankings for technology leadership *Ensures a safe environment to innovate and move ahead in technology and cost curves and shows commitment to domestic manufacturing*				
	Develop holistic hydrogen infrastructure roadmap *Infrastructure is a critical lever for the success of GH projects and a mere single point focus on GH production plants may not be useful in the long run*				
	Aim for vertically integrated component manufacturing *Focus should be more on a holistic and vertically integrated manufacturing ecosystem to truly decouple from geopolitical supply chain constraints and focus on mere low-tech assemblies should be avoided*				

VI. AI can be a game-changer that drives efficiency and slashes costs across the green hydrogen value chain

Key takeaways:

1. The role of AI in GH must be recognised as a transformative backbone rather than a supplementary tool, enabling system-level optimisation across the value chain from renewable energy forecasting and electrolyser control to predictive maintenance and certification.
2. By processing vast, real-time datasets and making adaptive decisions, AI reshapes the economic and operational model of GH production, ensuring cost efficiency, safety, and scalability.
3. Digital innovations can transform system-level operations and accelerate material and technical breakthroughs.

The use of AI is not merely an incremental improvement but a foundational enabling technology, uniquely capable of resolving some of the core challenges associated with GH (mainly related to costs) and unlocking the commercial viability and scalability of GH. By deploying a suite of advanced computational techniques from machine learning (ML) and deep learning to digital twins and natural language processing, AI is systematically optimising every node of the hydrogen value chain. In the critical domains of safety and certifications, AI enhances infrastructure integrity through predictive inspections and real-time leak detection while enabling the creation of trusted, automated "Guarantee of Origin" certification systems which is a prerequisite for a global, fungible GH market. Furthermore, AI is streamlining the complex logistics of hydrogen storage and transportation and accelerating innovation in end-use applications such as green steel and green ammonia production.

Applications of AI in GH ecosystem

Some important areas where AI-led R&D and digital platforms can deliver transformative impact across the GH ecosystem are discussed below:

A. System level optimisation of the GH plant

AI functions as the overarching nerve centre of the GH value chain. It enables the seamless integration of otherwise disconnected elements: RE sources, network and power flow optimisation, electrolyser plant, and end usage of GH. This capability to perform system-level optimisation is what distinguishes AI as a transformative technology, moving beyond localised efficiency gains to fundamentally reshape the operational and economic model of GH production. Unlike traditional control systems, AI is capable of managing multi-variable, non-linear, and dynamic environments. By analysing vast, heterogeneous datasets in real time, including meteorological forecasts, electricity market prices, grid stability data, real-time equipment sensor readings and downstream hydrogen demand signals, AI can make predictive and adaptive decisions. These decisions optimise the entire GH plant.

Some of the plant optimisation solutions which might be considered for integration with AI are as follows in Table 17[209].

209 Analysis for this report, 2025

Table 17: Key examples of current and emerging solutions related to GH plant optimisation using AI

GH value chain point	Specific application	Goals
RE configuration	Solar and wind power forecasting	Minimise electricity cost by aligning production with low-price periods and enabling the planning of stable RE power with high availability
Electrolyser operation	Real-time optimisation of variables like voltage, current, temperature, gas pressure etc	Maximise hydrogen yield and energy efficiency
Electrolyser maintenance	Predictive maintenance for component degradation	Reduce unplanned downtime and extend asset life
Safety overview	Automated inspection for corrosion, cracks, leaks	Enhance safety and reduce inspection costs
Governance	Automated regulatory compliance reporting	Ensure automated filings and applying for necessary approvals and certifications
Certification	Guarantee of Origin (GO) verification	Ensure compliance in "certificate of origin" as per target destinations
Storage & Transportation	Demand forecasting and route optimisation	Minimise transport costs and ensure timely delivery
Supply chain emission estimation	Estimation of emissions associated with equipment manufacturing or commodity production	Provides enhanced traceability to ensure compliance towards emission reduction
Financial simulations	Advanced AI algorithms for cost modelling and investment risk analysis	De-risk investment and optimise plant configuration

H2GO power in UK has launched HyAI project to trial the use of AI in GH project operating in European Marine Energy Centre (EMEC) in Orkney. The project received a funding of GBP494,000 from UK's Department of Business Energy and Industrial Strategy's Energy Entrepreneur Fund. The project is likely to run through 2 phases during the course of 12 months, to provide a proof of concept of using AI in the GH project, enabling the project to perform data driven optimisation of wind, solar and tidal energies to optimally generate, store and consume GH. Multiple tests will be conducted to integrate various portions of the GH value chain and ensure safe operations of the plant[210].

210 Hydrogen Innovation article (H2GO Power to trial AI hydrogen optimisation system at EMEC - Hydrogen & Fuel Cells Innovation). Accessed on 10 October 2025

B. Virtual proving infrastructure using Digital Twins

The concept of the Digital Twin is increasingly being recognised as a transformative application of AI in GH plant design and operations. A Digital Twin represents a high-fidelity virtual replica of a physical hydrogen facility, encompassing process equipment such as electrolysers, compressors, and purification units, along with instrumentation and control systems. Unlike static models, it functions as a dynamic simulation, continuously updated with real-time data from connected sensors and plant control systems, effectively mirroring the plant's lifecycle.

During the pre-construction phase, the Digital Twin may serve as a virtual testbed, enabling engineers to simulate a wide range of scenarios. These include evaluating different electrolyser technologies (AWE, PEM, SOEC, AEM or others), optimising renewables or GH balance-of-plant configurations, validating control strategies, and assessing plant resilience under extreme weather or grid conditions. This virtual commissioning process is expected to reduce design uncertainty, identify potential bottlenecks, and accelerate development timelines. Post-construction, the Digital Twin evolves into a tool for operational support. It may be used to monitor performance and safety, diagnose issues, and test optimisation strategies offline before implementation. Additionally, it offers a safe and realistic environment for operator training, allowing personnel to practise routine procedures and emergency protocols before engaging with the live plant.

Technology providers such as Siemens, Emerson, Honeywell and others, through their digital twin solutions, highlight the potential to enhance design accuracy and operational efficiency. Emerson estimates that Digital Twin applications could yield 3–5 per cent efficiency improvements in subsystems such as water and hydrogen purification[211]. By bridging the virtual and physical realms, the Digital Twin creates a continuous feedback loop, an essential feature for a rapidly evolving industry where learning from operational experience is critical to scaling effectively.

C. Advanced material research for improved electrolyser performance

Traditional material development is an iterative, trial-and-error process that can take years. AI, particularly through its suite of machine learning (ML) models, fundamentally changes this paradigm by enabling high-throughput computational screening. ML models are trained on vast databases of known materials and their properties, learning the complex relationships between atomic structure and performance characteristics. This allows researchers to perform virtual experiments, predicting the viability of thousands or millions of hypothetical compounds without costly and slow laboratory work. Some of the possible areas of advanced material research using AI are shown in Table 18 below[212].

Table 18: Possible uses of AI in advanced materials research to improve electrolyser performance and safety

Subcomponent or parameter	Possible use of AI
Electrodes and catalysts	A primary cost driver for electrolysers, especially for PEM, is the reliance on precious metal catalysts like platinum and iridium. AI algorithms can screen for alternative materials based on elemental compositions, identifying novel alloys from more abundant and less expensive metals that exhibit high catalytic activity and stability. This process not only reduces capital expenditure but also mitigates supply chain risks associated with rare earth metals.

211 Emerson article (article-digital-twin-technology-transforms-hydrogen-production-mimic-en-7425216.pdf). Accessed on 10 October 2025
212 Analysis for this report, 2025

Subcomponent or parameter	Possible use of AI
Membranes	The membrane is critical for separating hydrogen and oxygen and facilitating ion transport. AI can be used to model and predict the performance of new polymer or ceramic materials, optimising for properties such as proton conductivity, chemical stability, and resistance to degradation under fluctuating operational loads typical of renewable energy inputs.
Electrolyser stacks	Beyond individual components, AI helps in optimising the entire electrolyser stack. By simulating the interplay between different materials and designs, AI can predict how microstructural changes might affect overall performance, guiding the engineering of more efficient and robust stack architectures.
Enhancing performance, efficiency, and safety	The development of superior materials through AI directly translates into tangible improvements in electrolyser operation. More effective catalysts lower the energy required to split water, leading to significant gains in energy efficiency. Enhanced material durability extends the operational lifespan of the electrolyser, reducing maintenance costs and minimising downtime. From a safety perspective, AI contributes by predicting material failure modes. Models can analyse how materials are expected to behave under the high pressures and variable temperatures of an electrolyser, identifying risks such as hydrogen-induced metal embrittlement or cracking long before they pose a threat. This predictive capability allows for the proactive design of more resilient and inherently safer materials, which is crucial for the widespread adoption of hydrogen technologies.

Researchers in University of Toronto, Canada, utilised an AI programme to computationally screen over 36,000 different metal oxide combinations to find a superior catalyst for electrolysis. The AI model identified the optimal combination which is an alloy of ruthenium, chromium, and titanium in a matter of days, for a task that would have taken years using conventional methods. Subsequent laboratory testing confirmed the AI's prediction, revealing that the new material was 20 times more stable and durable than the existing benchmark catalyst[213].

D. Optimised manufacturing processes

AI can help optimise the manufacturing of GH sub-components such as electrolysers, membranes, and fuel cells. Usage of AI in electrolyser, fuel cell or other equipment's manufacturing lines can provide improved first-pass yield, tighter process control, and faster product manufacturing to help make GH equipment cost competitive.

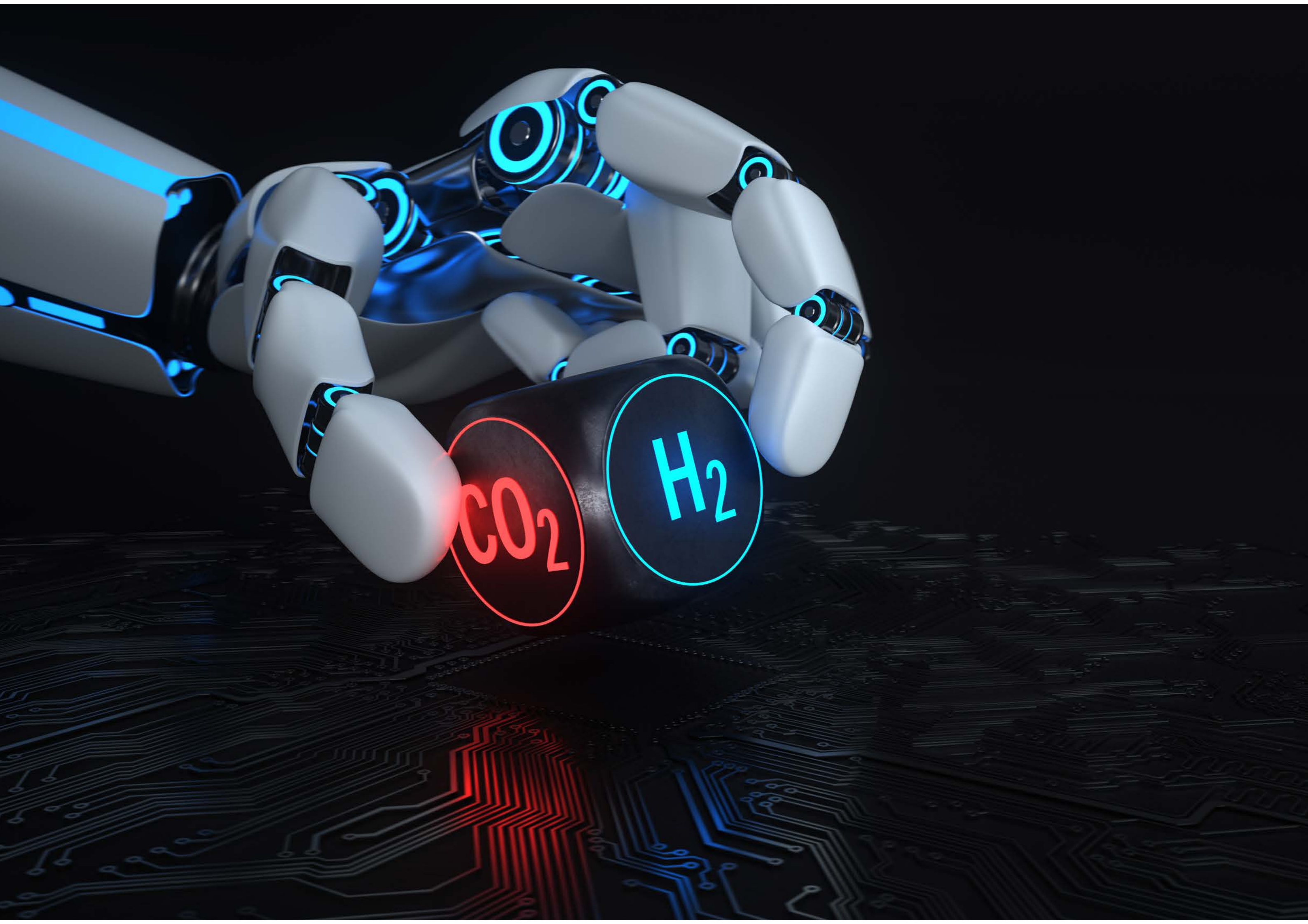
Key applications of AI span several stages of production. In slurry formulation, AI can help fine-tune multivariable recipes to maintain viscosity and coat performance, while soft sensors detect deviations at early stages of manufacturing. Computer vision systems identify coating defects at industrial speeds, and AI-driven control of drying and calendaring ensures structural integrity. Optical and infrared

213 Hydrogen Industry Leaders article (AI Technology Advances Efficiency of Green Hydrogen Production - Hydrogen Industry Leaders). Accessed on 10 October 2025

inspection powered by AI improves defect detection in membranes. Vision-guided assembly and digital twins streamline stack lamination and end-of-line testing, reducing errors and downtime.

Early industrial pilots indicate significant benefits in first-pass yields, scrap reduction, and shorter validation cycles. AI-driven inspection, process analytics, and predictive diagnostics can be central to achieving cost parity and reliability in global GH supply chains, provided manufacturers adopt robust data integration and continuous model retraining frameworks.

AI is used by Konica Minolta in Toyota Mirai FCEV stack separator defect identification and QC in Toyota's manufacturing plant, ensuring Right First Time (RFT)[214]. The AI learns continuously by reading and analysing visual images of FCEV stacks and identifies even minor defects like oil contamination from human skin, dirt, minor scratches which escape the human eye. Such defects might seem minor, but can negatively impact the performance of sensitive equipment like fuel cell stacks, and hence the overall FCEV.



214 Konica Minolta article (Fuel Cell Stack Inspection System | KONICA MINOLTA). Accessed on 26 October 2025

Key recommendations to harness the power of AI ab-initio in the GH ecosystem

A. AI must be embedded from the outset in GH strategies to unlock its full potential. Early integration ensures that countries and organisations can leverage AI-driven efficiencies, cost reductions, and operational resilience, positioning themselves competitively in a rapidly evolving global market.

B. Countries and organisations both need to integrate AI into their strategies and projects, from inception, to truly harness the efficiency and cost benefits which AI can offer and differentiate themselves in this highly competitive landscape of GH.

C. Holistic strategies and collaboration need to be developed to encourage organisations adopt AI in GH projects, especially in critical applications like safety and governance.

D. AI is already finding applications in several parts of the GH value chain, with key use cases coming from highly innovative countries or regions (top 10 percentile of GII 2025 rankings) like UK, Canada, Japan, EU. Grants or public funding for the application of AI in GH related projects is being rolled out for select projects in UK and EU.

Some of the strategic recommendations for policymakers and organisations alike to integrate AI in the emerging GH ecosystem are outlined in Table 19[215].

Table 19: Recommendations to harness the power of AI from inception in the GH ecosystem

	Foster open-source data sharing and collaboration *To avoid scarcity of data to train complex AI / ML models*
	Incentivise digitisation of GH ecosystem *Integrate the requirement for AI, Digital Twins etc for the grant of public funding*
	Develop AI centric standards for safety, governance *Collaborate with industry to roll out standards for using AI in critical areas like safety and governance*
	Prioritise AI in due diligence *Mandate usage of AI for technical and regulatory due diligence of GH projects*
	Develop industry relevant skillsets in AI and GH *Develop cross-disciplinary curricula that bridge the gap between energy engineering and data science*

215 Analysis for this report, 2025

VII. Financing is the silent barrier - but also the biggest opportunity

Key takeaways:

1. Global investments in clean hydrogen surged to USD4.3 billion in 2024, and is estimated to reach nearly USD8 billion by 2025.
2. In 2024, approximately 56 per cent of global clean hydrogen investments were directed toward electrolysis based GH projects, totalling approximately USD2.4 billion.
3. A significant share of investment still went into blue hydrogen projects, driven by its cost advantage as it is over three times cheaper than GH. This price gap remains a concern and may delay the conversion of announced GH investments into FIDs.
4. High borrowing costs pose a significant risk to the economic viability of GH projects; targeted instruments like CfDs, VGF, and blended finance are essential to unlock scale.

Global investment in low-emission hydrogen is rising sharply, led by electrolyser based projects

The global hydrogen sector has witnessed substantial growth in investment, primarily driven by the pressing need to decarbonise hard-to-abate industries and achieve net-zero emissions targets. In 2024, global investment in low-emission hydrogen projects reached USD4.3 billion, with 56 per cent (USD2.4 billion) directed towards electrolyser-based GH projects and 44 per cent (USD1.9 billion) allocated to low-carbon hydrogen projects incorporating CCUS[216].

216 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025

According to the IEA's recent publication "Global Hydrogen Review 2025", the FIDs indicate that China and Europe accounted for the largest share of the total investment in GH (refer to Figure 23)[217]. The investment in electrolysis projects has demonstrated a pronounced upward trajectory since 2022. In that year, global investment in GH projects was approximately USD0.4 billion, which subsequently increased sixfold to reach USD2.4 billion by 2024[218]. Looking ahead, IEA anticipated that investment in electrolysis projects is likely to rise to USD6.2 billion, while investment in CCUS-based hydrogen projects is expected to reach USD1.8 billion in 2025. This would bring the total to USD8 billion, representing an increase of more than 80 per cent compared with 2024[219]. This trend reflects growing confidence and strategic prioritisation of GH technologies within the global energy transition framework.

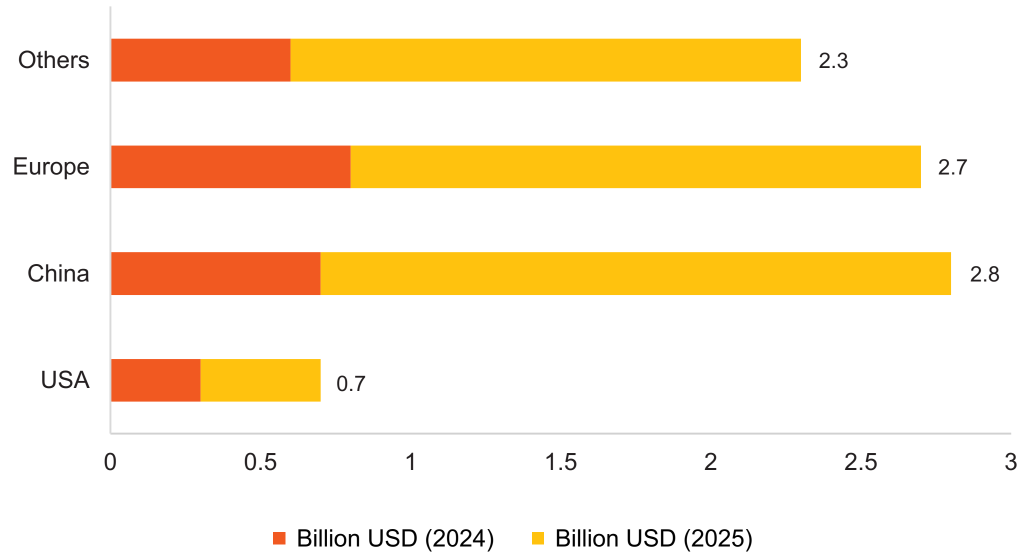


Figure 23: Estimated announced global investments in GH plants across key regions in 2024 and 2025

Investment in hydrogen infrastructure comprising of pipelines, storage facilities, and refuelling stations, remains limited but is critical for scaling the hydrogen economy. According to the IEA's NZE scenario, the average annual global investment in hydrogen infrastructure is projected to reach USD83 billion by 2050, underscoring the critical role of enabling infrastructure in supporting widespread adoption and integration of hydrogen technologies (refer to Figure 24)[220].

217 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
218 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
219 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
220 Energy technology perspectives 2023, IEA, January 2023 (Average annual global investment in hydrogen and natural gas infrastructure in the Net Zero Scenario, 2016-2050 – Charts – Data & Statistics - IEA). Accessed on 18 April 2025 (HRS: Hydrogen refuelling station, LH2: liquefied hydrogen)

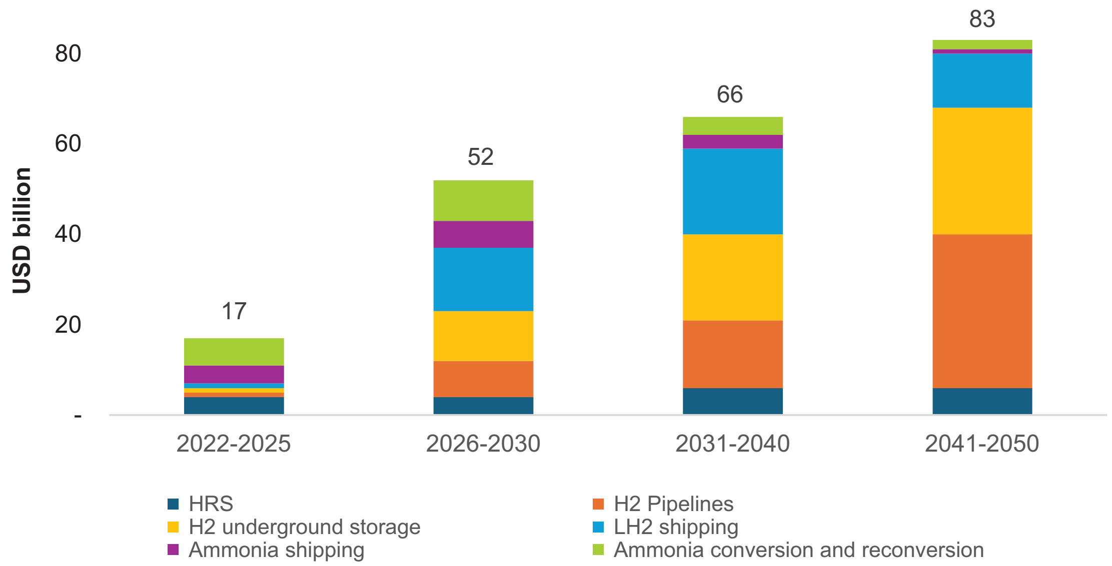


Figure 24: Current and projected global investments in hydrogen infrastructure in the NZE Scenario

Blended finance anchored by public incentives and complemented by private equity and debt is the dominant model for GH project funding.

GH projects are generally financed through a combination of funding sources rather than relying on a single source. A blended finance model is common, incorporating public grants, equity from both private and public investors, and debt from concessional and commercial lenders. Government support through grants, tax incentives, or low-interest loans, remains a critical component of the overall funding mix.

Large industrial firms sometimes choose to fund projects internally using retained earnings or cash reserves, a method known as balance sheet financing. While this approach avoids external borrowing or issuing new equity, it places the financial risk entirely on the company's own accounts.

For projects that are large-scale or capital-intensive, developers often form joint ventures and create special purpose vehicles (SPVs) to pool resources, share risks, and separate liabilities from parent companies. These structures typically involve initial equity contributions from partners, with the JV or SPV also seeking public grants, concessional finance, or external debt to meet total investment requirements. This model helps distribute risk and attract external capital, though it usually depends on securing long-term offtake agreements.

IEA has anticipated the financing structure of several GH projects, as illustrated in Figure 25[221]. The analysis indicates that these projects predominantly employ blended financing models, combining public grants, equity contributions, and debt from both concessional and commercial sources.

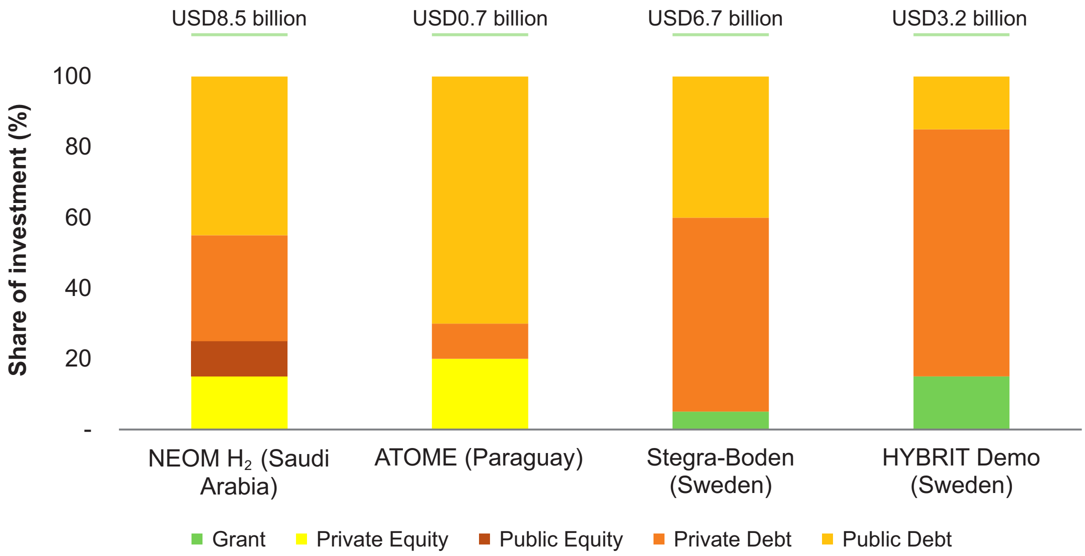


Figure 25: Financing structure of select GH projects (list not exhaustive)

Financing mechanisms (both financial and non-financial) are key to lowering LCOH and scaling GH deployment.

Finance costs significantly influence LCOH, making innovative financing solutions for GH projects a key opportunity for governments, International Financial Institutions (IFIs), and private players. The financing mechanisms can be categorised as financial enablers, which directly influence project economics and investment viability, and non-financial enablers, which underpin implementation through regulatory frameworks, infrastructure provision, and administrative facilitation. Collectively, they serve as a cornerstone for accelerating deployment and scaling up GH initiatives. Some of the suggested financial schemes which can be adopted by policymakers are as follows.

I. Contracts for Difference (CfD)

Financial mechanisms designed to ensure price stability and make clean hydrogen more competitive with conventional fuels. CfDs provide a guaranteed price for hydrogen producers by covering the difference between the market price of hydrogen and a pre-agreed strike price. If the market price of hydrogen falls below the strike price, the government or a designated authority compensates the producer for the difference. Conversely, if the market price exceeds the strike price, the producer pays back the difference.

221 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025

Example 1: The Hydrogen Allocation Rounds (HARs) are UK government initiatives that provide 15-year revenue support to low-carbon hydrogen projects, helping to close the cost gap between low-carbon hydrogen and high-carbon alternative fuels. HAR1 announced EUR2 billion in revenue support and EUR90 million in capital grants via the Net Zero Hydrogen Fund. HAR2 round aims to support 875 MW of low carbon hydrogen production capacity and has shortlisted 27 electrolytic hydrogen projects[222].

Example 2: French government launched its first tender under the CfD scheme which offers subsidy upto EUR4 per kg for 15 years targeting 200 MW of electrolysis capacity[(223),(224)].

II. Viability gap funding (VGF)

VGF is a government-backed financial mechanism that helps bridge the gap between project costs and expected returns, especially for capital-intensive projects with long gestation periods. It is typically disbursed during the construction phase to ensure project completion.

Example: A prominent example of VGF in India is the scheme approved by the Union Cabinet in June 2024 for the development of 1 GW offshore wind energy projects. The total outlay for this initiative is INR7,453 crore, which includes INR6,853 crore for the installation and commissioning of 500 MW each off the coasts of Gujarat and Tamil Nadu, and ₹600 crore for upgrading two ports to support logistics [225].

III. Proportionate risk sharing

This mechanism allows governments to act as intermediaries, absorbing part of the financial risk and uncertainty associated with early-stage hydrogen projects, thereby improving their bankability and attracting private investment. This can be achieved through financial grants, guaranteed offtake agreements, or technical support such as detailed engineering studies.

Example 1: India's Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme includes a guaranteed offtake mechanism as part of its broader strategy to de-risk GH investments. Under Component II of the scheme, the government offers incentives for GH production, and one of the key features is the assurance of offtake for a specified quantity of GH or its derivatives (like green ammonia)[226].

Example 2: A notable global example of proportionate risk sharing in GH is Germany's H2Global mechanism. This initiative is designed to foster a global market for GH by pairing long-term supply contracts with short-term demand contracts and using public funds to bridge the cost gap between production and market prices[227].

222 Hydrogen Allocation Round 2 (HAR2): shortlisted projects, Government of United Kingdom, April 2025 (Hydrogen Allocation Round 2 (HAR2): shortlisted projects - GOV.UK). Accessed on 5 April 2025
223 Fuel cells works article, December 2024 (France Launches Support for Decarbonized Hydrogen Production). Accessed on 5 April 2025
224 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
225 Press Release on VGF funding for offshore wind energy projects-MNRE, Press Information Bureau, June 2024 (Press Release: Press Information Bureau). Accessed on 18 April 2025
226 SIGHT scheme guidelines-Component II: Mode1 (Tranche II) of National Green Hydrogen Mission, MNRE (Government of India), July 2024 (172009404040530Scheme_guidelines.pdf). Accessed on 20 April 2025
227 New Climate Institute article, 2025 (Assessing safeguards for hydrogen sustainability in the H2Global Mechanism). Accessed on 5 April 2025

IV. Green bonds

A green bond refers to any type of debt instrument where the proceeds, or an equivalent amount, are exclusively allocated to finance or refinance either wholly or partially, new or existing projects that meet defined environmental criteria. These bonds are structured to support initiatives that contribute to sustainability, such as RE, clean transportation, or GH development.

Example 1: An example of green bonds being used to finance GH projects is the USD1.3 billion multi-currency green bond offering by Air Products. The proceeds from this issuance are being directed towards decarbonisation initiatives, including investments in the hydrogen economy. Air Products has emphasised its role in advancing hydrogen production and infrastructure as part of its broader net-zero strategy[228].

Example 2: RWE, a major European energy company, issued two green bond tranches of EUR500 million each in 2023. These bonds are part of RWE's "Growing Green" strategy and are being used to fund RE and GH projects across its portfolio, including over 30 hydrogen-related initiatives at various stages of development[229]

V. Blended finance structures

Blended finance mechanisms combine concessional finance from public or philanthropic sources with commercial capital to improve the risk-return profile of GH projects. This approach is particularly effective in emerging markets where perceived risks are higher. The Climate Investment Funds have supported blended finance models for clean energy projects, including hydrogen pilots in Africa. The Green Climate Fund has also co-financed hydrogen infrastructure in developing countries by partnering with multilateral development banks and private investors[230].

VI. Public-Private Partnerships (PPP)

PPPs enable joint investment and risk-sharing between governments and private entities, facilitating infrastructure and market development.

Example 1: The NEOM GH hub in Saudi Arabia is a collaborative venture between public and private sector entities. The project is being executed by the NEOM Green Hydrogen Company (NGHC), a joint venture formed through equal equity contributions from Air Products, ACWA Power, and NEOM and the latter being a government-backed initiative[231].

Example 2: The Hydrogen Valley Innovation Cluster (HVIC) in India is being developed under a Public-Private Partnership (PPP) mode as part of the National Green Hydrogen Mission[232]. This model is designed to bring together public sector support and private sector innovation and investment to create integrated hydrogen ecosystems, also known as hydrogen valleys that span production, storage, distribution, and end-use applications.

Under this PPP framework, the government provides policy support, infrastructure facilitation, and viability gap funding, while private players contribute capital, technology, and operational expertise.

228 S&P Global Commodity Insight Article, June 2023 (Industry turns to green bonds to finance decarbonization projects). Accessed on 25 April 2025
229 RWE Green Bond Report, 2023 (2023-10-30-rwe-green-bond-report-2023.pdf). Accessed on 25 April 2025
230 Climate Investment Fund and Green Climate Fund Report, 2020 (synergies_between_climate_finance_mechanisms_synthesis_report_2april.pdf). Accessed on 25 April 2025
231 Market Screener Article (ACWA Power Company: Shareholders, Shareholding Structure - MarketScreener). Accessed on 25 April 2025
232 Guidelines for Hydrogen Valley Innovation cluster, Department of Science and Technology, 2023 (SchemeId_2294_GuidelinesforHydrogenValleyInnocationCluster_0.docx). Accessed on 25 April 2025

Non-financial enablers

I. Regulatory process and approvals

Simplified regulatory processes, such as single-window clearances and fast-track approvals, can significantly reduce project delays.

Example 1: The RE Portal of Kenya outlines a structured approach to project licensing and clearances, including a clearances flow chart that consolidates various permits and approvals required for RE projects. This portal is part of Kenya's effort to develop a single-window clearance system to streamline regulatory procedures and reduce delays for developers[233].

Example 2: The National Green Hydrogen Mission (NGHM) includes provisions for streamlined approvals and regulatory facilitation to support GH project developers. The mission aims to create an enabling ecosystem by coordinating efforts across ministries and agencies, including simplified procedures for land acquisition, environmental clearances, and infrastructure access[234].

233 Renewable Energy Portal of Kenya, Government of Kenya (https://renewableenergy.go.ke/licensing/clearances-flow-chart/). Accessed on 25 April 2025

234 National Green Hydrogen Mission, Ministry of New and Renewable Energy, Government Of India (National Green Hydrogen Mission Portal of India). Accessed on 30 April 2025

II. Land and resource allocation

Preferential access to land, water, and RE resources can lower development costs and accelerate project timelines.

Example 1: Under the "Morocco Offer" for GH, the government has selected five national and international investors to implement six large-scale projects across the southern regions of the country. These projects, which include the production of ammonia, industrial fuel, and green steel, are being facilitated through the allocation of up to 30,000 hectares of land per project[235]. This land allocation is part of a broader strategy to attract global investment and accelerate project timelines.

Example 2: Oman has actively facilitated GH development by allocating land through structured auction rounds. In its third GH auction round, launched by Hydrogen Oman (Hydrom), the government offered a land block of up to 300 square kilometres in Al Duqm, inviting developers to submit proposals for projects covering a minimum of 100 square kilometres[236]. This initiative is part of Oman's integrated strategy to support scalable hydrogen projects by combining land allocation with common-use infrastructure, regulatory frameworks, and export corridors.

III. Shared infrastructure development

Government-led development of common infrastructure such as pipelines, storage, and export terminals reduce capital burden on individual projects.

Example 1: The EU's Hydrogen Backbone initiative aims to create a pan-European hydrogen pipeline network[237].

Example 2: The SalalaH2 Green Hydrogen Hub in Oman is being supported by the government through a range of non-financial enablers, including the provision of land, shared infrastructure such as hydrogen and ammonia pipelines, access to ports and jetties, and facilities for power evacuation[238]. In addition to these logistical and regulatory supports, the government is also contributing significantly through equity investment via OQ, a state-owned energy company and the lead partner in the project, thereby reinforcing its strategic commitment to the development of GH in the region.

235 The Head of Government Chairs a Steering Committee Meeting on the "Morocco Offer" for Green Hydrogen, Kingdom Of Morocco Head Of Government, March 2025 (The Head of Government Chairs a Steering Committee Meeting on the "Morocco Offer" for Green Hydrogen | Head of Government - Kingdom of Morocco). Accessed on 30 April 2025
236 Oman observer Article, 30 April 2025 (Oman announces 3rd GH auction round - Oman Observer). Accessed on 30 April 2025
237 European Hydrogen Backbone Roadmap, November 2023 (EHB-2023-Implementation-Roadmap-Part-1.pdf). Accessed on 30 April 2025
238 Zawya Article, December 2021($1bln project to create green ammonia export hub in Oman). Accessed on 30 April 2025

VIII. Complexity of challenges and opportunities underscore need for a cohesive policy framework for green hydrogen

Key takeaways:

1. More than 65 policies/roadmaps on GH have been released globally. Advanced economies such as United States, Germany, United Kingdom, Netherlands, Denmark etc. have largely concentrated on pioneering technological innovation and scaling up infrastructure to support hydrogen deployment. In contrast, emerging economies such as Sri Lanka, Bhutan, Chile, Egypt etc. have prioritised harnessing local renewable resources and establishing foundational hydrogen ecosystems, with a view to strengthening energy security and reducing reliance on energy imports.
2. Despite the publication of more than 65 GH policies / roadmaps on GH, strategies of a select few like EU, Japan, South Korea, USA, India appear holistic.
3. A six-point strategic framework is proposed to help countries design a holistic GH policy roadmap, integrating key elements such as projects, infrastructure, local manufacturing, and competitive financing.
4. Countries need to adopt this six-point framework to drive market creation and scale.

Global GH policies are expanding rapidly, with major public funding and national strategies accelerating early ecosystem development

Governments worldwide are implementing targeted policies and financial support mechanisms to make low-emission hydrogen more competitive with fossil fuels. In the past years, a cumulative amount of USD38 billion in public funding has been announced, allocated, or deployed to enhance the financial viability of hydrogen projects[239]. This significant investment reflects a growing commitment to hydrogen as a key component of the global energy transition.

The development of a comprehensive policy framework for low carbon hydrogen is observed to be unfolding in various ways, with some countries issuing roadmap or strategy while others issuing mission documents. The global adoption of green and low carbon hydrogen strategies has seen a substantial rise. As per IEA, a total of 65 countries have introduced low carbon hydrogen roadmaps and strategies, with 5 of these being added since 2024 [(240,241,242)]. While this surge in participation highlights the growing global commitment to low carbon hydrogen, most strategies remain non-binding and primarily serve to assess sectoral potential, identify investment opportunities, and outline short-term initiatives. These hydrogen strategies have mostly not yet translated into binding laws or associated with specific policy tools.

The national hydrogen strategies and roadmaps published by various countries differ significantly in content, style, and depth of assessment. At present, there is no international standard or protocol for drafting these strategic documents.

239 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
240 Global Hydrogen Review 2024, IEA, October 2024 (Global Hydrogen Review 2024). Accessed on 14 February 2025
241 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
242 Centre on Global Energy Policy article, February 2025 (H2 Strategies_ FIN_Feb2025). Accessed on 21 March 2025

IRENA definitions on hydrogen strategy and roadmap:

"A national hydrogen strategy is a long-term government document that outlines priorities, goals, barriers, opportunities and stages for developing a hydrogen sector within a country. It sets targets, addresses concrete policies and evaluates their coherence with existing energy policy"[243].

"A national hydrogen roadmap outlines the approach to hydrogen deployment within a country, lacking clear goals but serving more as a framework for discussion. Unlike strategies, roadmaps usually are not formally adopted by the government but provide integrated plans, prioritising short-term actions, research areas and crucial demonstration projects. They are sometimes referred to as 'vision documents', 'white papers', 'guidelines', etc."[244].

243 Green hydrogen strategy: A guide to design, IRENA, 2024 (Green hydrogen strategy: A guide to design). Accessed on 20 March 2025

244 Green hydrogen strategy: A guide to design, IRENA, 2024 (Green hydrogen strategy: A guide to design). Accessed on 20 March 2025

As per the reports published by IEA and IRENA, it was observed that around 48 hydrogen strategies and 17 hydrogen roadmaps have been published across various countries including developed and emerging economies; tailored to their specific hydrogen demand, renewable resource potential, and existing hydrogen ecosystems[245,246,247,248]. Developed economies like Germany, UK, Netherlands, Denmark, and USA published their hydrogen strategies earlier in 2022-23. These strategies have set clear milestones and comprehensive plans, which have significantly influenced and guided emerging economies in formulating their own hydrogen strategies. Annexure-4 provides a qualitative comparison of GH strategies and roadmaps of key countries.

Examples of hydrogen roadmap/strategy from emerging economies:

- Sri Lanka roadmap aims to utilise its abundant offshore wind and solar resources to produce GH, focusing on energy security and export potential. It highlights the importance of developing a skilled workforce to support the hydrogen sector and includes training and educational initiatives[249].
- Bhutan roadmap focusses on producing GH using its abundant hydropower to address energy security and climate change[250].

Examples of hydrogen roadmap/strategy from developed economies:

- USA's National Hydrogen Strategy and Roadmap published in 2023, is focussed on funding large scale infrastructure projects by including funding for Regional H2Hubs and driving research and innovation by implementing programs like Hydrogen Shot Initiative[251]. It outlines concrete long-term targets and metrics to measure progress and success, with scenarios projected for 2030, 2040, and 2050.
- European Union's Hydrogen Strategy published in 2020, prioritises development of renewable hydrogen from solar and wind energy in two phases. First phase (2020 to 2024), targets installation of 6 GW of electrolysers for production of 1 MMT of renewable hydrogen. The second phase (2025-2030) targets an installation of 40 GW of electrolysers for production of 10 MMT of renewable hydrogen in the European Union by 2030[252].

In the subsequent section, two detailed case studies on national hydrogen roadmaps or strategies are presented - one from the Global North, South Korea and one from the Global South, Egypt.

A. South Korea: A model of policy-driven innovation

South Korea's Hydrogen Economy Roadmap, announced in January 2019, aims to establish a comprehensive hydrogen ecosystem by 2040 to address economic growth and industrial competitiveness. As per South Korea's policy progress document, published in 2022, the nation's hydrogen roadmap initiatives have prompted industry to announce large-scale investments worth USD29.5 billion as of March 2021, across value chain including production of green and blue hydrogen, storage and distribution (liquefaction plants), and utilisation (power generation and hydrogen mobility)[253]. Table 20 depicts the salient features of the South Korea Hydrogen Economy Roadmap.

245 Centre on Global Energy Policy article, February 2025 (H2 Strategies_ FIN_Feb2025). Accessed on 21 March 2025)
246 Green hydrogen strategy: A guide to design, IRENA, 2024 (Green hydrogen strategy: A guide to design). Accessed on 20 March 2025
247 Global Hydrogen Review 2024, IEA, October 2024 (Global Hydrogen Review 2024). Accessed on 14 February 2025
248 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
249 Sri Lanka National Hydrogen Roadmap, Petroleum Development Authority of Sri Lanka (Government of Sri Lanka), 2023 (Sri-Lanka-National-Hydrogen-Roadmap_Final.pdf). Accessed on March 15 2025
250 Hydrogen Roadmap of Bhutan, Department of Energy Ministry of Energy & Natural Resources (Government of Bhutan), 2024 (Hydrogen Roadmap). Accessed on 16 March 2025
251 U.S. National Clean Hydrogen Strategy, U.S. Department of Energy, 2023 (U.S. National Clean Hydrogen Strategy and Roadmap). Accessed on 16 March 2025
252 A hydrogen strategy for a climate-neutral Europe, European Commission, 2020 (EU.pdf). Accessed on 15 March 2025
253 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025

Table 20: Salient features of South Korea Hydrogen Economy Roadmap

Parameters	Description
Name of Roadmap	Hydrogen Economy Roadmap of Korea[254]
Country	South Korea
Year of publication	2019
Type of hydrogen focussed	Green, Blue and Grey hydrogen
End-use sectoral focus	Industry, mobility and power
Hydrogen production targets[255]	• Hydrogen supply target: 3.9 MMT in which total hydrogen production targets are 1.94 MMT and hydrogen import targets are 1.96 MMT by 2030 • GH target: 0.25 MMT by 2030
Electrolyser capacity targets	Commercialisation of 10 MW water electrolysis by 2030 with a target to deploy GW-class electrolysis by 2050[256]
Other targets[257]	• Hydrogen powered passenger vehicles: 850,000 units by 2030 • Hydrogen commercial vehicles: 30,000 units by 2030 • Hydrogen fuelling stations: 660 units by 2030 • Support to H2 specialised companies: 500 units (32 selected as of May 2022)
Earmarked budget/fund	• USD5.9 million allocated in subsidies to 152 hydrogen refuelling station (HRS) operators to help cover the cost of purchasing hydrogen[258] • USD910 billion is earmarked for R&D support for technology development[259] • USD340 million allocated for financial support to SMBs and middle-standing companies manufacturing fuel cells
Infrastructure development support[260]	• Subsidy for hydrogen vehicle (FCEV) purchases and installation subsidy for hydrogen fuelling stations • Support for designated GH cluster using RE in Jeonbuk, Gangwon. This includes construction of 100 MW water electrolysis plant linked with Saemangeum Renewable Complex and Integrated GH Support Center in Jeonbuk. • Support for GH pilot city in Ansan by demonstration of GH production using the RE from SIWHA Solar plant. • Support for special regulatory free zones for GH in Ulsan and Chungbuk. The Ulsan special regulatory free zone is designated for GH mobility and Chungbuk zone is dedicated for GH industry.

254 Outlook on Hydrogen Economy and Roadmap Korea, Republic of Korea, May 2022 (Outlook-on-Korean-Hydrogen-Economy-and-Roadmap (5).pdf). Accessed on 18 March 2025
255 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025
256 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025
257 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025
258 Hydrogen Insight article, May 2024 (South Korea hands out billions of won in hydrogen fuel subsidies to support struggling refuelling station owners | Hydrogen Insight). Accessed on 18 March 2025
259 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025
260 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025

B. Egypt: Emerging leader with strategic potential

Egypt envisions to play a transformative role as a future hydrogen hub, serving both as a critical transport corridor for international hydrogen trade and as an active participant in hydrogen production. The country's vast land resources and considerable RE potential positions it as a credible producer of renewable power and GH, while its proximity to the Suez Canal enhances its strategic appeal as a supply hub[261]. The continuous flow of maritime traffic through the canal could create a sustained demand for clean energy solutions.

Table 21 discusses the initiatives taken under the recently published hydrogen strategy of Egypt. At COP27 in November 2022, the government unveiled the National Low Carbon Hydrogen Strategy, aiming to establish itself as a hub for low-carbon hydrogen. The strategy aspires to capture up to 8 per cent of the global tradable market by 2040.

Table 21: Key points of Egypt's National Low Carbon Hydrogen Strategy

Parameters	Description
Name of Roadmap	Egypt National Low Carbon Hydrogen Strategy
Country	Egypt
Year of publication	2024
Type of hydrogen focussed	Green and blue, pink hydrogen would also be explored in future
End-use sectoral focus	Industry, Mobility, Power
Import/Export	Export-focused (EU, Japan); with growing domestic use in industry and transport
Hydrogen production targets[262,263]	1.5 MMTPA by 2030 and 5.75 MMTPA by 2040 of GH with a target of 3.75 MMTPA of GH export by 2040
Electrolyser capacity targets[264]	13 GW by 2040 and 48 GW by 2040
Incentives [265,266]	• 33–55 per cent rebate on income tax • 100 per cent exemption on taxes related to property like stamp duty, real estate tax and registration fees • 100 per cent exemption on customs duty • 100 per cent exemption on Value Added Tax (VAT) on imports/exports • 25 per cent rebate in industrial land usufruct fees • 20 per cent rebate in port land usufruct fees • 30 per cent rebate in transit/port fees

261 Frontiers in Energy Research article, 2025 (Frontiers | Green tides: the Suez Canal as key hub and green corridor for a hydrogen future between the Middle East and Europe). Accessed on 20 March 2025

262 Egypt's National Low Carbon Hydrogen Strategy – Short Version, European Bank for Reconstruction & Development (EBRD) and Advisian, January 2024 (Egypt Hydrogen Strategy – FULL Version). Accessed on 12 March 2025

263 Medium article, August 2024 (Egypt Publishes Hydrogen Strategy — Key Points | by Yury Erofeev | Areas & Producers | Medium). Accessed on 12 March 2025

264 Egypt's National Low Carbon Hydrogen Strategy – Short Version, European Bank for Reconstruction & Development (EBRD) and Advisian, January 2024 (Egypt Hydrogen Strategy – FULL Version). Accessed on 12 March 2025

265 Readiness assessment of green hydrogen in African Countries, ISA, 2024 (https://isa.int/uploads/publiction_pdf/1730792896Denmark-ISA_Readiness_Assessment_of_Green_Hydrogen_in_ African_countries_Printing.pdf). Accessed on 24 March 2025

266 Readiness assessment of green hydrogen in African Countries, ISA, 2024 (https://isa.int/uploads/publiction_pdf/1730792896Denmark-ISA_Readiness_Assessment_of_Green_Hydrogen_in_ African_countries_Printing.pdf). Accessed on 24 March 2025

Parameters	Description
Regulatory framework[267]	• Fast-Track Licensing & Approvals: Streamlined permitting and regulatory procedures are provided, especially for projects in key zones like the Suez Canal Economic Zone. • Land Allocation Policies: Simplified land leasing and allocation procedures forrenewable energy projects linked to hydrogen production
Infrastructure development support[268]	• The Suez Canal Economic Zone (SCZone) has invested USD3 billion in infrastructure to attract investors. • Egypt plans to develop desalination plants powered by RE, aiming for an output of around 4 Million Cubic Metres (MCM) per day (or 1.4 Billion Cubic Metres (BCM) per year). • To support its expanding RE and GH ecosystem, the country is enhancing its power infrastructure, including upgrading transmission grids to Extra High Voltage (EHV) levels of approximately 765 kV. • With 18 commercial ports along the Mediterranean and Red Seas, Egypt is considering developing three ports namely Abu Qir, Edco, and Damietta for hydrogen trade. Notably, Abu Qir and Damietta ports already have ammonia handling capabilities.

It may be noted that ISA, in association with the Embassy of Denmark in India, had performed a deep dive on GH ecosystem readiness of four select African countries (including Egypt). The study "Readiness Assessment of Green Hydrogen in African Countries" can be referred to for further details[269].

Hydrogen strategies are increasingly translating into targeted, regulated policies, with ~29 countries adopting financial measures since 2023

Strategic plans and roadmaps often lay the groundwork for actionable policies that address short-term priorities through targeted support and incentives. These policies are typically reinforced by regulatory measures to ensure effective execution. Globally, many governments have introduced hydrogen-specific policy measures to accelerate its adoption across production, distribution, and end-use. Around 29 countries have introduced GH specific financial measures since 2023[270]. Table 22 describes few of the most widely adopted policy-driven financial instruments.

Table 22: Key policy-driven financial instruments from the global hydrogen policies (list is not exhaustive)

Policy instruments	Country	Name of policy instrument	Description
Grants	EU	EU Innovation Fund	EU Innovation Fund provides grants to help accelerate innovation and demonstration projects in the field of green hydrogen[271].

267 Egypt, GHIC, (Green Hydrogen Innovation Centre | International Solar Alliance). Accessed on 25 March 2025
268 Readiness assessment of green hydrogen in African Countries, ISA, 2024 (https://isa.int/uploads/publiction_pdf/1730792896Denmark-ISA_Readiness_Assessment_of_Green_Hydrogen_in_ African_countries_Printing.pdf). Accessed on 24 March 2025
269 Readiness Assessment of Green Hydrogen in African Countries, ISA, Embassy of Denmark in India, November 2024 (PowerPoint Presentation). Accessed on 03 October 2025
270 Global Hydrogen Review 2024, IEA, October 2024 (Global Hydrogen Review 2024). Accessed on 14 February 2025
271 European Commission, 20 January 2026 (Six winners of the 2024 Innovation Fund hydrogen auction sign grant agreements, advancing renewable). Accessed on 16 March 2026

Policy instruments	Country	Name of policy instrument	Description
	USA	Industrial Demonstration programme (IDP), Regional H2Hubs	• CAPEX grants totalling USD1.7 billion across six projects as part of the IDP to support integrated carbon capture and storage (CCS) project[272]. • USD7 billion allocated to provide infrastructure support for the establishment of seven hydrogen hubs across USA (H2Hubs initiative). • USD98 million allocated for infrastructure support for HRS and research facilities.
	South Korea	New Power Industry Fund R&D-export-finance package	• Financial support of USD340 million for Small and Medium Business (SMB) and middle-standing companies involved in manufacturing of fuel cells [273]. This fund supports fuel cell technology innovation and enhance production capacity of the SMBs. • USD5.9 million as subsidies to 152 HRS operators to help cover the cost of purchasing Hydrogen[274] • Funding for GH innovation to establish priority R&D centres focused on water electrolysis technologies[275].
	Spain		EUR1.3 billion allocated for the development of seven hydrogen valley projects with a cumulative electrolyser capacity of 2.3 GW[276].
Competitive bidding schemes	EU	European Hydrogen Bank	USD781 million approved for seven GH projects (1.5 GW of electrolysis) in the first auction of the bank which was announced in April 2024. The projects are expected to receive funds from EU Emissions Trading System's Innovation Fund in terms of per kg of hydrogen produced, with premia ranging from EUR0.37 to EUR0.48 per kg hydrogen[277]. The second domestic auction closed on 20 February 2025 which attracted 61 bids from projects across 11 countries within the European Economic Area (EEA) and receive award up to EUR1.2 billion[278]

272 U.S. DOE article, (Industrial Demonstrations Program | Department of Energy). Accessed on 20 March 2025

273 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025

274 Hydrogen Insight article, May 2024 (South Korea hands out billions of won in hydrogen fuel subsidies to support struggling refuelling station owners | Hydrogen Insight). Accessed on 18 March 2025

275 Korea to push forward transition to clean hydrogen ecosystem, Press release-Ministry of Trade, Industry and Energy, December 2023 (Press Releases < PRESS CENTER - Ministry of Trade, industry and Energy). Accessed on 18 March 2025

276 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025

277 European Hydrogen Bank pilot auction results spark renewable hydrogen competitiveness, Hydrogen Europe, May 2024 (Hydrogen Europe). Accessed on 20 March 2025

278 European Hydrogen Bank, European Commission, 2022, (European Hydrogen Bank - European Commission). Accessed on 20 March 2025

Policy instruments	Country	Name of policy instrument	Description
	India	SIGHT Programme	The SIGHT scheme under the National Green Hydrogen Mission has financial outlay of approximately USD1.9 billion (INR17,490 crores)[279]. This scheme is designed to provide production-linked incentives for investments in GH generation, manufacturing of electrolysers and green ammonia. The overall target of this scheme is to produce 5 MMTPA GH by 2030, reduction of 50 MMTPA of CO_2 emissions and creating over 6 lakh jobs[280].
Tax incentives	USA	Inflation Reduction Act (IRA)	• IRA is shaping new eligibility guidelines for clean hydrogen projects, determining the conditions for federal tax credits and subsidies. • Clean Hydrogen Production Tax Credit (45V) provides up to maximum of USD3 per kg of clean hydrogen produced with a carbon intensity threshold of 0.45 kg CO_2e per kg H_2. This incentive can be combined with electricity production credit (45Y) which provides incentive up to USD30 per MWh of electricity consumed by hydrogen producers[281]. • Investment Tax Credit (ITC) up to a 30 per cent can be claimed by projects that produce clean hydrogen[282]. • Advanced Energy Project Credit (48C) is the expansion of 30 per cent investment tax credit for manufacturing projects, including those producing electrolysers, hydrogen infrastructure[283].
	Canada	Clean Hydrogen Investment Tax Credit (CHITC)	The credit applies from March 2023 to 2035. The CHITC is expected to provide USD17.7 billion in tax incentive support to the sector by 2035. The levels of support may vary from 15 per cent to 40 per cent of eligible project costs, based on carbon intensity of the process up to 4 kg CO_2e per kg H_2[284].
	Australia	Hydrogen Production Tax Incentive	This incentive was launched in February 2025, which is expected to provide operational expenditure at the rate of USD1.3 per kg for 10 years between 2027 to 2040[285].

279 Press Release MNRE, Press Information Bureau, August 2023 (Press Release: Press Information Bureau). Accessed on 18 March 2025
280 Press Release MNRE, Press Information Bureau, August 2023 (Press Release: Press Information Bureau). Accessed on 18 March 2025
281 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025
282 Financial Incentives for Hydrogen and Fuel Cell Projects, U.S. Department of Energy, (Financial Incentives for Hydrogen and Fuel Cell Projects | Department of Energy). Accessed on 15 March 2025
283 Financial Incentives for Hydrogen and Fuel Cell Projects, U.S. Department of Energy, (Financial Incentives for Hydrogen and Fuel Cell Projects | Department of Energy). Accessed on 15 March 2025
284 Hydrogen Strategy of Canada: Progress Report, Government of Canada, May 2024 (Hydrogen Strategy for Canada: Progress Report - Natural Resources Canada). Accessed on 25 March 2025
285 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025

Global green hydrogen standards and certifications are in an early stage of development, with key organisations working to harmonise safety and performance requirements

Green hydrogen standards and certifications are fundamental towards ensuring safety, reliability, traceability and interoperability across the entire value chain, encompassing production, storage, transportation, and end-use applications. Given hydrogen's flammable nature and the technical complexity of its handling, robust standards are indispensable for mitigating operational risks and safeguarding infrastructure and human health. They also provide a common technical framework that enables compatibility of equipment and processes, thereby facilitating international trade and supporting large-scale deployment. At present, global standards remain in an early stage of development, with international bodies such as International Organisation for Standardisation (ISO) and International Electrotechnical Commission (IEC), alongside regional and national agencies, working to establish guidelines. While progress has been made in certain jurisdictions, the absence of a harmonised global framework limits consistency and scalability. Greater coordination among governments, industry stakeholders, and standard-setting organisations will be essential to develop unified protocols that underpin safety, performance, and innovation. Annexure 5 provides some indicative international hydrogen safety standards across the GH value chain.

GH certification schemes are equally critical as they validate that hydrogen is produced in accordance with recognised environmental performance criteria and greenhouse gas emission thresholds. These schemes enhance transparency, build market confidence, and enable cross-border trade in hydrogen and its derivatives. Several initiatives, such as the EU's Renewable Fuels of Non-Biological Origin (RFNBO), CertifHy, and emerging frameworks in Japan, United States, and India, represent important steps towards establishing credible certification systems. However, the coexistence of multiple schemes presents real challenges. Divergent emission thresholds, varying lifecycle assessment methodologies, and fragmented tracking systems create barriers to interoperability and increase compliance costs for producers. Furthermore, some national schemes, lack mandates for additionality, temporal matching, and geographic correlation of renewable energy, which are considered essential under global frameworks. This lack of mutual recognition between certification frameworks risks market fragmentation and limits liquidity, making international trade more complex. To support the development of a global hydrogen economy, countries need to work towards internationally accepted methodologies, harmonised definitions, and mutual recognition agreements. Such alignment is likely to ensure that GH can be traded seamlessly across borders, fostering investment and accelerating the transition to a low-carbon future. Annexure 5 describes the key certification schemes for green and low carbon hydrogen, developed by various countries.

A six-point strategic framework is suggested for policy formulation

A six-point strategic framework is proposed to help countries design a holistic GH policy roadmap, integrating key elements such as projects, infrastructure, local manufacturing, and competitive financing as depicted in Figure 26[(286)].

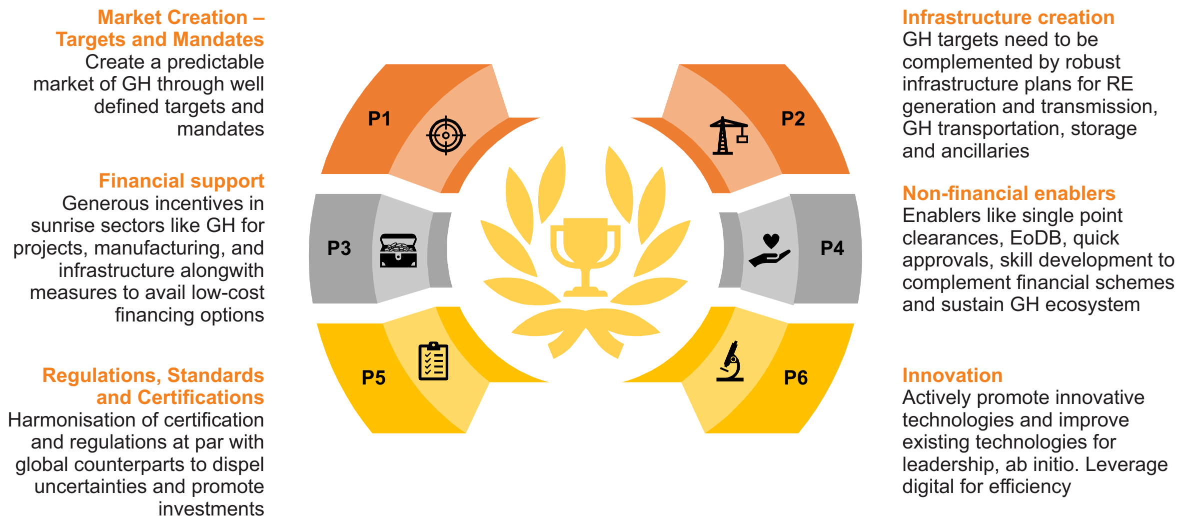


Figure 26: Six-point strategic framework for policy formulation

The proposed policy framework must be reinforced with enabling legislation to ensure effective implementation of guidelines for building a holistic GH ecosystem at competitive cost. This framework integrates physical infrastructure with critical enablers such as innovation and workforce skilling, essential for the success of a local GH ecosystem.

Holistic implementation of the six-point strategic framework can catalyse domestic GH development. This approach might stimulate local manufacturing and infrastructure, create project-based construction jobs, permanent roles in production, and future opportunities in research and innovation, enabling countries to progress from project announcements to FID readiness.

286 Analysis for this report, 2025

Each stakeholder must play a pivotal role in accelerating the GH ecosystem. Governments, IFIs, and industry bodies must align and coordinate efforts for maximum impact. Figure 27 outlines the roles and responsibilities for some key stakeholders of the GH ecosystem.

Policy Makers	• Develop clear GH and RE strategy, policies, mandates, and incentives • Establish standards, regulations, processes, and market design (e.g., carbon markets) • Plan infrastructure for power evacuation, water supply, ports, hubs, and pipelines • Encourage R&D, skilling
Developers/ Suppliers	• Drive innovation in round the clock RE, identifying cost improvement levers and leverage digital • Collaborate with policy makers, financiers and academia in sector evolution • Align investment horizons with evolving technology types • Create conducive environment for deep tech R&D and innovation
Financiers/ MDBs	• Develop project risk assessment frameworks • Design financial products to derisk investments (eg, credit guarantees, insurance) • Create financing solutions for R&D and commercial deployment of green hydrogen • Explore blended-finance options in partnership with multilateral development banks and key global intermediary organisations to help lower overall financing costs
Consumers	• Embed green hydrogen as a core aspect of decarbonisation strategy • Deploy pilots
Academia	• Encourage R&D, skilling • Deploy pilots, share lessons • Inform policy decisions

Figure 27: Role of stakeholders in accelerating the GH ecosystem

IX. ISA tools for strategic decision making

ISA's initiatives for member countries, particularly the GH tools hosted on the GHIC platform are designed to support policymakers and organisations in addressing critical questions related to strategy and planning for green hydrogen projects. The aim is to provide a suite of tools which may allow countries and investors to assess a countries readiness for GH ecosystem, evaluate low low carbon hydrogen pathways, understand cost drivers, evaluate project risks, etc. These tools can also assist IFIs, private equity firms, and venture capitalists by enabling comparative country assessments through customisable, weighted parameters aligned with specific investment criteria.

Specific tool of ISA for GH

Country readiness assessment tool[287]

Key questions answered:

- Is the country ready to host large-scale GH projects?
- Is there sufficient infrastructure available? What gaps need to be fulfilled?'
- How strong are the RE resources in the country, especially high-quality baseload RE resources?
- Are the policies holistic enough (as per 6-point policy recommendation)?
- Does the country have domestic demand to absorb the GH produced?

Project risk assessment tool[288]

Key questions answered:

- What are the overall risks associated with projects in the country?
- Does the GH project have sufficient and firm domestic and global offtakers?
- How ready are the sources of funds for the GH project?
- Does the project have critical infrastructure, or approvals (like power transmission, water supply, contiguous land) in place?
- What is the status of pre-construction, construction and post-construction permits and approvals?

GH cost assessment tool[289]

Key questions answered:

- What is the LCOH under different assumptions and scenarios for power cost, financing cost, financing structure, equipment cost, equipment efficiency, etc?
- Which configurations for RE like solar, wind, battery storage and any other RE source help optimise costs?
- How profitable would the project be?

287 Country readiness assessment tool, ISA, ACEF 2025, Manila, June 2025 (Country Readiness Tool - Green Hydrogen Innovation Centre | International Solar Alliance). Accessed on 03 November 2025

288 Project risk assessment tool, ISA, ACEF 2025, Manila, June 2025 (ISA project risk assessment tool - Green Hydrogen Innovation Centre | International Solar Alliance). Accessed on 03 November 2025

289 Green hydrogen cost assessment tool, ISA, ACEF 2025, Manila, June 2025 (Green hydrogen cost assessment tool - Green Hydrogen Innovation Centre | International Solar Alliance). Accessed on 03 November 2025

Specific tool of ISA for GH	
	<u>Hydrogen carbon accounting tool</u>[290] Key questions answered: • What is the quantum of emission produced per kg of hydrogen given the choice of feedstock (like coal, natural gas, biomass or electricity) and pathway (like gasification, electrolysis etc)? • What are the types of emissions (like methane, NOx, CO_2) emitted under scope 1 and 2?
	<u>GH hub tool</u> *<u>[upcoming]</u>* Key questions to be answered: • What are the critical parameters and frameworks to identify the type of hub for a country (like import, export, domestic or hybrid)? For a given type of hub, how can an appropriate location be shortlisted and what are the gaps in such location? • What are the key stakeholder considerations for the proposed hub location?

290 Hydrogen carbon accounting tool, ISA, ACEF 2025, Manila, June 2025 (Hydrogen carbon accounting tool - Green Hydrogen Innovation Centre | International Solar Alliance). Accessed on 03 November 2025


Annexures

Annexure 1: Mature water electrolysis technologies

Alkaline and PEM electrolysers are commercially available and both stand at a high technology readiness level (TRL 9), though continued policy and performance improvements are required to compete with unabated fossil-based hydrogen[291]. SOECs are approaching commercialisation with TRL 8, evidenced by multi-megawatt deployments and expanding manufacturing lines in Europe and the United States, with further industrial-scale capacity expected online in the near term. AEM electrolysers are earlier in their maturation (TRL 7), with products available at kilowatt scale and plans for factory-led scaling, signalling momentum across the technology landscape despite differing degrees of market readiness. As per IRENA, the operating conditions and the characteristics of the components of four key electrolysers are summarised in Table 23[(292,293)].

Table 23: Characteristics of the key water electrolysers

Parameters	AWE	PEM	SOEC	AEM
Operating temperature	70-90 °C	50-80 °C	700-850 °C	40-60 °C
Operating pressure	1-30 bar	< 70 bar	1 bar	< 35 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 mol/L	PFSA membranes	Yttria-stabilized Zirconia (YSZ)	DVB polymer support with KOH or $NaHCO_3$ 1 mol/L
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	Perovskite-type (e.g., LSCF, LSM)	High surface area Nickel or NiFeCo alloys
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	Ni/YSZ	High surface area nickel
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Coarse Nickel-mesh or foam	Nickel foam

291 Electrolysers-Energy System, IEA, 2024 (Electrolysers - Energy System - IEA). Accessed on 15 April 2025

292 Green hydrogen cost reduction, IRENA, 2020 (Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal). Accessed on 15 April 2025

293 PFSA = Perfluoroacidsulfonic; PTFE = Polytetrafluoroethylene; ETFE = Ethylene Tetrafluorethylene; PSF = Poly (bisphenol-A sulfone); PSU = Polysulfone; YSZ = Yttria Stabilized Zirconia; DVB = Divinylbenzene; PPS = Polyphenylene sulphide; LSCF = Lanthanum Strontium Cobalt Ferrite; LSM= Lanthanum Strontium Manganite; Ni=Nickel; ZrO2=Zirconia Oxide; NiFeCo=Nickel Iron Cobalt

Parameters	AWE	PEM	SOEC	AEM
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	None	Nickel foam or carbon cloth
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	None	Nickel-coated stainless steel
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Cobalt-coated stainless steel	Nickel-coated Stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	Ceramic glass	PTFE, Silicon

i) Alkaline Water Electrolysis

AWE is a mature technology with technology readiness level 9 (TRL9) which has been in use in the chlor- alkali industry since more than 100 years[294]. However, its application in hydrogen production has only recently been explored and commercialised. This technology offers several advantages over other methods due to its simple design, ease of operation at moderate temperatures, and the use of low-cost catalysts such as nickel.

Nevertheless, AWE operates at relatively lower conversion efficiencies (60-80 per cent) due to the use of thicker ion-permeable membranes and operation at low current densities[295]. Recent innovations have led to improvements in the efficiencies of AWE electrolysers.

- A 2.2 GW scale AWE electrolyser is being installed for one of the world's largest GH projects at NEOM in Saudi Arabia, with production set to commence by 2026[296]. The AWE technology provided by Thyssenkrupp, claims a high overall stack efficiency of around 82 per cent[297].
- **Innovations in AWE technology:**
    - High current densities up to 2 A/cm^2, 400 per cent higher than traditional AWE[298]
    - Zero-gap electrolyser design for improved stack efficiency by 70-95 per cent[299]

ii) Proton Exchange Membrane

PEM is an advanced technology with a TRL9, having been developed to address the limitations of alkaline electrolysis[300]. Its application in hydrogen production has been extensively explored and commercialised in recent years.

294 Electrolysers-Energy System, IEA, 2024 (Electrolysers - Energy System - IEA). Accessed on 15 April 2025
295 Royal Society of Chemistry review article, 2024 (Recent advancements in catalyst coated membranes for water electrolysis: a critical review - Energy Advances (RSC Publishing) DOI:10.1039/D4YA00143E). Accessed on 10 April 2025
296 Press release of Thyssenkrupp and Air Products, December 2021 (211213_thyssenkrupp x Air Products press release_One of the largest GH project in the world). Accessed on 10 April 2025
297 Large scale Modular AWE Technology for Green Hydrogen plants, Thyssenkrupp, 2021 (PowerPoint Presentation). Accessed on 15 April 2025
298 Verdagy article, 2025 (20250311-Dynamic-AWE-White-Paper.pdf). Accessed on 10 April 2025
299 Verdagy article, 2025 (20250311-Dynamic-AWE-White-Paper.pdf). Accessed on 10 April 2025
300 Electrolysers-Energy System, IEA, 2024 (Electrolysers - Energy System - IEA). Accessed on 15 April 2025

This technology offers several advantages over other methods due to its high current density, greater energy efficiency, compact design, and the ability to operate at high pressures. PEM electrolysis operates at higher efficiencies (80-90 per cent) compared to alkaline water electrolysis, primarily due to the use of solid polymer electrolytes that allow for thinner perfluoro sulfonic acid membranes and higher current densities [(301),(302)]. Recent innovations have further improved the efficiencies and reduced the costs of PEM electrolysers.

- Siemens Energy and BASF have collaborated with Rhineland-Palatinate state government to install a GH project at BASF's Ludwigshafen site in Germany which features a 54 MW PEM electrolyser, with a production target of 8 KTPA of GH[303].
- The project has received substantial governmental support through the Important Project of Common European Interest (IPCEI) Hydrogen initiative, with funding of up to USD134.6 million[304]. The Rhineland-Palatinate state government contributed approximately USD40.4 million, while BASF invested around USD27.1 million[305].
- **Innovations in PEM technology:**
    - Modified catalyst layer with molybdenum oxide in PEM electrolyser enabled GH production from tap water[306].
    - Zero-Iridium PEM catalyst have demonstrated exceptional durability, with over 15,000 hours of operation and a voltage drift of just 4 μV/hr[307].
    - Membranes incorporating hybrid organic-inorganic structures and nanostructured fillers exhibited enhanced proton conductivity, improved chemical resilience, and superior mechanical durability[308].

iii) Solid Oxide Electrolyser

SOEC technology is an advanced method for hydrogen production, with TRL 8, indicating it is nearing commercialisation[309]. SOEC technology has been extensively researched and developed for its high efficiency and ability to operate at elevated temperatures. This technology offers several advantages over other methods due to its high efficiency, ability to utilise waste heat, and the use of solid oxide electrolytes.

SOEC operates at higher efficiencies (up to 90 per cent) compared to alkaline water electrolysis, primarily due to the high operating temperatures (500-850°C) which enhance the electrochemical reactions and reduce energy consumption[310]. Recent innovations have further improved the efficiencies and durability of SOEC systems.

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301 Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal. Abu Dhabi: International Renewable Energy Agency, IRENA, 2020 (Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal). Accessed on 15 April 2025

302 Green Hydrogen from Anion Exchange Membrane Water Electrolysis: A Review of Recent Developments in Critical Materials and Operating Conditions, Sustainable Energy and Fuels, 2020 (https://doi.org/10.1039/c9se01240k). Accessed on 15 April 2025

303 Sustainability Magazine article, March 2025 (Behind Siemens & BASF's World-First Green Hydrogen Project | Sustainability Magazine). Accessed on 15 April 2025

304 Hydrogen projects within the framework of IPCEIs, European Commission (Hydrogen projects within the framework of IPCEIs - European Commission). Accessed on 15 April 2025

305 Sustainability Magazine article, March 2025 (Behind Siemens & BASF's World-First Green Hydrogen Project | Sustainability Magazine). Accessed on 15 April 2025

306 Hydrogen Fuel News, June 2025 (New Catalyst Innovation Enables Green Hydrogen From Tap Water Using PEM Electrolyzers – Hydrogen Fuel News). Accessed on 1 July 2025

307 Hydrogen central article, February 2025 (Calicat Breaks the 2V Barrier with Zero-Iridium PEM Electrolyzer Catalyst - Hydrogen Central). Accessed on 15 April 2025

308 Energy materials article, 2025 (OAE Publishing Inc. - Gold Open Access Journal Publisher). Accessed on 20 June 2025

309 Electrolysers-Energy System, IEA, 2024 (Electrolysers - Energy System - IEA). Accessed on 15 April 2025

310 Hydrogen Production by PEM Water Electrolysis – A Review, Materials Science for Energy Technologies December 2019 (https://doi.org/10.1016/j.mset.2019.03.002). Accessed on 15 April 2025

- A SOEC demonstration plant have been recently installed at the NASA Ames research facility in Mountain View, California, with a capacity of 4 MW electrolyser and producing 0.8 KTPA of GH[311]. The SOEC technology provided by Bloom Energy, claims high efficiency, with a power consumption of approximately 40 kWh per kg of hydrogen at the system level[312].
- Innovations in traditional SOEC technology include development of advanced electrolyte materials and tubular cell stack design with enhanced sealing and thermal robustness, enabling higher current density, reduced hydrogen leakage, and improved durability exceeding 15,000 hours with minimal degradation[313].

iv) Anion Exchange Membrane

AEM water electrolysis is a new technology with a TRL 7, indicating at a demonstration stage[314]. AEM technology has been developed to combine the advantages of both alkaline and PEM electrolysis. This technology offers several advantages over other methods due to its ability to operate at moderate temperatures and low pressures (1-30 bar) and use of low-cost catalysts such as nickel[315].

AEM electrolysis operates at relatively higher conversion efficiencies as compared to AWE, primarily due to the use of thinner ion-permeable membranes and higher current densities. Recent innovations have further improved the efficiencies and durability of AEM electrolysers.

Innovations in AEM technology include multi-layered radical scavenging membrane with ion conductivity up to twice that of conventional membranes improving operational lifespan up to 60,000 hours with 95 per cent efficiency[316].

311 Press release, Bloom Energy, March 2024 (Bloom Energy - Bloom Energy Inc. Signs Agreements with Shell to Investigate Opportunities for Innovative Large-Scale, Renewable Hydrogen Energy Projects). Accessed on 15 April 2025
312 Hydrogen Electrolyzers for a Clean Energy Future, Bloom Energy (An Efficient Electrolyzer for Clean Hydrogen - Bloom Energy). Accessed on 15 April 2025
313 Mitsubishi Heavy Industries Technical Review, March 2025 (Current Development Status of Key Technologies for Solid Oxide Electrolysis Cell,Mitsubishi Heavy Industries Technical Review Vol.62 No.1(2025)). Accessed on 15 April 2025
314 Electrolysers-Energy System, IEA, 2024 (Electrolysers - Energy System - IEA). Accessed on 15 April 2025
315 Green Hydrogen from Anion Exchange Membrane Water Electrolysis: A Review of Recent Developments in Critical Materials and Operating Conditions, Sustainable Energy and Fuels, March 2020 (https://doi.org/10.1039/c9se01240k). Accessed on 15 April 2025
316 Hydrogen Tech world article, February 2024 (Horizon's new Anion Exchange Membrane (AEM) expected to operate for over 60,000 hours | Hydrogen Tech World.com). Accessed on 15 April 2025

Annexure 2: Advanced and emerging technologies of electrolysis

Table 24 summarises the key existing and emerging electrolyser technologies, categorising them into three distinct groups: matured technologies, advanced or new technologies, and emerging technologies[317,318].

Table 24: Overview of mature, advanced and emerging electrolyser technologies

Mature technologies	**Alkaline Water Electrolysis**	**Proton Exchange Membrane**	**Solid Oxide Electrolysis Cell**	**Anion Exchange Membrane**
	• Uses aqueous alkaline (KOH/ NaOH) electrolyte • Low-cost catalyst • Longer lifetime • Operating temperature 60-80°C	• Uses solid membrane electrolyte (PFSA) • High-cost catalyst • Moderate lifetime • Operating temperature 50-80°C	• Uses solid ceramic-based electrolyte • Low-cost catalyst • Stable at high temperatures (500-850°C)	• Ion permeable thin polymeric membranes • Low-cost catalyst • Stable at moderate temperatures
Advanced technologies	**Capillary Fed Electrolysis**	**Protonic Ceramic Electrolysis**	**Decoupled Electrolysis**	**Supercritical Electrolysis**
	• Uses a capillary structure to feed water to the electrodes • Higher efficiency	• Uses proton-conducting ceramic electrolyte • Operates at high temperature (500°C) • High conversion efficiency	• OER and HER occurs at different time intervals • Highly efficient and reduces explosion of gases	• Uses water in its supercritical state • Low energy consumption
Emerging technologies	**Membrane Free electrolysis**	**Nanofluidic / Microfluidic Electrolysis**	**Plasma-Assisted Electrolysis**	**Direct Air Electrolysis**
	• Lacks membrane • H_2 and O_2 mixtures are separated by liquefying O_2 by using cryogenic systems	• Uses tiny microfluidic channels to separate gases • Membrane less design	• Uses plasma electrolyte • Higher H_2 production rates	• Produces H_2 by extracting water directly from the air • Does not require freshwater
	Magnetohydrodynamic Electrolysis			
	• Uses magnetic fields to enhance the electrolysis process • MHD electrolysis improves bubble detachment and overall efficiency			

317 Analysis for this report, 2025
318 PFSA: Perfluorosulfonic Acid, OER: Oxygen evolution reaction, HER: Hydrogen evolution reaction

Advanced water electrolysis technologies

This category is defined for the technologies that have evolved from existing ones through innovation and are currently at the prototype stage.

Capillary Fed Electrolysis (CFE)

Capillary-Fed Electrolysis (CFE), developed by Hysata, is an emerging technology that leverages capillary action through specialised membranes to minimise bubble formation at the electrode–fluid interface during electrolysis[319]. This significantly reduces energy losses and enhances efficiency. Hysata reports that CFE achieves an efficiency of approximately 95 per cent (on a Higher Heating Value basis), markedly higher than conventional technologies, which typically operate around 75 per cent[320]. The company plans to commission a 100 MW/year manufacturing facility in Port Kembla, Australia in 2025, offering 5 MW stack modules, with future expansion plans to scale up to gigawatt-level production[321]. Hysata has also recently announced their new agreement with ACWA Power to deliver commercial scale demonstrations of its high-efficiency CFE technology in Saudi Arabia[322].

ii) Protonic Ceramic Electrolysis (PCEC)

PCECs utilise proton-conducting ceramics, specifically a barium cerium zirconium oxide co-doped with ytterbium and yttrium (BCZYYb) electrolyte layer, to perform high-temperature water splitting, typically operating at around 500°C[323]. This technology offers high efficiency and durability. PCEC technology is currently at the prototype stage and has been validated in laboratory settings. While specific large-scale projects are still in development, ongoing research and pilot projects are focusing on scaling up PCEC technology for commercial use. The US DOE’s Fuel Cell Technologies Office (FCTO) has funded a three-year project with a budget of USD1.5 million to advance the development of PCEC technology, which has the potential to integrate renewable electricity and excess process heat for cost-effective hydrogen production[324].

iii) Decoupled Water Electrolysis (DWE)

Decoupled water electrolysis technologies separate the production of hydrogen and oxygen into different steps rather than generating both gases simultaneously, as in conventional electrolysis. This means the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) occurs at different times, and not simultaneously. This approach improves safety by avoiding the risk of explosive gas mixtures and can reduce costs by eliminating the need for expensive membranes. One well-known example is E-TAC (Electrochemical–Thermally Activated Chemical) water splitting, developed by H2PRO in Israel[325,326]. In E-TAC, hydrogen is produced electrochemically at room temperature, while oxygen is generated later through a heat-driven chemical reaction. This method achieves comparatively higher efficiency and allows hydrogen to be produced at high pressures without compressors, making it suitable for industrial applications and RE integration.

Beyond E-TAC, other decoupled electrolysis methods use redox mediators to store and transfer energy between the two steps. These mediators can be soluble compounds like phosphomolybdic acid or silico-tungstic acid, or solid-state materials such as nickel hydroxide. The process typically involves two stages: in the first, electricity drives one half-reaction (e.g., hydrogen evolution) while the mediator changes its oxidation state; in the second, the mediator reacts chemically to complete the other half-reaction (e.g., oxygen evolution). Some systems even resemble batteries, combining energy storage and electrolysis in one device. These designs allow flexible operation under variable renewable power,

319 Hysata article, December 2022 (Hysata delivers the step-change needed in electrolysis – Hysata). Accessed on 25 September 2025

320 Hysata article, December 2022 (Hysata delivers the step-change needed in electrolysis – Hysata). Accessed on 25 September 2025

321 Hysata article, 14 August 2023 (Hysata opens new electrolyser manufacturing facility in Port Kembla with $21m vote of confidence from Australian Government – Hysata). Accessed on 25 September 2025

322 Hysata news article, February 2025 (Hysata and ACWA Power sign game-changing deal to unlock GH in the Kingdom of Saudi Arabia and the Gulf with world-leading high efficiency electrolysers – Hysata). Accessed on 17 April 2025

323 Colorado School of Mines article (Intermediate-Temperature Water Splitting Using Protonic Ceramic Electrolysis Cells - Advanced Energy Systems Group). Accessed on 17 April 2025

324 Colorado School of Mines article (Intermediate-Temperature Water Splitting Using Protonic Ceramic Electrolysis Cells - Advanced Energy Systems Group). Accessed on 17 April 2025

325 Nature Energy article, September 2019 (Decoupled hydrogen and oxygen evolution by a two-step electrochemical–chemical cycle for efficient overall water splitting | Nature Energy). Accessed on 25 September 2025

326 H2PRO website (Home | H2Pro). Accessed on 25 September 2025

reduce reliance on costly membranes, and enable modular, scalable systems. These are however in laboratory or early demonstration stages.

Decoupled electrolysis is also being currently developed by Clyde Hydrogen Systems, a UK based company, though there is limited visibility as of now on the exact methodology used or manufacturing plans[327].

iv) Supercritical Water Electrolysis (SWE)

Supercritical water electrolysis is an advanced hydrogen production method that operates above water's critical point which is 374 °C and 220 bar where water becomes a single-phase fluid with unique characteristics, which combines the properties related to both gaseous phase (steam) and liquid phase (water). In the supercritical state, water exhibits high ionic conductivity, enhanced diffusion, and a higher dissociation constant, which significantly improves reaction kinetics, reduces internal resistance and offers higher miscibility to hydrogen and oxygen gases, reducing the creation of bubbles. The reversible cell voltage decreases with temperature, lowering electrical energy demand and drastically improving efficiency. Pressurising steam, rather than hydrogen, reduced the energy demand even further and minimises the need for hydrogen compressors.

Supercritical Solutions, a UK-based company, is pioneering a membrane-less electrolyser that uses this principle to deliver high-pressure hydrogen (up to 220 bar) directly, eliminating the need for costly compressors. Their system achieves 99 per cent HHV stack efficiency, uses no PFAS or iridium, and promises a 21 per cent lower LCOH compared to PEM technology[328]. By pressurising water before electrolysis, rather than compressing hydrogen afterwards, the process simplifies plant design and reduces operational risk. This makes it highly attractive for industries like ammonia, methanol, and refining, which require hydrogen at pressures between 50 and 200 bar. Supercritical Solutions in partnership with Beam Suntory, have recently demonstrated a trial as a part of the 'WhiskHy' project, using their proprietary electrolyser to produce and store hydrogen on-site at Suntory's Yamazaki distillery in Japan[329]. This trial used 100 per cent hydrogen in direct-fired distillation for the first time in whisky production.

The X-SEED project, funded by the EU, is also developing a supercritical alkaline membrane-less electrolyser. Its goal is to validate a short stack operating at 374 °C and 220 bar, producing high-purity hydrogen (greater than 99 per cent by volume) with energy demand below 42 kWh/kg in HHV terms and costs in the range of EUR2–3/kg[330]. X-SEED integrates waste heat and wastewater into its design, enhancing sustainability and circularity. The project also focuses on advanced catalysts with minimal critical raw material content (less than 0.3 mg/W) and aims to reach TRL 4 by 2027, paving the way for industrial-scale deployment[331].

While supercritical water electrolysis introduces engineering complexities, especially with regards to high pressure and temperature requirements, these challenges present opportunities for innovation rather than barriers. Operating at high temperature and pressure requires robust pressure vessels and advanced thermal management, but these are well within the capabilities of modern materials and design standards used in power, nuclear and chemical industries. Corrosion resistance and sealing technologies are improving rapidly, enabling long-term durability even in harsh alkaline environments. Scaling from prototypes to multi-megawatt systems is expected to demand careful integration of safety and efficiency measures, yet this also opens the door for modular designs and hybrid systems that leverage waste heat. With strong R&D momentum and growing industrial interest, these hurdles are likely to be overcome, positioning supercritical electrolysis as a commercially viable and highly efficient solution for large-scale GH production.

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327 Technology, Clyde Hydrogen (Technology – Clyde Hydrogen). Accessed on 17 April 2025

328 Supercritical Solutions website (Supercritical | Solutions). Accessed on 25 September 2025

329 Supercritical article, April 2024 (Supercritical | Firing Up Sustainability: The WhiskHy Breakthrough). Accessed on 17 April 2025

330 Supercritical Electrolyzer development for H2 Production, Pau Bosch-Jimenez, Marian Garcia, Sandra Martínez-Crespiera, Giovanna Massobrio, Anna Ramunni, Anna Testolin, Francesco Cartasegna, Paolo Costa, Marco Miola, Arash Nemati, Henrik Lund Frandsen, EFCF, Lucerne, Switzerland, 1-4 July 2025 (EFCF-2025_Paper_B1301_11031_Supercritical_electrolyzer_Bosch-Jimen.pdf)

331 Supercritical Electrolyzer development for H2 Production, Pau Bosch-Jimenez, Marian Garcia, Sandra Martínez-Crespiera, Giovanna Massobrio, Anna Ramunni, Anna Testolin, Francesco Cartasegna, Paolo Costa, Marco Miola, Arash Nemati, Henrik Lund Frandsen, EFCF, Lucerne, Switzerland, 1-4 July 2025 (EFCF-2025_Paper_B1301_11031_Supercritical_electrolyzer_Bosch-Jimen.pdf)

Emerging water electrolysis technologies

i) Membrane Free Electrolysis (MFE)

Membrane-free electrolysis is an innovative alternative to conventional water electrolysis, which typically relies on costly and fragile membranes to separate hydrogen and oxygen gases. By removing the membrane, these systems aim to reduce capital costs, simplify design, and improve durability. Instead of physical separation within the cell, membrane-free systems employ alternative strategies such as cryogenic separation, fluid dynamics, or sequential gas evolution to ensure product purity and safety. Lack of membranes also remove the potential concerns of toxic PFAS chemicals, which is a concern during decommissioning or the end of stack life.

One notable example is Clean Power Hydrogen PLC (CPH2) in UK, which has developed a patented Membrane-Free Electrolyser (MFE). This system uses an alkaline electrolyte without a membrane and separates hydrogen and oxygen downstream using dryer and cryogenic separation techniques. The approach eliminates the need for expensive polymer membranes and precious metal catalysts, offering high-purity gases and improved operational resilience. As per CPH2, the stack efficiency of MFE electrolysers can reach upto 78 to 82 per cent. The cryogenic separation technology ensures the availability of highly pure hydrogen (99.999 per cent by volume) and oxygen (99.5 per cent by volume), with the latter exceeding even medical grade specifications[332].

It may be noted that E-TAC technology developed by H2PRO is also an example of membrane-less electrolysis technology (explained previously in this report in Chapter V).

These approaches share a common goal: to overcome the limitations of traditional electrolysers by improving cost-effectiveness, scalability, and compatibility with RE. While most technologies are still in early commercialisation or demonstration phases, they represent a promising pathway for accelerating the adoption of GH.

ii) Nanofluidic and Microfluidic Water Electrolysis (NMWE)

NMWE applies the unique properties of fluids at micro and nano scales to split water into hydrogen and oxygen. NMWE use tiny microfluidic channels, allowing precise control over fluid dynamics and improving interaction between the electrolyte and electrodes. They feature a membrane-less design, relying on fluidic forces to separate gases within the channels[333].

Currently, these technologies are in the research and development phase. There have been several demonstrations of these technologies in academic and research settings. For instance, researchers at École Polytechnique Fédérale de Lausanne (EPFL), Switzerland developed a microfluidic electrolyser that has exhibited high throughput production of hydrogen with high purity[334]. However, large-scale commercial deployment remains in its early stages.

iii) Plasma-Assisted Water Electrolysis (PAWE)

In PAWE, a high voltage is applied to the electrolyte solution to create plasma. This plasma electrolyte generates reactive species that help break down water molecules into hydrogen and oxygen[335]. The presence of plasma significantly boosts reaction rates, resulting in hydrogen production rates up to 3.9 times higher than traditional methods like alkaline electrolysis[336]. Although still in the research and development phase, PAWE has shown promising results in laboratory settings, with ongoing efforts to scale up for industrial applications.

332 CPH2 article, July 2025 (CPH2-White-Paper-July-2025-Membrane-Free-Electrolysis-for-Low-Cost-Hydrogen-FINAL-Rev.1.pdf). Accessed on 25 September 2025

333 RSC research article, March 2021 (A membrane-less electrolyzer with porous walls for high throughput and pure hydrogen production - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D1SE00255D). Accessed on 17 April 2025

334 RSC research article, March 2021 (A membrane-less electrolyzer with porous walls for high throughput and pure hydrogen production - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D1SE00255D). Accessed on 17 April 2025

335 MDPI research article, October 2022 (Overview of the Hydrogen Production by Plasma-Driven Solution Electrolysis). Accessed on 18 April 2025

336 AZO Materials news article, October 2022 (Plasma-driven Solution Electrolysis for Hydrogen Production). Accessed on 18 April 2025

iv) Direct Air Water Electrolysis (DAWE)

DAWE innovatively produces hydrogen by extracting water directly from the air. The system uses a hygroscopic material to absorb moisture, even in low-humidity environments[337]. Once absorbed, the water undergoes standard electrolysis to split into hydrogen and oxygen gases. Unlike traditional methods, DAE doesn't require freshwater, making it ideal for arid regions. Although still in the research phase, it has shown promising results. For instance, a prototype from the University of Melbourne can produce significant hydrogen even in low-humidity conditions[338].

v) Magnetohydrodynamic Water Electrolysis (MHD)

MHD is an advanced technique that utilises magnetic fields to enhance the electrolysis process. By applying magnetic fields, MHD electrolysis improves bubble detachment and overall efficiency[339]. Reduced bubble growth time increases the rate of hydrogen production, making MHD water electrolysis more efficient and faster than traditional methods. This technique is still primarily in the research phase, with ongoing studies exploring its potential applications and scalability.

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337 Revolution.aero news article, September 2022 (Hydrogen from humidity: World first direct air electrolyser | Revolution.aero). Accessed on 18 April 2025

338 The University of Melbourne article, September 2022 (A New Device Creates Hydrogen from Air | Climate Hub). Accessed on 18 April 2025

339 Surface Engineering and Applied Electrochemistry, April 2024 (Magnetohydrodynamics with Application to the Study of Electrolysis and Turbulence | Surface Engineering and Applied Electrochemistry). Accessed on 18 April 2025

Annexure 3: Green hydrogen storage technologies

GH storage is vital to the hydrogen value chain. Owing to its low volumetric energy density, hydrogen must be compressed to high pressures or liquefied at cryogenic temperatures for practical storage, both demanding advanced technology and materials. Key storage methods such as compressed gas, liquid hydrogen, and material-based solutions are essential for balancing supply and demand, ensuring safety, and improving efficiency. By enabling safe and efficient handling, storage solutions support hydrogen transportation and utilisation across diverse sectors, including mobility, industry, and power generation.

The technological evaluation of using hydrogen based energy storage solutions for LDES has been performed in ISA's report on "Development of an implementation roadmap and identification of project pipelines for scaling solar-integrated LDES technologies in developing nations" released in ACEF 2025 in Manila, Philippines[340].

Storage of gaseous hydrogen

i) Compressed hydrogen tanks

Compressed hydrogen storage is a mature technology which can store large amount of hydrogen within a small volume. However, this type of storage requires strict safety measures to prevent leakage and explosions. These tanks are made from advanced composite materials to safely withstand high pressures. The outer layers, often made from glass or carbon fibre, provide the necessary strength to contain hydrogen at pressures up to 700 bar, while inner liners of metal or polymer ensure a gas-tight barrier.

Compressed hydrogen storage tanks

- Compressed hydrogen storage tanks are categorised into four types: Type I, Type II, Type III, and Type IV based on their materials, construction, and pressure ratings[341].
- Type I tanks are made up of metal (steel or aluminium) with pressure range up to 200 bar, used for industrial gas storage, backup power systems, and stationary hydrogen applications.
- Type II tanks are made up of metal liners wrapped with composite fibres with pressure range up to 250 bar and usage in hydrogen-powered forklifts in warehouses.
- Type III tanks are made up of metal liners with fully wrapped composite. Pressure ranges from 350-700 bar suitable for automotive and aerospace applications.
- Type IV tanks, with plastic liners and outer composite cover, with pressure range up to 700 bar. These are the most advanced and commonly used, especially in hydrogen fuel cell electric vehicles (FCEV)[342].
- The volume range of compressed hydrogen storage tanks varies by application and type. In hydrogen fuel cell vehicles, tanks typically range from 40 to 200 litres[343]. For larger stationary storage systems, volumes can exceed 1,000 litres.

340 Development of an implementation roadmap and identification of project pipelines for scaling solar-integrated Long Duration Energy Storage (LDES) technologies in developing nations, ISA, June 2025 (1752568431ISA_ADB_ACEF_2025_LDES_Full_Report_06.06.pdf). Accessed on 29 September 2025

341 Piping Technology article (Hydrogen Tanks Storage And Hydrogen Tank Sizes: A Comprehensive Guide - Piping Technology System). Accessed on 20 April 2025

342 U.S. DOE article, U.S. Department of Energy, March 2017 (Hydrogen Storage). Accessed on 20 April 2025

343 U.S. DOE article, U.S. Department of Energy, March 2017 (Hydrogen Storage). Accessed on 20 April 2025

With further innovations, another category has been introduced-the Type V tanks, which is currently under research and development stage. Type V tanks are constructed entirely from composite materials without any metal or polymer liner, making them the lightest among all hydrogen storage tank types. The National Composites Centre (NCC) in the UK has developed a Type V tank demonstrator, achieving significant weight savings for aerospace applications[344]. Companies like Virgin Orbit and RocketLab are exploring these tanks for space propulsion[345].

ii) Metal hydride tanks

Metal hydride tanks are advanced hydrogen storage solutions that utilise metal alloys like magnesium hydride (MgH_2) and lithium hydride (LiH) to absorb and release hydrogen[346]. These tanks offer high storage density and safe, low-pressure operation. Hydrogen is stored by chemically bonding with metal alloys to form metal hydrides, and heat is applied to release the hydrogen gas when needed. Although still in the early stages of commercialisation, metal hydride tanks are used in specific applications such as industrial forklifts, where their safety and efficiency are beneficial. Broader adoption is developing, with ongoing research to improve cost-effectiveness and performance. Metal hydride storage systems are used for stationary, marine, transport sectors, and back-up power systems integrated with microgrids[347,348].

iii) Geological hydrogen storage

Geological storage of hydrogen involves storing hydrogen gas in underground formations, such as rock caverns and salt caverns. This method is considered economical and safe for large-scale hydrogen storage.

Salt caverns are created by injecting water into underground salt deposits to dissolve the salt, forming large, hollow spaces. These caverns are ideal for hydrogen storage due to their excellent sealing properties and ability to withstand high pressures.

Salt caverns

- Currently, there are four significant hydrogen storage sites in salt caverns used as strategic reserves for hydrocarbon refining[349].
- Teesside in the UK, operated by Sabic Petroleum since 1972 with a capacity of 210 million litres.
- Moss Bluff in the USA, operated by Parxair since 2007 with a capacity of 566 million litres.
- Clemens in the USA, operated by Conoco Phillips since 1983 with a capacity of 580 million litres.
- Spindletop in the USA with a capacity of 906 million litres.

Rock caverns, typically constructed in hard rock formations, are another option for hydrogen storage. These caverns are engineered to store gases under high pressure and are used in regions where suitable salt formations are not available. USA has constructed several hard rock caverns for various storage purposes, including hydrogen[350].

344 Composite World article, December 2021 (NCC's all-composite Type V tank demonstrates future composite space tank technology | CompositesWorld). Accessed on 20 April 2025
345 Composite World article, December 2021 (NCC's all-composite Type V tank demonstrates future composite space tank technology | CompositesWorld). Accessed on 20 April 2025
346 Piping Technology article (Hydrogen Tanks Storage And Hydrogen Tank Sizes: A Comprehensive Guide - Piping Technology System). Accessed on 20 April 2025
347 Friendly Hydrogen Storage, Methydor (Methydor – Friendly Hydrogen Storage). Accessed on 20 April 2025
348 GKN hydrogen solutions (www.gknhydrogen.com/technology-2). Accessed on 20 April 2025
349 Discover the Greentech article, 2025 (Hydrogen storage in salt caverns). Accessed on 20 April 2025
350 Hydrogen Storage in Salt and Hard Rock Caverns, Lane power & energy solutions, Inc., 2022 (Hydrogen Storage in Salt and Hard Rock Caverns). Accessed on 20 April 2025

Storage of liquid hydrogen

i) Cryogenic tanks

Cryogenic tanks are specialised containers designed to store liquid hydrogen at extremely low temperatures, around -252.8°C. These tanks are typically made from high-strength materials like stainless steel and are insulated to minimise heat transfer and prevent the hydrogen from evaporating. Cryogenic liquid hydrogen storage tanks have played crucial role in supporting large-scale hydrogen projects.

Example

- The Tanegashima Space Centre in Japan, operated by Kawasaki Heavy Industries, have developed Japan's largest liquid hydrogen storage tank with a capacity of 2400 cubic metres, for its application as rocket fuel[351].
- The largest cryogenic tank for liquid hydrogen storage is being developed and announced by Samsung C&T. This tank has a capacity of 40,000 cubic metres, capable of storing up to 2,800 tons of liquid hydrogen at cryogenic temperatures as low as -252.8°C, enough to refuel over 500,000 hydrogen cars[352].

ii) Liquid Organic Hydrogen Carriers (LOHC)

LOHCs are organic compounds that can absorb and release hydrogen through chemical reactions. They store hydrogen by chemically bonding it to a liquid carrier, which can be transported and stored under ambient conditions. When hydrogen is needed, it is released from the carrier through a dehydrogenation process. LOHCs are less flammable and easier to handle than compressed or liquid hydrogen. They are used in stationary energy storage systems, hydrogen refuelling stations, and for long-distance hydrogen transport.

Evos, Hydrogenious LOHC technologies, and the Port of Amsterdam are collaborating to develop large-scale hydrogen import facilities[353]. These facilities may include a LOHC dehydrogenation plant with a final release capacity of up to 100-500 tonnes of hydrogen per day.

351 Kawasaki Heavy Industries article, February 2017 (Japan's Largest Liquid Hydrogen Storage Tank. The Intricacies of Keeping Hydrogen at -253°C | ANSWERS | Kawasaki's Solutions for the Future | Kawasaki Heavy Industries). Accessed on 20 April 2025

352 The Korea economic daily global edition article, November 2023 (Samsung C&T to build world's largest liquid hydrogen tank - KED Global). Accessed on 20 April 2025

353 Joint Press Release, October 2022 (221025_Joint_Press_Release_H2A_-MoU_FINAL_EN.pdf).

Annexure 4: Green hydrogen strategies and roadmaps

Globally, countries have demonstrated strong commitment to hydrogen development, with approximately 65 national hydrogen strategies and roadmaps published to date as discussed in Chapter 8. These strategies outline diverse approaches to production, infrastructure, and market creation, reflecting regional priorities and resource endowments.

Table 25 provides key insights from the published hydrogen strategies and roadmaps across several countries. The list of countries is not exhaustive and includes nations from various regions. It may be noted that the some of the policy parameters mentioned in this non-exhaustive table might be available with the indicated countries in legislations, policies or roadmaps separate from the hydrogen policy or roadmap.

Table 25: Qualitative analysis of global hydrogen strategies and roadmaps (list is not exhaustive)

Country	Name of strategy or Roadmap	Year of publication	Electrolyser based GH	Infrastructure support	R&D support	Skill development	GH hub support	Financial incentives for GH	Import of GH	Export of GH	Standards and regulations
Argentina	National Strategy for the Development of the Hydrogen Economy[354]	2023	✓	✓	×	×	✓	×	×	✓	✓
Australia	National Hydrogen Strategy[355]	2024	✓	✓	✓	✓	✓	✓	×	✓	✓
Chile	National Green Hydrogen Strategy[356]	2020	✓	✓	✓	✓	✓	✓	×	✓	✓
China	Medium and Long-Term Plan for the Development of Hydrogen Energy Industry[357]	2022	✓	✓	✓	×	×	×	×	×	×
Egypt	National Strategy for Low-Carbon Hydrogen[358]	2024	✓	✓	✓	✓	×	✓	×	✓	✓
EU	EU Hydrogen Strategy[359]	2020	✓	✓	✓	✓	✓	✓	✓	×	✓

354 National Strategy for the Development of the Hydrogen Economy, September 2023 (https://emarr.cancilleria.gob.ar/userfiles/strategie_nationale_de_developpement_de_leconomie_de_lhydrogene_0.pdf). Accessed on 16 June 2025

355 National Hydrogen Strategy 2024, Australian Government, 2024 (https://www.dcceew.gov.au/sites/default/files/documents/national-hydrogen-strategy-2024-summary.pdf). Accessed on 16 June 2025

356 National Green Hydrogen Strategy, Gobierno de Chile, November 2020 (https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf). Accessed on 18 June 2025

357 Hydrogen Industry Development Plan (2021-2035), IEA, September 2025 (https://www.iea.org/policies/16977-hydrogen-industry-development-plan-2021-2035) Accessed on 18 june 2025

358 Egypt's National Low Carbon Hydrogen Strategy – Short Version, European Bank for Reconstruction & Development (EBRD) and Advisian, January 2024 (Egypt Hydrogen Strategy – FULL Version). Accessed on 12 March 2025

359 A hydrogen strategy for a climate-neutral Europe, European Commission, July 2020 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301). Accessed on 16 June 2025

Country	Name of strategy or Roadmap	Year of publication	Electrolyser based GH	Infrastructure support	R&D support	Skill development	GH hub support	Financial incentives for GH	Import of GH	Export of GH	Standards and regulations
Germany	National Hydrogen Strategy[360]	2023	✓	✓	✓	✓	✓	✓	✓	×	✓
India	National Green Hydrogen Mission [361]	2022	✓	✓	✓	✓	✓	✓	×	✓	✓
Japan	Basic Hydrogen Strategy[362]	2023	✓	✓	✓	✓	✓	✓	✓	×	✓
Korea	Hydrogen Economy Roadmap 2040[363]	2019	✓	✓	✓	×	×	✓	✓	×	✓
USA	National Clean Hydrogen Strategy and Roadmap[364]	2023	✓	✓	✓	✓	✓	✓	×	✓	✓

360 The National Hydrogen Strategy, The Federal Government (One-Stop-Shop - Hydrogen | The National Hydrogen Strategy). Accessed on 16 June 2025

361 National Green Hydrogen Mission, Ministry of New and Renewable Energy, Government Of India (National Green Hydrogen Mission Portal of India). Accessed on 30 April 2025

362 Overview of Basic Hydrogen Strategy, June 2023 (https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_4.pdf). Accessed on 20 June 2025

363 Achievements and Vision of Korea's Hydrogen Economy Policy, Ministry of Trade, Industry and Energy (Republic of Korea), 2022 (4b._korea_hydrogen_policy_2022.pdf). Accessed on 18 March 2025

364 U.S. National Clean Hydrogen Strategy, U.S. Department of Energy, 2023 (U.S. National Clean Hydrogen Strategy and Roadmap). Accessed on 16 March 2025

Annexure 5: Global hydrogen standards

This section details the key international and national standards governing hydrogen safety, performance, and interoperability, along with certification schemes that validate environmental compliance and enable transparent trade in green and low-carbon hydrogen. Tables 26 and 27 details the safety standards of GH across the value chain and GH certification schemes across countries.

Table 26: List of international standards related to the hydrogen value chain and safety (list is not exhaustive)

GH value chain	Code	Name of standard
Production	ISO 22734:2019[365]	Hydrogen generators using water electrolysis for industrial, commercial and residential applications
	ISO 26142:2010[366]	Hydrogen detection apparatus: Stationary applications
	ISO/TS 19870:2023[367]	Hydrogen technologies: Methodology for determining the GHG emissions associated with the production, conditioning and transport of hydrogen to consumption gate
	ISO 11114-4:2017[368]	Transportable gas cylinders: Compatibility of cylinder and valve materials with gas contents; Part 4: Test methods for selecting steels resistant to hydrogen embrittlement
Storage and transportation	ASTM G142-98[369]	Standard test method for determination of susceptibility of metals to embrittlement in hydrogen containing environments at high pressure, high temperature, or both
	ISO 21029-1:2018[370]	Cryogenic vessels: Transportable vacuum insulated vessels of not more than 1,000 litres volume – Design, Fabrication, Inspection and Tests

365 ISO 22734:2019 Hydrogen generators using water electrolysis — Industrial, commercial, and residential applications, ISO, 2019 (ISO 22734:2019 - Hydrogen generators using water electrolysis — Industrial, commercial, and residential applications). Accessed on 8 April 2025

366 ISO 26142:2010Hydrogen detection apparatus — Stationary applications, ISO, 2010 (ISO 26142:2010 - Hydrogen detection apparatus — Stationary applications). Accessed on 8 April 2025

367 ISO/TS 19870:2023Hydrogen technologies — Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate, ISO, 2023 (ISO/TS 19870:2023 - Hydrogen technologies — Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate). Accessed on 8 April 2025

368 ISO 11114-4:2017Transportable gas cylinders — Compatibility of cylinder and valve materials with gas contents, ISO, 2017 (ISO 11114-4:2017 - Transportable gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 4: Test methods for selecting steels resistant to hydrogen embrittlement) Accessed on 8 April 2025

369 ASTM G142-98
Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both, ANSI, (ASTM G142-98 - Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both). Accessed on 8 April 2025

370 ISO 21029-1:2018Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume, ISO, 2018 (ISO 21029-1:2018 - Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume — Part 1: Design, fabrication, inspection and tests). Accessed on 8 April 2025

GH value chain	Code	Name of standard
	ISO 11119: Parts 1: 2020[371]	Gas cylinders: Design, construction and testing of refillable composite gas cylinders and tubes; Part 1: Hoop wrapped fibre reinforced composite gas cylinders and tubes up to 450 litre
	ASME STP/PT-0005:2006[372]	Design factor guidelines for high pressure composite hydrogen tanks
End-use application	ISO 13984:1999[373]	Liquid hydrogen: Land vehicle fuelling system interface
	ISO-10380:2012[374]	Minimum requirements for the design, manufacture, testing and installation of corrugated metal hose and metal hose.
General safety	ISO 13850:2015[375]	Standard specifies functional requirements and design principles for the emergency stop function on machinery, independent of the type of energy used.
	ISO 14001: 2015[376]	Environment management system (Fire and explosive safety)
	IEEE 463-2019[377]	Standard for Electrical Safety Practices in Electrolytic Cell Line Working Zones
	ISO/TR 15916[378]	Basic considerations for the safety of hydrogen systems. Provides guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides).
	IEC 62282-3-100:2019 RLV[379]	Stationary fuel cell power systems - Safety

Table 27: National certification schemes of low carbon hydrogen

Country	Name of certification	Description
Australia	Product Guarantee of Origin	This scheme aims to provide a methodology for quantification of GHG missions to be applicable from June 2025[(380)].

371 ISO 11119-1:2020Gas cylinders — Design, construction and testing of refillable composite gas cylinders and tubes, ISO, 2020 (ISO 11119-1:2020 - Gas cylinders — Design, construction and testing of refillable composite gas cylinders and tubes — Part 1: Hoop wrapped fibre reinforced composite gas cylinders and tubes up to 450 l). Accessed on 8 April 2025

372 ASME STP/PT-005 Design factor guidelines for high pressure composite hydrogen tanks, Global Spec, August 2006 (ASME STP/PT-005 - DESIGN FACTOR GUIDELINES FOR HIGH PRESSURE COMPOSITE HYDROGEN TANKS | GlobalSpec). Accessed on 8 April 2025

373 ISO 13984:1999Liquid hydrogen — Land vehicle fuelling system interface, ISO, 1999 (ISO 13984:1999 - Liquid hydrogen — Land vehicle fuelling system interface). Accessed on April 8 2025

374 ISO 10380:2012Pipework — Corrugated metal hoses and hose assemblies, ISO, 2012 (ISO 10380:2012 - Pipework — Corrugated metal hoses and hose assemblies). Accessed on 10 April 2025

375 ISO 13850:2015Safety of machinery — Emergency stop function — Principles for design, ISO, 2015 (ISO 13850:2015 - Safety of machinery — Emergency stop function — Principles for design). Accessed on 10 April 2025

376 ISO 14001:2015Environmental management systems — Requirements with guidance for use, ISO, 2015 (ISO 14001:2015 - ISO 14001 - Environmental management systems). Accessed on 10 April 2025

377 IEEE 463-2019-IEEE Standard for Electrical Safety Practices in Electrolytic Cell Line Working Zones, IEEE Standards Association, 2019 (IEEE SA - IEEE 463-2019). Accessed on 10 April 2025

378 Standards by ISO/TC 197- Hydrogen technologies, ISO, (ISO/TC 197 - Hydrogen technologies). Accessed on 10 April 2025

379 IEC 62282-3-100:2019 RLV Fuel cell technologies - Part 3-100: Stationary fuel cell power systems – Safety, International Electrotechnical Commission, 2019 (IEC 62282-3-100:2019 RLV | IEC). Accessed on 10 April 2025

380 Global Hydrogen Review 2025, IEA, September 2025 (Global Hydrogen Review 2025). Accessed on 15 September 2025

Country	Name of certification	Description
Brazil	Brazilian Hydrogen Certification Scheme (SBCH2)[381]	This scheme defines GHG emission threshold of 7 kg CO_2e per kg H_2 to qualify as low-carbon hydrogen. This move aims to position Brazil as a global hydrogen exporter
EU	Renewable Fuels of Non-Biological Origin (RFNBO) certification[382] and CertifHy[383]	RFNBO certification is a regulatory requirement under the RE Directive (RED II and III) that ensures hydrogen, and its derivatives are produced using renewable electricity and meets criteria of additionality, temporal and geographical matching and lifecycle GHG emissions accounting. The maximum GHG emission threshold is defined as 70 per cent below a fossil fuel comparator equivalent to ≤3.38 kg CO_2eq per kg H_2. CertifHy is a voluntary certification scheme that provides proofs of sustainability for hydrogen and e-fuels. This provides certification to both RFNBO and non-RFNBO (low carbon) hydrogen.
India	**Green Hydrogen Certification Scheme of India (GHCI)[384]**	**GHCI is a GH certification scheme launched by India in April 2025, with emission threshold of ≤2 kg CO_2eq per kg H_2 for the production process of GH including all stages up to the compression, purification and onsite storage. This certification is applicable for GH produced by electrolysis or biomass conversion pathways.**
Japan	Hydrogen Society Promotion Act[385]	Japan has proposed GHG emissions thresholds for hydrogen, ammonia, synthetic methane, and synthetic fuels. Final regulations are still under review.
Latin America	**CertHiLAC[386]**	**CertHiLAC is a regional hydrogen certification initiative by 14 countries of LATAM and supported by Multilateral Development Banks. This aims to create a unified standard for GH production and trade across Latin America**
UK	Low-Carbon Hydrogen Standard[387]	UK has updated its Low-Carbon Hydrogen Standard, refining emissions thresholds and sustainability requirements to provide clearer guidance for producers and investors. The emission threshold is ≤2.4 kg CO_2eq per kg H_2.
USA	Clean Hydrogen Production Standard[388]	The CHPS sets a target of 4.0 kg CO_2e per kg H_2 for the lifecycle GHG emissions associated with hydrogen production. This standard is part of the roader efforts under the Bipartisan Infrastructure Law (BIL) to promote clean energy technologies and reduce carbon emissions

381 Mattos Filho news article, August 2024 (Bill establishing legal framework for low-carbon hydrogen signed into law in Brazil - Mattos Filho). Accessed on 15 April 2025
382 Hydrogen Europe article, March 2023 (Impact-Assessment-on-the-RED-II-DAs.pdf). Accessed on 14 April 2025
383 Certifhy EU RFNBO Scheme, (CERTIFHY EU RFNBO SCHEME - CERTIFHY). Accessed on 14 April 2025
384 Green Hydrogen Certification Scheme of India, Ministry of New and Renewable Energy, GoI, April 2025 (MNRE_Green Hydrogen Certification Scheme of India_April 2025.pdf). Accessed on 14 April 2025
385 Joint press release with the Ministry of the Environment, Ministry of Economy, Trade and Industry (METI) Japan, February 2024 (Cabinet Approvals on the “Bill for the Act on Promotion of Supply and Utilization of Low-Carbon Hydrogen and its Derivatives for Smooth Transition to a Decarbonized, Growth-Oriented Economic Structure” and the “Bill for the Act on Carbon Dioxide Storage Businesses”). Accessed on 15 April 2025
386 Guide for the implementation of a hydrogen certification system in Latin America and the Caribbean, Inter-American Development Bank-Energy Division, December 2023 (Guide-for-the-Implementation-of-a-Hydrogen-Certification-System-in-Latin-America-and-the-Caribbean (1).pdf). Accessed on 15 April 2025
387 UK Low Carbon Hydrogen Standard, Government of UK, April 2022 (UK Low Carbon Hydrogen Standard - GOV.UK), Accessed on 10 April 2025
388 Clean Hydrogen Production Standard Guidance-Hydrogen Program, U.S. Department of Energy, June 2023 (U.S. Department of Energy Clean Hydrogen Production Standard (CHPS) Guidance). Accessed on 10 April 2025https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard

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