FOR THE CLEAN HYDROGEN PARTNERSHIP

Final report on European hydrogen competitiveness

03.07.2026

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Executive summary

Strategic context and study purpose

- **Meeting energy security and decarbonisation goals requires a shift energy systems**. Clean hydrogen will play a key role, particularly in hard-to-abate sectors where electrification is at a disadvantage or where low-carbon hydrogen molecules are required.
- Despite pockets of strong growth and support, **hydrogen technologies have been deployed more slowly than expected in Europe**. Progress has been hindered by challenging business cases, complex and uncertain policy, technology and market immaturity, and supply chain limitations.
- Hydrogen must **compete with fossil fuels and other low-carbon alternatives** on cost, technical performance, and emissions reduction potential, and be underpinned by investable business cases.
- **Most projects are not yet bankable without public funding or incentives**. The Clean Hydrogen Partnership has supported innovation in the sector by providing targeted funding for research and development.
- This study builds on recent assessments such as the Draghi Report and the EU Competitiveness Compass. It examines Europe's current competitiveness, **identifies the areas where innovation can deliver the greatest impact**, and provides evidence-based recommendations to help the EU strengthen its position in the global hydrogen economy.

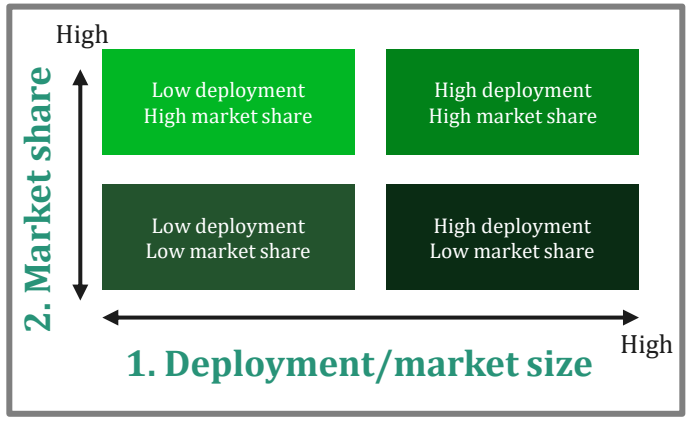
Throughout this report, 'Europe' refers to the EU27 Member States as of 2026, unless otherwise specified.

What competitiveness means for Europe

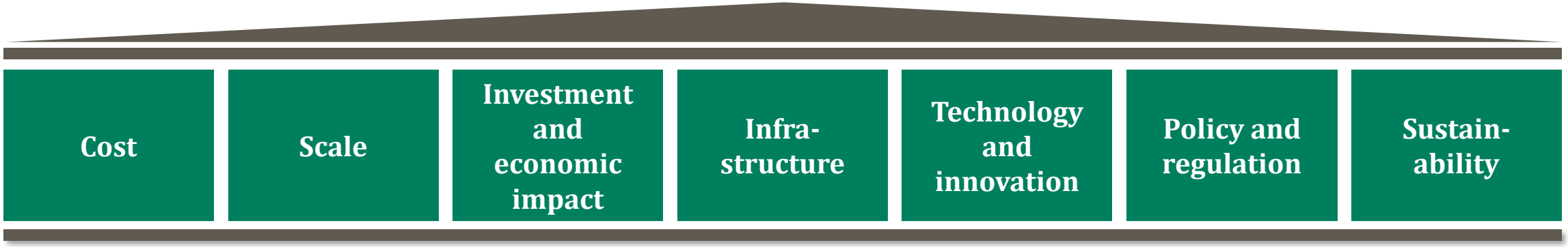
Competitiveness of the EU hydrogen sector can be measured across two dimensions

1. The first is Europe's ability to deploy hydrogen technologies at scale in order to **support domestic decarbonisation**.
2. The second is Europe's ability to secure a meaningful **share of global hydrogen value chains**, including manufacturing and production volumes.

Dimensions of competitiveness



These dimensions do not always align. Rapid deployment in Europe may require imported technologies and supply-chain inputs, which can run counter to efforts to develop strong EU players. Conversely, focusing primarily on EU manufacturing could slow deployment and increase costs for early projects. A balanced strategy needs to recognise these trade-offs and target innovation where it can strengthen both deployment outcomes and Europe's long-term industrial position.

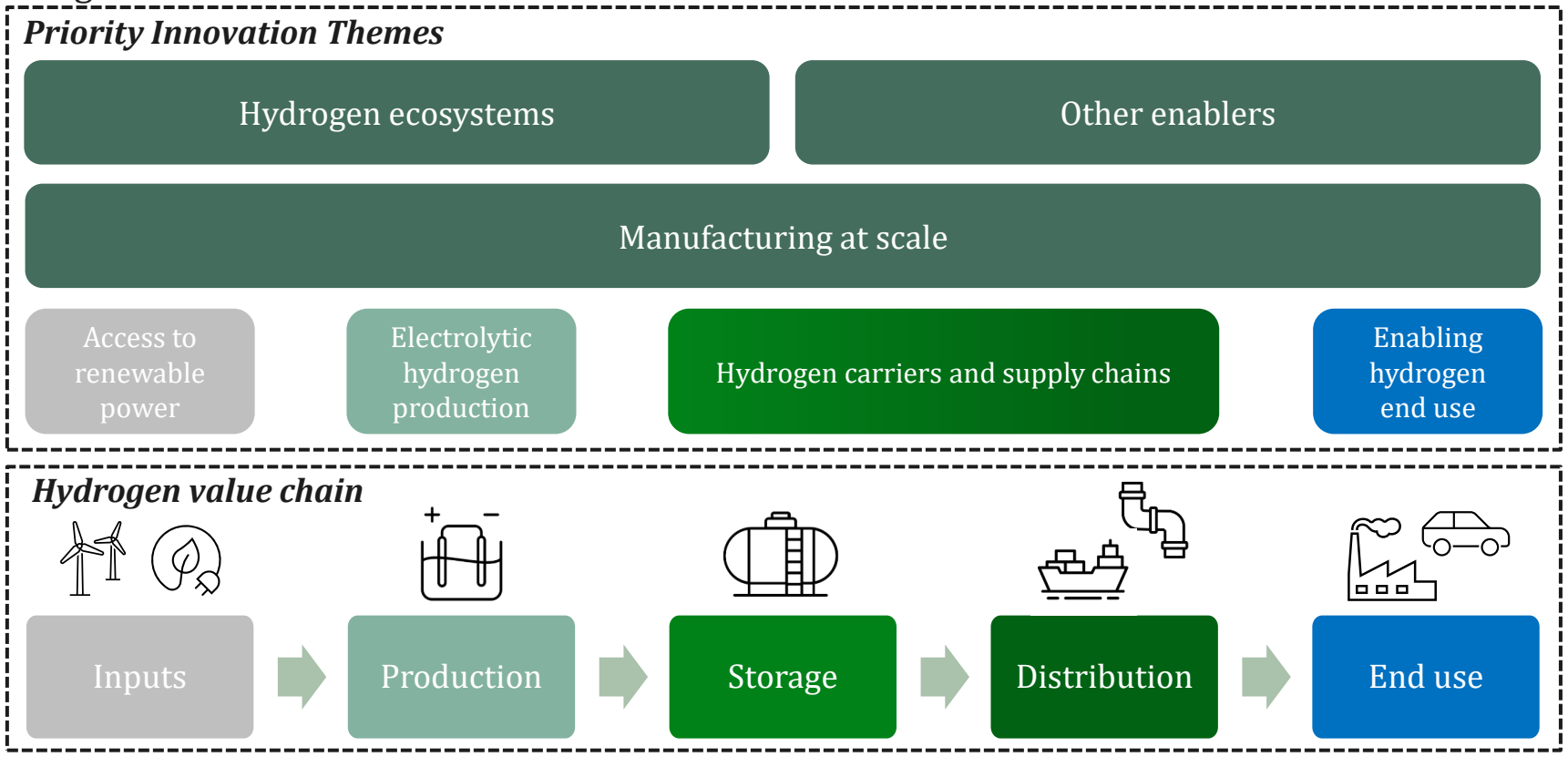


Within this study, seven factors of competitiveness have been defined in order to benchmark current EU competitiveness against peer regions. These factors constitute the core pillars which are necessary in a competitive domestic supply chain.

7 Key innovation themes have been identified that have significant impact on European hydrogen competitiveness

ERM reviewed the European hydrogen value chain, evaluated the impact of existing funding initiatives, and identified priority innovation areas where future support should be targeted to strengthen sector development and enhance Europe's competitiveness.

The **7 key innovation themes span the entire** hydrogen value chain, allowing individual opportunities to be organized into a consistent hierarchical structure and interface risks to be mitigated to ensure the full value chain can be realised.



Key trends identified

- Shift from R&I to delivery and execution
- Scaling through industrialisation, rather than specific marginal technology gains
- System-level innovation favoured over component-level innovation

Beyond these innovation themes there are adjacent critically important topics that need to be addressed to help support the sector.

These 7 innovation themes each have discrete innovation areas and opportunities

- **Access to renewable power**: Improves affordability and reliability of hydrogen production through a **regulatory framework for electricity production** that reduces connection costs, enables flexible electrolyser operation and supports alignment with variable renewables.
- **Electrolytic hydrogen production**: Enhances system performance through **reduce CRM dependency** measures such as AEM development and recycling, and **increased electrolyser performance** via better membranes, catalysts, system integration and flexible operation.
- **Hydrogen carriers and storage**: Enables large-scale transport and system balancing through innovations in **hydrogen carriers and storage media** such as LOHCs, ammonia cracking and liquid hydrogen, together with improved development of **sub-surface storage**.
- **Enabling hydrogen end use**: Accelerate market uptake with **demand side support measures** that reduce switching costs and aggregate demand, alongside development of **fuel agnostic hydrogen technologies** for power and industrial applications.
- **Manufacturing at scale**: Focuses on **manufacturing advancements** such as automation, gigascale production lines and design for manufacture, together with **component standardisation** across stacks and balance of plant to reduce cost and accelerate deployment.
- **Hydrogen ecosystems**: Strengthens integrated market development through **advancing hydrogen valleys**, **business model and financing innovations**, and **clustering of supply chain manufacturing** to support coordinated rollout and reduce delivery risk.
- **Other enablers**: Addresses cross-cutting needs through applying the **role of AI** in optimization and operations, tackling **regulatory barriers** that slow deployment, and driving **increased knowledge sharing** to spread best practice and shorten delivery times.

The EU hydrogen sector is at a crossroads: strong foundations exist but global competitors are scaling fast with strong strategic alignment

Europe is at a critical moment in the development of its hydrogen sector. Strong foundations remain, but global competitors are scaling faster and with greater strategic alignment. The innovation priorities identified in this report target the areas with the highest potential to shift Europe's competitive position.

- **Innovation remains essential**, with the highest impact opportunities focused on reducing cost and accelerating deployment at scale, including manufacturing scale up, ecosystem development and hydrogen carriers.
- **Europe's competitiveness gaps are driven by structural factors,** which define priority areas where innovation can deliver the greatest impact, including high electricity prices, slow infrastructure build out, limited manufacturing scale and weak demand.
- **The EU will need a differentiated approach across the value chain**. Some technologies/value chain segments justify global competition, others benefit from collaboration or exploitation of others capability, and some can be deprioritised without undermining overall strategic objectives.
- **Long term competitiveness depends on aligning innovation support with EU system level planning**, coordinated industrial strategy and stable policy signals that unlock scale, investment and supply-chain resilience.
- **Non-innovation enablers are critical to enabling innovation impact at scale**, with stakeholders highlighting renewables access and pricing, streamlined permitting, grid capacity connection times, financing models and clear demand as key conditions for translating innovation into real competitiveness gains.

Introduction

This study aimed to identify what innovation is needed and where it be targeted to strengthen Europe's competitiveness

The Clean Hydrogen Partnership Joint Undertaking (Clean H2 JU) has supported the European hydrogen sector for many years, through innovation support, initiatives to support the development of hydrogen projects and facilitation of information exchange and knowledge sharing. Since 2020, year-on-year committed investment in hydrogen has grown 50%, with committed investment growing by USD 35 billion from 2024 to USD 110 billion in 2025[1].

However, while there has been a significant amount of interest in clean hydrogen in recent years, the **pace of deployment** of clean hydrogen-related technologies in existing energy and industry, alongside new markets using hydrogen as a fuel and energy carrier has been **slower than anticipated**. For the **hydrogen sector** to be **competitive** against other incumbent decarbonisation technologies, as well as fossil fuels, there is a need for attractive business cases for investors and technology developers, and a more sustained drive for the adoption of hydrogen technologies by end users.

This study was undertaken to **identify** where innovation support could deliver the greatest impact on European competitiveness. In particular, it examined how targeted innovation can strengthen domestic value chains, support manufacturing capability, and position Europe effectively against lower-cost and rapidly scaling international competitors. Europe faces increasing pressure from regions with lower production costs and faster manufacturing scale-up, particularly China and emerging Middle Eastern exporters. Strengthening the EU's position therefore requires not only identifying priority innovation areas, but also understanding how these innovation choices can support domestic manufacturing capability, protect strategic value chains, and maintain the EU's competitiveness in global hydrogen technology markets.

The analysis focused on the following guiding question: **What innovation is needed, and where in the value chain should it be targeted, to strengthen Europe's competitiveness relative to global peers?**

1 – Hydrogen Council's Global Hydrogen Compass Report

The analysis builds on previous studies to support actionable recommendations on innovation, aligned with EU priorities

- Several previous studies underpin this new analysis, which aims to provide an updated view and a more holistic analysis, rather than focusing on specific segments (e.g. infrastructure, cost or value chain).
- While other reports have benchmarked the EU internally or against select regions, this study has **systematically profiled and compared the EU's hydrogen competitiveness with key global regions** (e.g., Japan, China, Saudi Arabia), identifying both strengths and gaps across multiple competitiveness indicators.
- The study provides a **holistic review of current sector status and competitiveness** across the entire hydrogen supply chain, whilst considering key interdependencies and innovation priorities and ensure the EU can be competitive with other regions.
- Beyond identifying sector challenges, this study has also **assessed the impact of innovation actions to date** and **shortlisted key innovation opportunities and mechanisms** which can accelerate future EU hydrogen sector growth, drawing from cost analysis, case studies, lessons from other sectors and stakeholder input.

The analysis provides a forward-looking strategic perspective, linking strategic innovation opportunities with targeted change mechanisms to support actionable recommendations aligned with EU priorities.

Definition of competitiveness

Our analysis takes a multi-faceted definition of what competitiveness means for Europe, reflecting the recent Draghi report

Europe's hydrogen sector is evolving within a rapidly changing global landscape. Understanding the forces shaping competitiveness today is essential to identify where targeted action is most needed.

Competitiveness to drive sustainable growth

Competitiveness has long been a key priority for the European Union and, as defined by the European Union Lexicon (EU LEX), is the ability of an economy to drive sustainable growth and provide its population with high and rising standards of living and high rates of employment.

Supporting the energy transition

The European Green Deal frames this ambition by linking industrial competitiveness with the energy transition. It aims to transform Europe into the first climate-neutral continent by 2050, driving sustainable growth, innovation, and job creation. By prioritizing clean technologies, circular economy principles, and resource efficiency, the Green Deal strengthens Europe's ability to compete globally while ensuring environmental and social sustainability. These elements are essential for Europe to thrive in a rapidly changing world, and they underpin strategic sectors such as hydrogen, digital technologies, and advanced manufacturing.

Building resilient value chains

In the hydrogen context, competitiveness depends on whether Europe can build a cost-effective, innovative and resilient value chain. This includes developing domestic supply chains, scaling deployment, attracting investment, and ensuring that hydrogen solutions deliver value compared with global alternatives.

Achieving a strong global position

Europe therefore needs a clear view of what hydrogen competitiveness means, how competitive it is today, and which innovation opportunities are most likely to strengthen its position in the global hydrogen market.

We considered hydrogen adoption in the energy system and wider supply chain development when assessing competitiveness

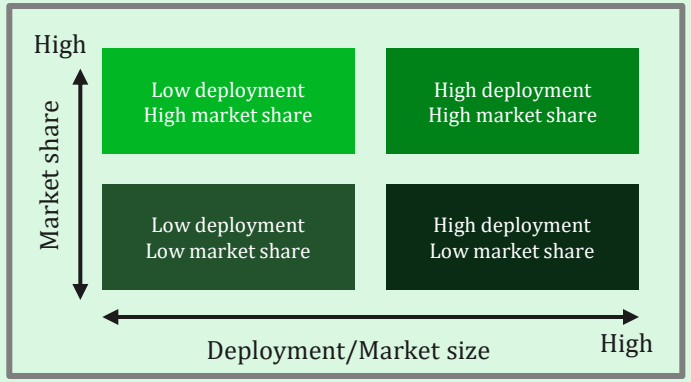
The competitiveness of the European hydrogen sector depends on:

- The competitiveness of hydrogen against other decarbonisation options.
- The competitiveness of the European supply chain compared to other regions.

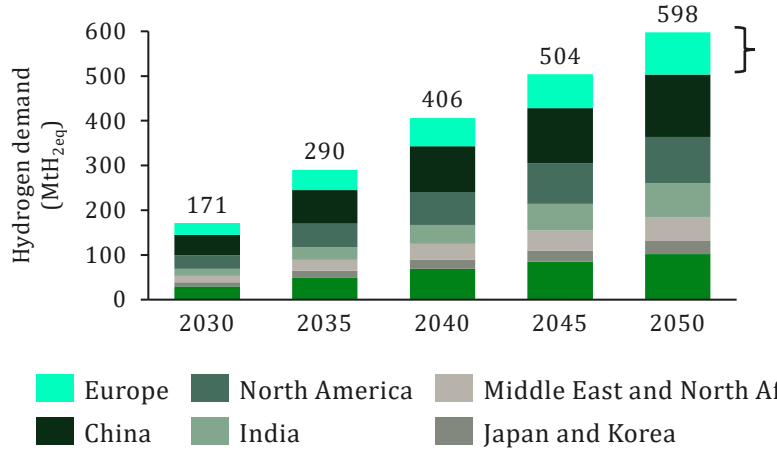
Increasing competitiveness will require innovation to increase the overall **scale** of the hydrogen sector and strengthen the European **market** and **supply chain**.

Growing Europe's competitiveness will require growth along both axes to result in a hydrogen economy at sufficient scale to achieve decarbonisation targets, while securing local value retention[1].

Market scenarios

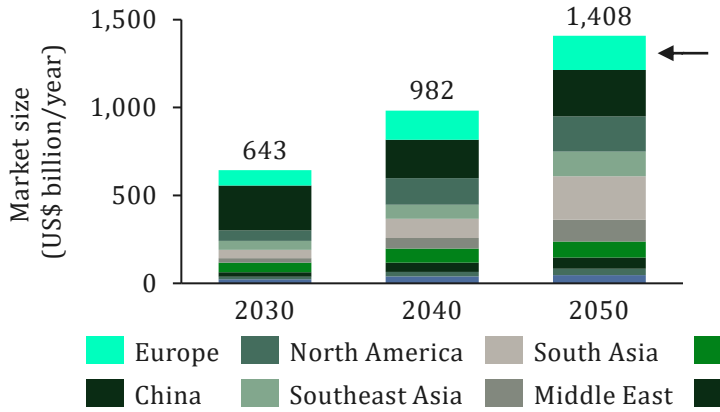


Regional demand for clean hydrogen and its derivatives, 2030 to 2050 (MtH_{2eq})



Achieving European hydrogen market growth projections hinges on rapid deployment and further policy support. These global and EU projections outpace current supply capacities which leaves a growth opportunity that Europe could maximise.

Clean hydrogen market size (US$ billion per year), 2030 to 2050



Europe's hydrogen production and supply chain market could reach $190 billion in 2050, contingent on its competitiveness against other regional producers. This represents a significant economic opportunity for the strong innovation base Europe has developed in recent years.

Source: Deloitte Analysis

1 - Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies

We identified seven hydrogen competitiveness factors reflecting the EU definitions of competitiveness and sector-specific considerations

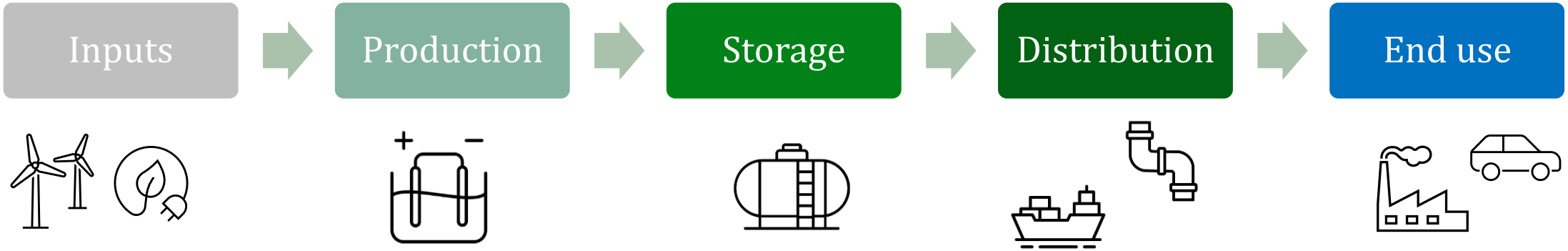
This report integrates definitions of competitiveness adopted across the EU as well as any relevant studies, including the EU lexicon definition[1], the 'Future of EU competitiveness' report[2] and the Clean Industrial Deal[3].

Definition of competitiveness						
The EU hydrogen sector's ability to scale and fulfil energy transition needs, while achieving a strong position relative to global peers and deliver value to the EU.						
Constituting factors						
Cost	**Scale**	**Investment and economic impact**	**Infrastructure**	**Technology and innovation**	**Policy and regulation**	**Sustainability**
The ability of hydrogen producers and developers to offer hydrogen or hydrogen equipment at a competitive price compared to other decarbonisation options and global regions. This includes production, distribution, and end-use costs.	The capacity of the EU hydrogen sector to scale and meet energy transition needs, including the ability to deploy infrastructure and technologies at sufficient volume.	The availability of investment (public and private) to drive sector growth and technology development, alongside the extent to which this delivers economic and social value to EU regions (e.g. job creation and local economic benefits).	Infrastructure for hydrogen use is crucial, encompassing production, grid support, distribution, transport, storage, and import/export solutions. Adequate infrastructure ensures reliable hydrogen supply and market connectivity at scale.	The degree to which the EU leads in hydrogen technology and equipment development, supports research and development, while fostering innovation through public-private partnerships and other frameworks.	The effectiveness of policy and regulatory frameworks in supporting sector growth, enabling investment, and mitigating key risks, including alignment across member states.	The ability of the EU hydrogen sector to produce hydrogen with minimal emissions intensity across its full lifecycle and secure critical materials, supporting a clean energy transition and environmental sustainability.

Benchmarking EU performance

We mapped the hydrogen value chain to identify those elements critical to market growth drawing on stakeholder insights

To best evaluate competitiveness across the hydrogen sector, we have **mapped out the value chain across** 5 key stages to include **all relevant technologies** from energy input to end use considering key steps, technologies and parameters which are central to the hydrogen sector development.

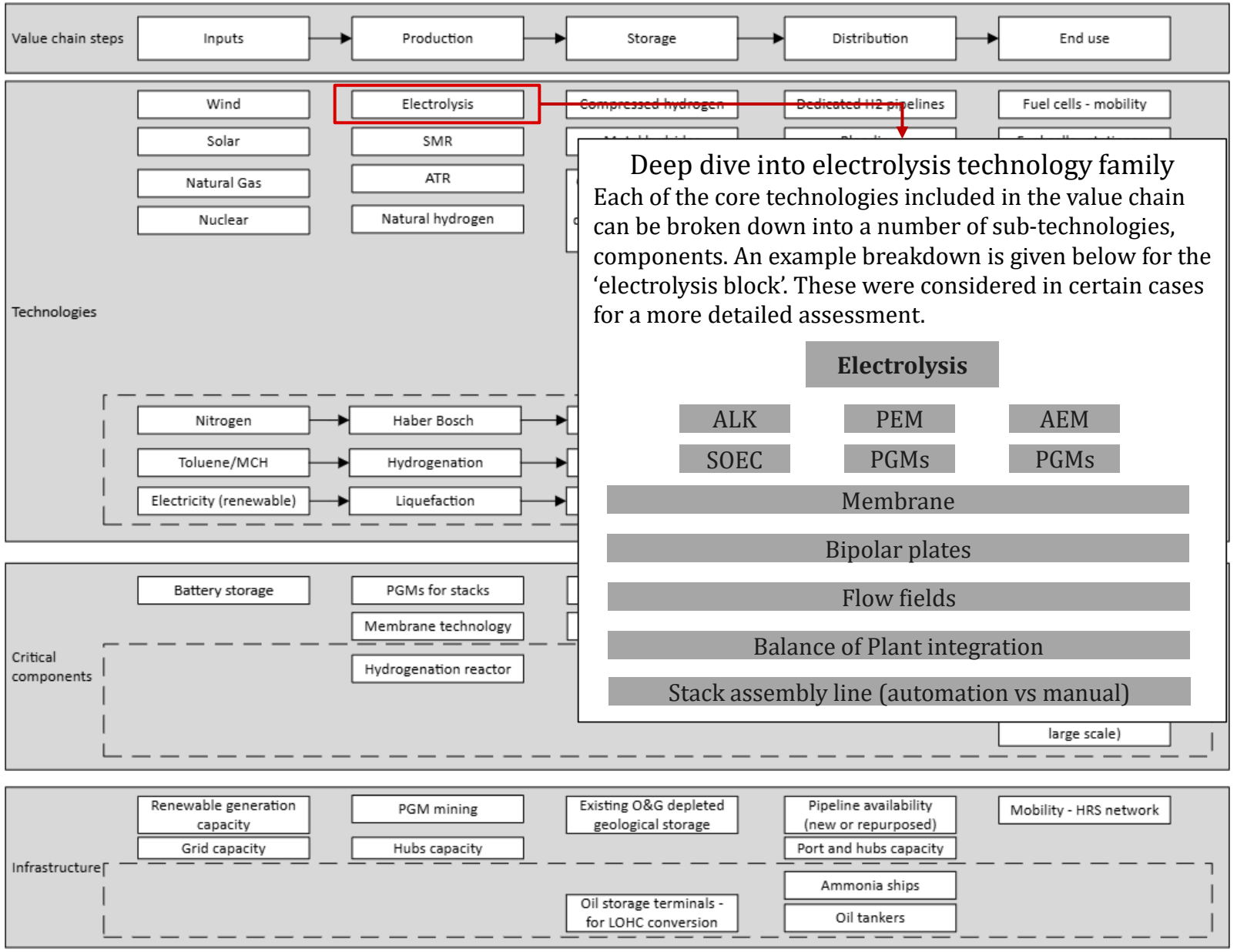


- We noted **critical elements needed to grow the market** beyond technology development, as well as the **infrastructure required** to support their roll out.
- We drew on **stakeholder insights** and the **challenges** they identified to contextualize the wider market and clarify the conditions and actors required to support its growth.

Each comparator region's current market presence is mapped across the stages of the value chain to illustrate how its strategic priorities align with its ambition to compete in these technologies and markets.

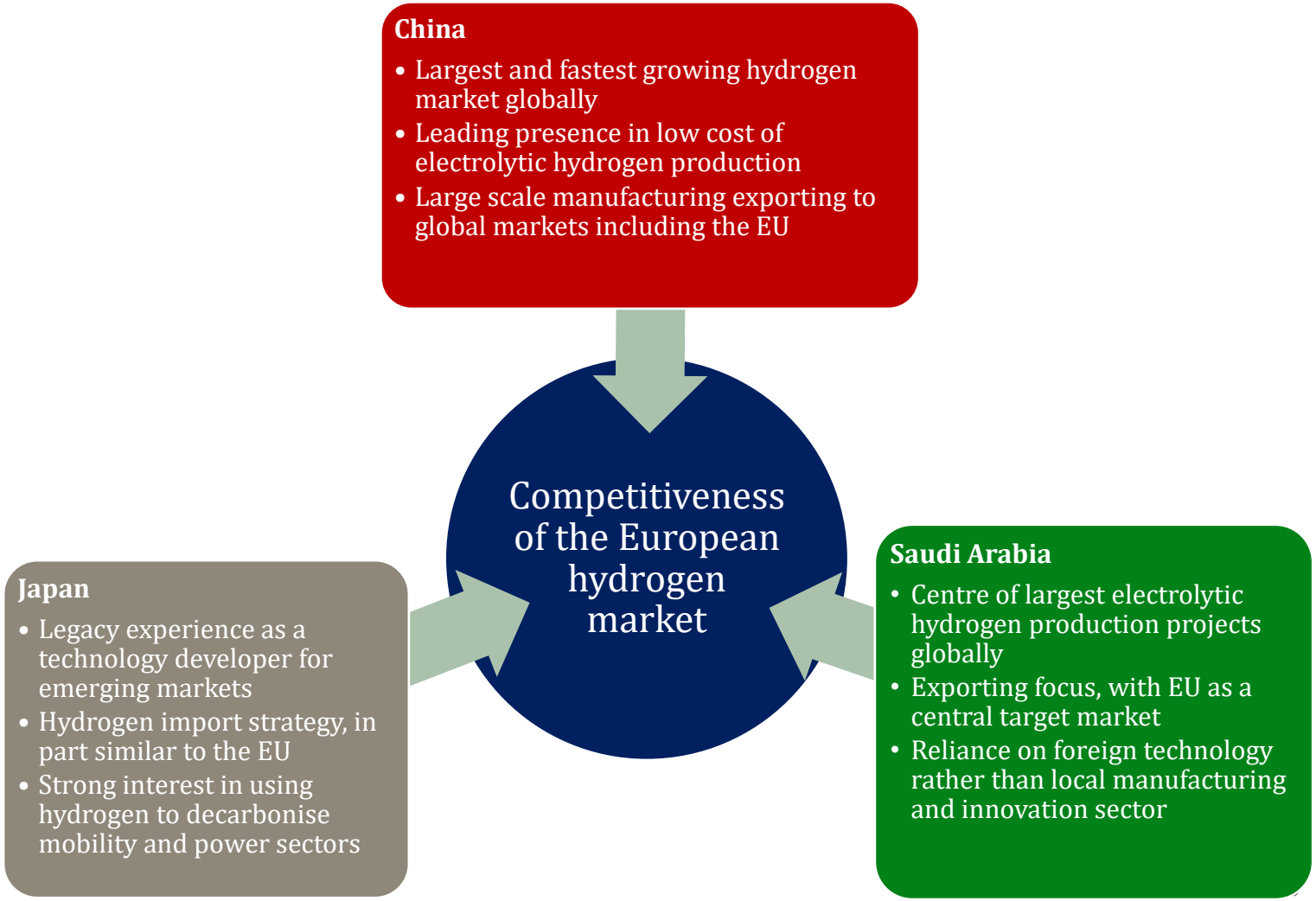
Detailed supply chain maps were used to deepen the evaluation

- We **mapped out the hydrogen value chain** to provide a comprehensive but non-exhaustive overview of the steps, technologies and components that are required.
- Our evaluation highlighted key supply chain technologies that can offer differentiation for the markets considered, and that provide most open opportunity for innovation in the coming years.
- Similarly, the critical components and infrastructure shown on the value chain represent areas where Europe or other regions can have a differentiating market presence.



Emerging hydrogen leaders, China, Japan and Saudi Arabia provide contrasting profiles against which to evaluate EU competitiveness

- We have selected other leading countries to benchmark the competitiveness of the EU hydrogen sector against.
- China, Japan and Saudi Arabia were selected as having among the most developed hydrogen sectors globally, albeit each with key differences and some similarities in their hydrogen strategy and interface with Europe.
- This study has assessed how these countries are positioned across the hydrogen value chain in order to identify areas where the EU may have a competitive advantage, or where collaboration with these markets can be most beneficial.



This analysis shows that the EU has some clear strengths in hydrogen innovation but faces material competitiveness gaps

EU strategic aims - EU aims for affordability, energy security and sustainability, all of which can be provided by hydrogen

- REPowerEU 2022 strategy aimed to produce 10 million tonnes and import 10 millions tonnes of hydrogen by 2030, to decarbonise heavy industry and some of the transport sector.
- A strong focus on development of a local hydrogen sector, relying on EU technology development to grow the economy and maximise energy security .

Assessment of EU competitiveness:

- The EU is heavily involved across the value chain, and is **currently a technology leader,** compared to other regions, in storage and distribution. **China's focus on production** and inputs makes it score highest in these areas. Across the end-use sectors, the EU lacks some technology development, scale and uptake compared to **China and Japan where heavy focus has been given to end use.**
- **Costs of these technologies remains high** compared to other regions, limiting the growth of the sector to date. This is in part affected by high costs of energy inputs, such as electricity, compared to other regions.
- The **EU regulatory landscape surrounding hydrogen and other decarbonisation technologies is well developed**, particularly compared to other regions where higher uncertainty persists.
- There is **high investment** at the EU level through schemes such as the Innovation Fund to help develop the sector in its early stages.

Based on the competitiveness assessment against peer countries, we have identified areas of the value chain that the EU must focus on to fulfil its targets and increase competitiveness against other regions. These areas informed the shortlisting of innovation opportunities.

Benchmarking highlights Europe's strengths and gaps, the structural barriers that limit scale, and where focused innovation is needed

Europe's current position

Benchmarking shows that Europe has **strong foundations** but faces **clear competitiveness gaps**.

Europe leads in innovation capability, midstream expertise and regulatory frameworks, but it continues to **lag on cost, project scale and manufacturing speed** compared with China, Japan and Saudi Arabia.

This establishes that Europe begins from a position of strength, but **some of these strengths are not translating into market advantage**.

Barriers holding Europe back

Structural barriers now limit Europe's ability to convert technology strengths into market leadership.

High electricity and EPC costs, slow infrastructure build out, fragmented supply chains and limited demand visibility **constrain the scale needed for competitiveness**.

These barriers explain why **Europe's strong innovation base and policy frameworks** are **not yet delivering cost-competitive deployment** at pace.

Global competition and implications

Global competitors are scaling at pace, with China rapidly expanding manufacturing and deployment, Saudi Arabia building low-cost export capacity and Japan consolidating its end use technology advantage.

Benchmarking highlights where innovation can deliver impact, with key areas such as **scaling manufacturing, hydrogen ecosystems and carriers**.

Targeted innovation support is essential to protect strategic EU strategic value chains and accelerate deployment.

This shows that Europe risks being overtaken unless innovation support is focused directly on the constraints highlighted by benchmarking.

Current EU initiatives provide a strong foundation, but further action is needed to address competitiveness gaps

Benchmarking shows that Europe has strong foundations in innovation, regulation and infrastructure planning, but continues to face challenges in cost competitiveness, manufacturing scale and deployment pace. While existing EU initiatives address many of these challenges, several gaps remain. Understanding these gaps helps identify where future innovation support can have the greatest impact on European hydrogen competitiveness.

Current initiatives and focus

- ❑ Hydrogen Strategy / REPowerEU – Scaling production, imports and deployment targets
- ❑ Innovation Fund / Clean Hydrogen Partnership – Technology development and demonstration
- ❑ Net Zero Industry Act – Manufacturing scale up and strategically important technologies
- ❑ Hydrogen Backbone / Trans-European Networks for Energy – Infrastructure planning and cross-border networks
- ❑ AFIR – Hydrogen refuelling infrastructure deployment
- ❑ State aid / National schemes – Funding, subsidies and project support

Gaps in competitiveness

- ❑ Strong focus on supply targets, but less progress on cost competitiveness and demand creation
- ❑ Fragmentation between R&D and commercial scale-up, limited translation to market deployment
- ❑ Early stage with unclear impact on cost competitiveness and global positioning
- ❑ Infrastructure timelines lag demand development and project pipelines
- ❑ Risk of infrastructure build-out ahead of demand and low utilisation
- ❑ Fragmentation across Member States and inconsistent incentive design

Future focus areas

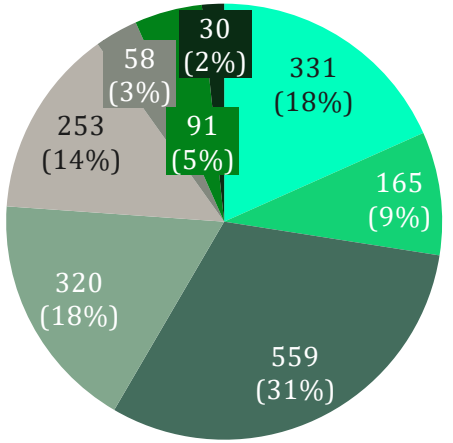
- ❑ Shift towards demand-side measures, cost reduction, and stronger integration with end-use markets
- ❑ Stronger linkage between innovation funding and deployment, with clearer pathways to scale
- ❑ Greater focus on supply chain depth, standardisation, and industrial clustering
- ❑ Improved system-level coordination and alignment with demand and supply development
- ❑ Stronger alignment with fleet roll-out and demand aggregation mechanisms
- ❑ Further coordination and harmonisation to enable scale and cross-border markets

Hydrogen innovation opportunities for Europe

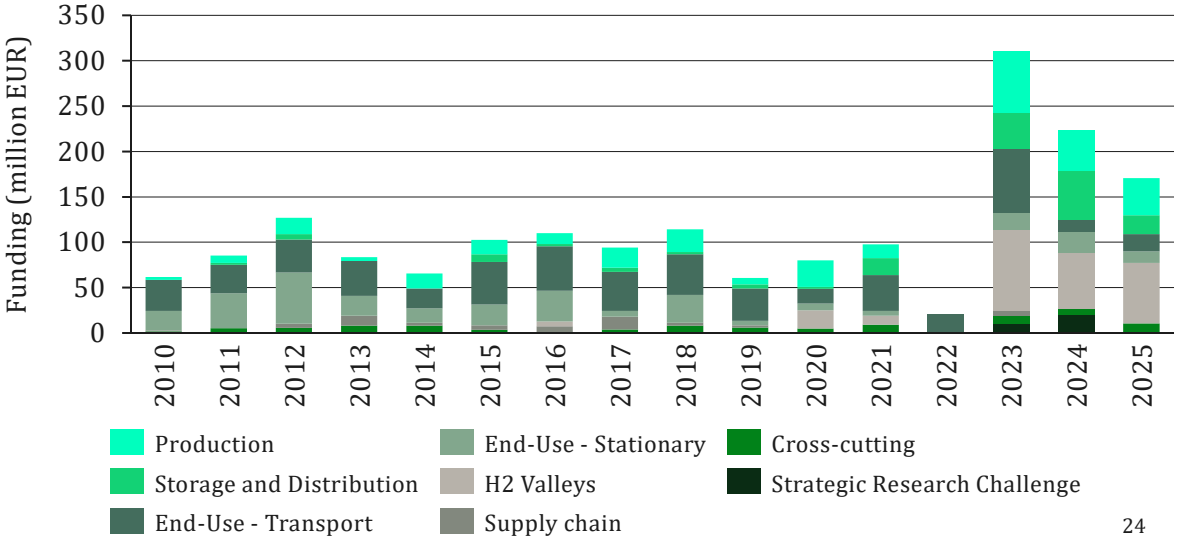
Past hydrogen innovation funding from the CH JU was concentrated on end uses, with a more recent focus on hydrogen valleys and storage

Pillar	Trends in Clean H2 JU Funding
Production	18% of the JU's contributions to projects starting between 2010 and 2025 focused on hydrogen production technologies. Projects have focused mainly on PEM and Alkaline technologies, but funding for solid-oxide technology has been steadily increasing, as has that for AEM, albeit to a significantly lower degree.
Hydrogen Valleys	Although hydrogen valley funding has significantly increased since 2022, the capital-intensive nature of valleys projects result in a low funding rate for these projects. The deployment of these projects relies significantly on external funding sources.
Storage and distribution	Storage and distribution technologies have so far constituted 9% of the total JU contributions during this period. Nearly 70% of the funding has been for projects starting since 2023, highlighting the recent resurgence in the pillar, and strategic shift towards hydrogen trade which has been shaped by structured dialogue between public and private stakeholders to meet future sector needs. This has manifested in recent European policies such as REPowerEU. In this period, 50% of the funding has been allocated to underground storage and liquid hydrogen carrier and storage development.
End-use	The JU has invested significantly in end use applications, as 31% of the funding for projects starting between 2020 and 2025 has focused on transportation applications, and 18% has focused on stationary applications. Funded projects covering transport end use has significantly declined since 2023, when 23% of the funding focused on transport applications, particularly towards storage and distribution. This funding has played a foundational role in reducing the unit cost of several applications such as fuel cell buses which have reduce in cost by over 50%. However, subsequent deployment of these buses is primarily driven by policy and mandates, which have not been sufficient to stimulate large scale deployment.

Cumulative Clean Hydrogen JU contribution for projects up to 2025



Clean Hydrogen JU contribution for projects commencing from 2010 to 2025

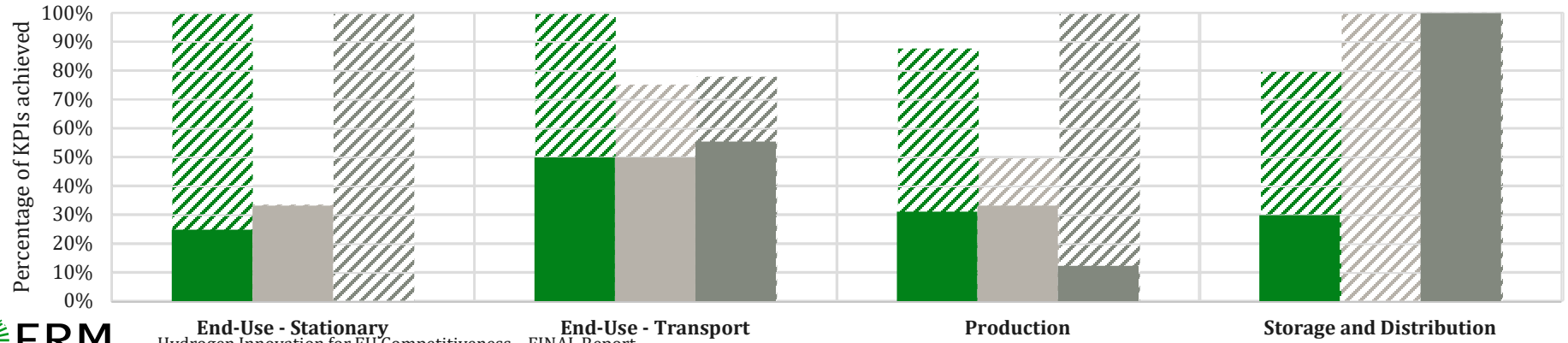


Innovation progress across the value chain highlights uneven progress and ongoing innovation gaps

KPIs appear to have been largely met by the best performing Clean H2 JU funded projects, however most projects are struggling to achieve KPIs, suggesting many areas of further innovation are still required to meet performance targets. However, even where KPIs are not achieved, projects often generate significant knowledge and capability building which are vital for scale and implementation.

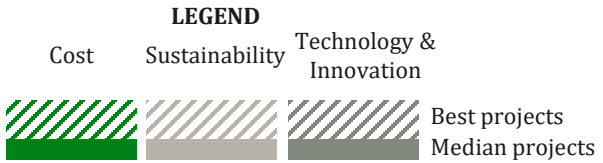
Percentage of considered KPIs achieved [2,3]

End-Use - Stationary	End-Use - Transport	Production	Storage and Distribution
Cost and technology & innovation KPIs, e.g. SO fuel cell production costs, have been met by the highest performing projects. However, stationary end-use projects have struggled overall to meet their KPIs. This suggests that there is significant further opportunity to innovate across stationary applications such as Clean H2 JU, industrial burners and power applications. Additionally, many sustainability KPIs have not been achieved, which needs further exploration to confirm specific areas of improvement.	While end-use transport applications have not achieved all KPIs (e.g. PGM recycling in PEMFCs), even on the best performing projects, the median projects have performed better across the board than stationary, production and storage & distribution applications. This implies that the funding in the transport sector has been relatively successful and achieved strong maturation against project aims.	There is a significant gap between the median and leading production projects, indicating the underlying technology challenges need further exploration, building on existing learnings. There may need for focussed support towards more promising production technologies, or this could imply there are some less mature technologies with significant room for development, Cost KPIs remain challenging because CAPEX and energy input costs still dominate electrolytic hydrogen costs.	Storage and distribution projects have scored high for technology & innovation, implying that significant gains have been achieved and further innovations may not lead to the same improvements as other project areas like production. However, cost appears to remain a challenge, with high CAPEX for hydrogen refuelling stations and limited scale up restricting the number of projects achieving KPIs.



Note:

1. 'Best' projects are viewed as those leading in the achievement of a KPI.
2. The allocation of KPIs are outlined in the Appendix.
3. While these KPIs have been taken to reflect progress on cost, sustainability and technology and innovation, the Clean Hydrogen Partnership projects' impact on other competitiveness factors: scale, infrastructure, investment and economic impact, and policy and regulation are also assessed in the following slides.



Europe can draw policy and market lessons from these other low-carbon sectors to strengthen EU hydrogen competitiveness

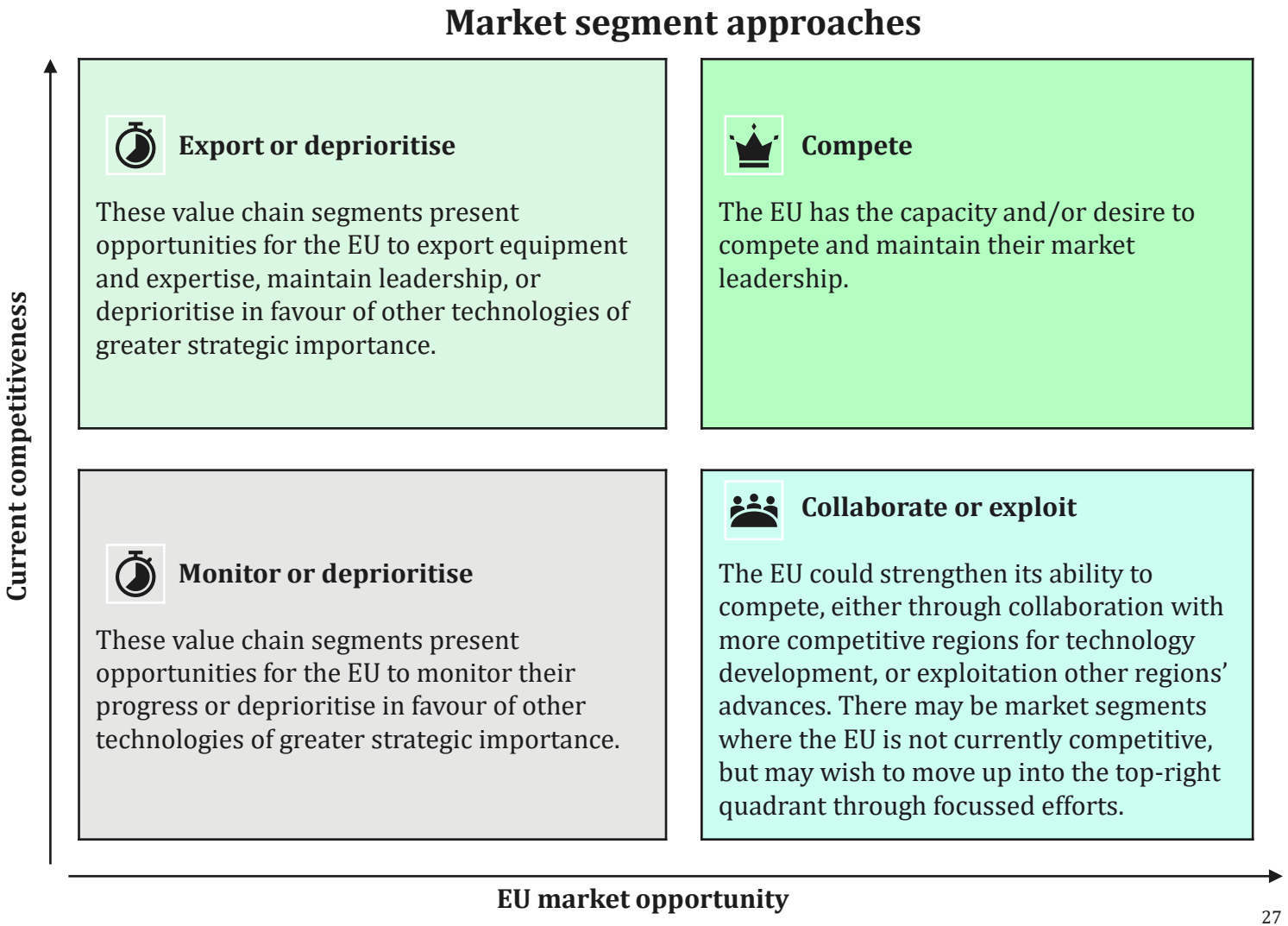
These levers are starting points for a complex challenge. Addressing structural risks will require deeper policy, industry coordination, and long-term strategy

	Potential competition levers
Economic strategy	Replicate long-term, state-backed scaling strategies seen in PV and batteries, aligning public funding, procurement and trade measures to support domestic players and avoid loss of strategic industries
Dominant raw material supply chains	Avoid the material concentration seen in batteries by securing upstream and refining capacity early, combining EU sourcing, recycling and strategic partnerships to prevent dependency on externally controlled value chains
Massive capacity building	Accelerate manufacturing scale ahead of demand, as seen in PV and batteries, through coordinated gigafactory investment and supply chain clustering to drive cost reductions via learning effects and economies of scale, while avoiding underutilised assets
Technology acquisition	Protect and retain strategic technologies within Europe, while strengthening pathways from innovation to commercial deployment in order to maximise returns from R&D investment and leadership
Low-cost base	Address structural cost disadvantages that enabled PV and battery cost leadership elsewhere, through lower-cost power, automation, and optimised EPC and financing structures to remain competitive at scale
End use case diversification	Create diversified and policy-backed demand, as seen in batteries, through mandates and incentives across multiple sectors (industry, transport, power etc.) to stabilise investment cycles and support scale up of hydrogen valleys
Cultural and political differences	Use sustainability and security criteria in procurement to favour trusted suppliers

A framework was developed to assess EU innovation priorities by market segment considering competitiveness and market opportunity

The EU's approach to maximising competitiveness in each market segment depends on where it sits on the Competitiveness / EU Market Opportunity matrix, reflecting strategic priorities and regional strengths.

- The EU's strategic priorities have previously included supporting electrolytic hydrogen production and its deployment for mobility, industrial decarbonisation and power generation applications.
- As well as strategic alignment, priorities should also capitalise on Europe's regional strengths, which include technology development and industrial engineering heritage, especially in electrolysis and fuel cells.
- Europe doesn't need to innovate uniformly across the hydrogen value chain. Rather, innovation should be targeted where it can deliver the greatest competitive impact, supported by the right mix of change mechanisms. These mechanisms define how innovation is translated into deployment, scale, and market leadership; and consist of funding initiatives, business models and policy or regulatory change.



Each market approach will demonstrate a different role for innovation and demand a different set of change mechanisms

Compete

- **Aim**: The EU aims to compete across the value chain with other regions, decreasing dependencies on imported components, materials and skills.
- **Role of innovation**: High-impact innovation is required across production, infrastructure and end use to achieve lower costs, scale and manufacturing capability within the region.
- **Change mechanisms**: Strong, active levers such as mandates, targeted public funding, and coordinated industrial collaboration are needed to accelerate technology development and deployment.
- **Risks**: Attempting to advance too many segments simultaneously may dilute focus, slow progress toward 2030 targets and leave space for other regions to outpace the EU in cost, scale and export capability.

Collaborate or exploit

- **Aim:** Leverage existing strengths in the supply chain and benefit from other region's expertise in areas where the EU currently lags (e.g. importing low-cost hydrogen or cheaper electrolysers).
- **Role of innovation:** Targeted innovation activities within specific areas of the value chain (e.g. storage and distribution) where the EU strategy is to become a global leader.
- **Change mechanisms:** more targeted funding towards specific applications to ensure those areas of the value chain are able to sufficiently develop.
- **Risks:** Reliance of foreign components, hydrogen or skills could reduce energy security of the EU, which given the current geopolitical situation remains a focus area. Lack of development at the expected pace in other regions could mean delays in growing scale of the hydrogen sector in Europe.

Export or deprioritise

- **Aim:** Focus EU effort on areas where strategic importance is lower, relying on competitive international supply while maintaining niche areas of European strength.
- **Role of innovation:** Targeted, limited innovation to preserve exportable EU expertise (e.g. standards, safety, specialised engineering) rather than broad technology development.
- **Change mechanisms:** Light touch support through standardisation, certification influence, and policies that enable efficient imports without duplicating global manufacturing scale.
- **Risks:** Greater dependence on external suppliers, reduced domestic capability over time, lower influence over global standards, and exposure to trade or geopolitical disruption.

Monitor or deprioritise

- **Aim:** The EU choses to deprioritise innovation in the hydrogen sector, focusing on other decarbonisation technologies such as electrification, and letting the EU hydrogen market develop with minimal support.
- **Role of innovation:** Innovation becomes limited and relies on private funding and R&I, rather than a centralised effort to fill gaps of the value chain.
- **Change mechanisms:** Limited public funding, mandates and policy support for hydrogen uptake and technology development, as these are instead shifted to other technologies.
- **Risks:** Europe growing increases dependencies on foreign regions for import of hydrogen molecules, equipment and skills. This leaves the EU hydrogen sector deprived of momentum and funding, leaving manufacturers and project developers without room for significant growth.

We shortlisted innovation opportunities by evaluating them based on competitiveness and feasibility factors in an MCA approach

We took a structured approach to score and assess opportunities in innovation themes to arrive at a shortlist of the most strategically aligned, feasible, and high-impact concepts.

Phase 1

Structure innovation opportunities

Innovation opportunities are organised into a consistent hierarchical structure (Theme, Area, Opportunity) to ensure that each opportunity is assessed at the appropriate level of granularity.

Example:

- *(Theme) manufacturing at scale,*
- *(Area) component standardization*
- *(Opportunity) interoperability of standardized stack designs*

Phase 2

Competitiveness factors

Each opportunity is evaluated against the full set of competitiveness factors defined in the study. These reflect the potential for an opportunity to strengthen European hydrogen sector competitiveness across the value chain.

They include: Cost, Scale, Investment and Economic Impact, Infrastructure, Technology and Innovation, Policy and Regulation, Sustainability.

Feasibility factors

To ensure that proposed innovations are both competitive and implementable, each opportunity is screened against feasibility factors. These test the realism, practical constraints, and strategic fit of each idea.

They include: Deliverability, Additionality, Dependencies, Strategic Alignment

Each opportunity is **assigned a numerical score from 1 to 5** for every competitiveness and feasibility factor, creating a transparent and evidence-based scoring matrix that captures expected impact, reflects feasibility risks, and highlights alignment with EU priorities.

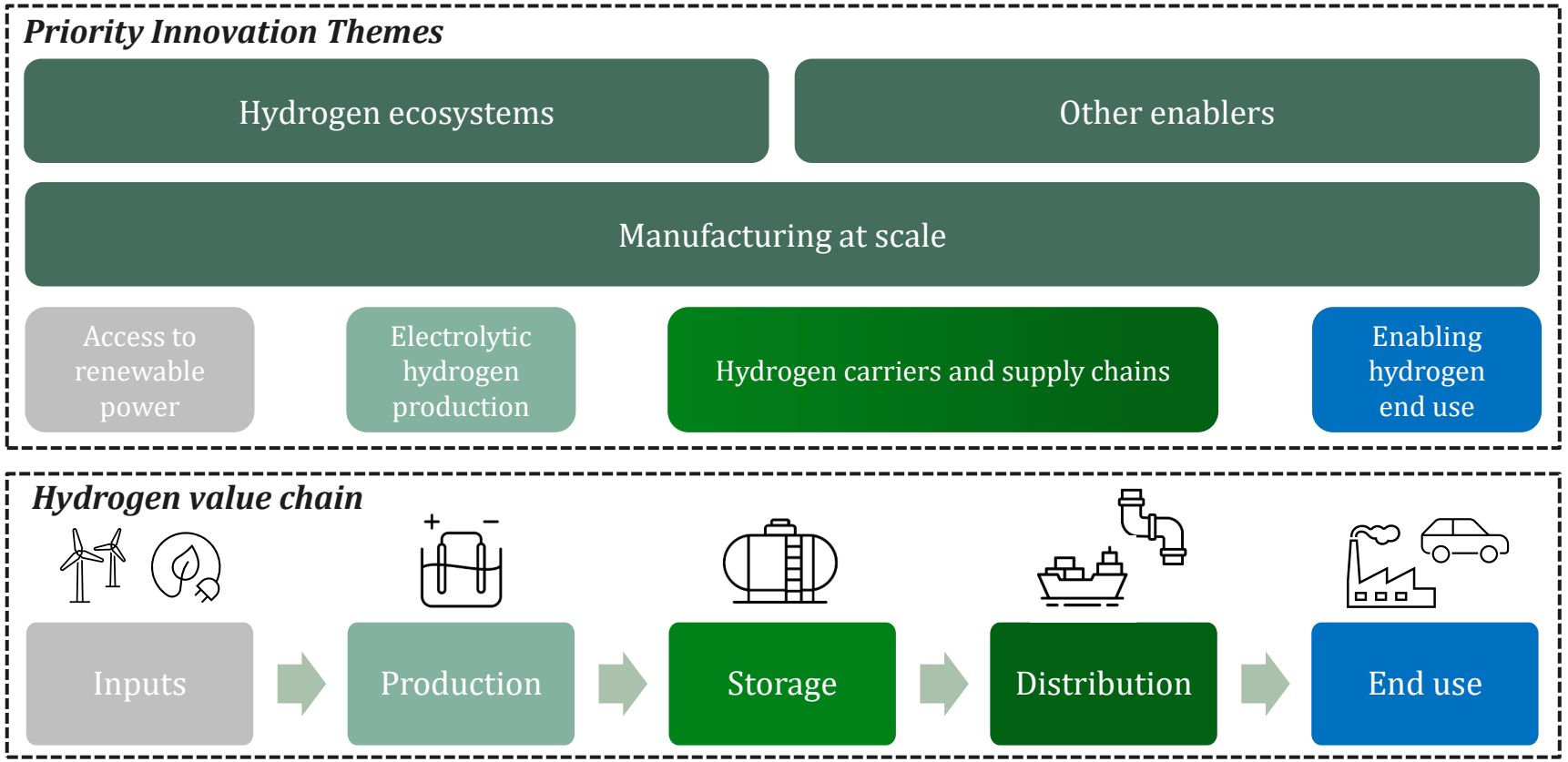
The **scores are then aggregated** across all dimensions to identify the most feasible opportunities, those offering the strongest competitiveness benefits, and the concepts with the highest strategic relevance.

Only high-scoring ideas were progressed to detailed assessment.

These shortlisted innovation areas have been categorised into 7 common themes which can support EU hydrogen competitiveness

ERM reviewed the European hydrogen value chain, evaluated the impact of existing funding initiatives, and identified priority innovation areas where future support should be targeted to strengthen sector development and enhance Europe's competitiveness.

The **7 key innovation themes span the entire** hydrogen value chain, allowing individual opportunities to be organized into a consistent hierarchical structure and interface risks to be mitigated to ensure the full value chain can be realised.



Priority innovation opportunities for EU hydrogen competitiveness

Innovation theme	Priority innovation opportunities
Manufacturing at scale: Accelerating cost reduction and deployment by shifting from today's low-volume, highly manual, and fragmented production methods to scalable, standardised, and automated manufacturing systems.	• **Manufacturing advancements,** including increased use of automation and AI, design for manufacture of key components and establishment of gigascale production lines. • Increased **standardisation** of BoP components across OEMs and interoperability of standardised stack designs
Supporting hydrogen ecosystems: Innovation to accelerate hydrogen market formation through better coordination across supply, demand, infrastructure and finance, enabling scalable, repeatable ecosystem models beyond individual pilots.	• **Advancing hydrogen valleys** through certified suppliers and audited services, a valleys delivery body and increased access to operational environments for novel technology. • **Business model and investment:** increase the risk borne by public sector (CfDs, last resort demand, RAB, ECAs) and rebalancing of investment/risk allocation; creation of insurance products tailored to hydrogen sector to mitigate the risks to the users. • **Co-location of supply chains and shared facilities** with controlled environments for testing, certification and qualification.
Access to renewable power: Improve cost and reliability of hydrogen production through integration with electricity systems.	• **Regulatory framework for electricity production** including regulatory innovation in grid capacity connection timelines and fees and policy innovations in the price of electricity to be supplied to electrolysis projects.
Enabling hydrogen carriers and supply chains: Innovation to enable cost-effective, scalable hydrogen transport and storage through carriers and infrastructure enabling reliable large-volume logistics and import pathways, essential to meeting EU hydrogen demand and supply security.	• Development of innovative business models may enable other forms of **hydrogen carriers and other storage media** to provide long duration, stationary hydrogen storage. Innovations remain across LOHCs, Ammonia and LH_2 value chains. • Acceleration of site characterization, permitting and planning for **sub surface storage** as well as development of cycling methods that align operation with variable production.
Electrolytic hydrogen production: Innovation to improve the competitiveness of electrolytic hydrogen production by reducing CAPEX, improving efficiency, durability and flexible operation, whilst reducing CRMs.	• **Reduce CRM dependency:** Continue to develop AEM technologies that have little requirement for CRMs and progress innovative thrifting and recycling processes. • **Increased electrolyser performance through i**mproved BoP interface with stack and increased efficiency through novel membranes, catalysts and project configurations.
Enabling hydrogen end use: Accelerate uptake across industrial end-use applications. The focus is on reducing initial CAPEX investment and de-risking early deployments through technology, integration and innovation.	• Establish **demand side support measures** including CAPEX support for hydrogen offtakers and targeted support/incentives for switching grey users to green hydrogen. • Develop **fuel agnostic hydrogen technologies** such as multi-fuel combustion and conversion equipment that can fuel switch across hydrogen, ammonia and methanol.
Other enablers: Other supporting innovations which may act to increase the viability of hydrogen supply chains from either a technology or commercial perspective.	• Develop the **role of AI** in short-term price forecasting, optimising hydrogen production. Reduce **regulatory barriers** by acceleration of infrastructure permitting timelines through digitalization and standardization. • **Increased knowledge sharing** through best-practice databanks, including open test data from projects across the value chain.

The mechanisms to scale hydrogen are evolving, moving from R&D to commercial deployment demanding new innovation mechanisms

The EU's challenge is no longer early-stage innovation, but translating innovation into cost-competitive, scalable deployment. Barriers are increasingly structural and system-level (cost, infrastructure, demand), rather than technology performance focused.

Innovation must continue to span the technology and system development lifecycle, but needs to pivot towards realising commercial deployment and achieving global competitiveness

Hydrogen R&D

Shifting from public sector led, to private sector led requires:

- Demand creation
- Revenue certainty
- Infrastructure integration

Commercial Deployment

Public private partnerships have played a key early role in supporting innovation and de-risking pilot projects. However, they must evolve to support commercialisation, key areas of focus should include market building instruments (e.g. CfDs, mandates), investment grade structures and whole value chain coordination.

Alongside PPPs, other change mechanisms are necessary to drive scale within the hydrogen sector; **industrialisation** is required to avoid fragmentation and a lack of system integration, increased **coordination** efforts are needed to derisk and align stakeholder expectations, **blended finance and targeted investment are** also critical to move projects towards FID and overcome first of a kind cost premiums. Seven core change mechanisms have been assessed across the priority innovation areas to determine which enablers need to considered to drive progress in each area.

The following change mechanisms have been identified as potential enablers of these innovation areas

Matching change mechanisms to innovation areas (1/3)

Innovation theme	Innovation areas	Primary change mechanisms	Secondary change mechanisms
Manufacturing at scale	Manufacturing advancements	• Targeted investment • Industrial collaboration	• Public funding and financing instruments • Market creation and demand mechanisms • Capacity building and knowledge sharing
	Component standardization	• Industrial collaboration • Capacity building and knowledge sharing	• Targeted investment
Hydrogen ecosystems	Advancing hydrogen valleys	• Industrial collaboration • System integration planning • Capacity building and knowledge sharing	• Public funding and financing instruments • Market creation and demand mechanisms
	Business model and investment	• Market creation and demand mechanisms • Targeted investment	• Policy, regulation and standards • Industrial collaboration
	Clustering of supply chain manufacturing	• Industrial collaboration	• Capacity building and knowledge sharing • Targeted investment
Renewable power	Regulatory framework for electricity production	• Policy, regulation and standards	• Industrial collaboration • System integration planning

The following change mechanisms have been identified as potential enablers of these innovation areas

Matching change mechanisms to innovation areas (2/3)

Innovation theme	Innovation areas	Primary change mechanisms	Secondary change mechanisms
Hydrogen carriers and supply chains	Hydrogen carriers and storage media	• Policy, regulation and standards • Industrial collaboration • System integration planning	• Public funding and financing instruments • Market creation and demand mechanisms • Capacity building and knowledge sharing
	Sub-surface storage	• Policy, regulation and standards • System integration planning	• Public funding and financing instruments • Market creation and demand mechanisms
Green hydrogen production	Reduce CRM dependency	• Public funding and financing instruments • Industrial collaboration	• Capacity building and knowledge sharing
	Increased electrolyser performance	• Public funding and financing instruments • Industrial collaboration • Targeted investment	• Capacity building and knowledge sharing
Enabling hydrogen end use	Demand side support measures	• Policy, regulation and standards • Public funding and financing instruments • Market creation and demand mechanisms	• Industrial collaboration • Capacity building and knowledge sharing
	Fuel agnostic hydrogen technologies	• Industrial collaboration • Targeted investment	• Public funding and financing instruments

The following change mechanisms have been identified as potential enablers of these innovation areas

Matching change mechanisms to innovation areas (3/3)

Innovation theme	Innovation areas	Primary change mechanisms	Secondary change mechanisms
Other enablers	Role of AI	• Industrial collaboration • Capacity building and knowledge sharing	• Public funding and financing instruments
	Regulatory barriers	• Policy, regulation and standards	• Industrial collaboration • System integration planning
	Increased knowledge sharing	• Industrial collaboration • Capacity building and knowledge sharing	

The contribution of PPPs to European hydrogen competitiveness

PPPs have also been a key driver of some of Europe's hydrogen innovation leadership to date by combining public support with private-sector expertise, investment and deployment capability. Four key contribution areas which have been identified through this analysis are outlined below:

Accelerating innovation

- Support R&I and demonstration activities
- Reduce technology development risk
- Advance development of electrolyser, fuel cell and infrastructure technologies

Mobilising investment

- Leverage private capital
- Improve investor confidence
- Support demonstration and FOAK projects

Building ecosystems

- Connect industry, academia and public institutions
- Support hydrogen valleys and industrial clusters
- Facilitate and encourage knowledge sharing

Supporting strategic priorities

- Ensure innovation is aligned with climate, energy and competitiveness objectives
- Develop European technology leadership in key areas

PPPs have been particularly effective because they address multiple barriers simultaneously, including technology, investment, coordination and deployment.

The role of PPPs must also evolve as the hydrogen sector scales

Public–private partnerships have been key development mechanisms to date, but must evolve to support future competitiveness

WHAT PPPs DO TODAY
Current role & proven value

- Drive R&I priorities
- Fund early-stage TRL deployments and de-risk first movers
- Mobilise private investment through co-funding mechanisms
- Enable project delivery (e.g. Mallorca green H_2 ecosystem)

Proven benefits:

✓ Enabled early market investment

✓ Driven cross-industry collaboration

WHY THIS MAY NOT SCALE
Tensions emerging at scale

⚠ Public-to-private handover gap remains unresolved

⚠ At scale, revenue support and certainty matter more than capital grants

⚠ Current PPP models do not consistently drive Final Investment Decisions

⚠ Risk of abandoned projects if market imperfections go unaddressed

HOW PPPs COULD EVOLVE
New models for a maturing sector

▶ Continue early TRL funding for strategic technologies, but add market mandates

▶ Bridge the gap from flagship projects to commercial demonstration, such as through targeted equity investment.

▶ Shift from funding to financing and market-building instruments (e.g. CfDs, RFNBO quotas, purchase mandates)

▶ Consider concession-style PPPs or options such as design-build-operate models for large H_2 infrastructure, such as pipelines, storage, and terminals) which can reduce investor risk

PROVEN MODEL → SCALING TENSIONS → EVOLVED APPROACH

The preceding analysis identified a set of change mechanisms that can help address Europe's competitiveness gaps across cost, scale, infrastructure, demand and industrial development. PPPs have historically been a key vehicle for delivering many of these interventions, combining public policy objectives with private-sector expertise, investment and delivery capability. As the hydrogen sector matures, the role of PPPs must evolve beyond technology development to ensure the EU can achieve competitiveness in the global market.

A coordinated governance structure is required to deliver hydrogen competitiveness objectives

The competitiveness barriers identified in this study span technology development, infrastructure deployment, market creation and industrial scale-up. Addressing these challenges requires coordination across multiple governance levels whilst maintaining clear accountability for strategic direction, implementation and oversight.

Governance function	Direction	Decision	Delivery	Assurance
Purpose	Set strategic objectives and priorities	Approve programmes, investments and funding priorities	Implement projects, infrastructure and market interventions	Monitor performance, competitiveness outcomes and return on public investment
Typical owner	EU institutions	EU institutions & Member States	Member States, regions, industry, supply chains and PPPs	EU institutions, funding bodies and programme governance
EU Institutions, CHP	Set competitiveness objectives, innovation priorities, industrial strategy alignment and long-term hydrogen vision	Approve funding programmes, strategic priorities and cross-border initiatives	Coordinate European programmes and strategic infrastructure initiatives	Monitor competitiveness outcomes, return on public investment and overall programme performance
Member States	Translate EU objectives into national hydrogen, industrial and energy strategies	Allocate national funding, incentives and support mechanisms	Deliver permitting reform, market creation measures and national infrastructure plans	Monitor effectiveness of national interventions and progress against deployment targets
Regions, valleys, clusters	Identify regional strengths, industrial opportunities and investment priorities	Prioritise regional projects, cluster development and infrastructure investments	Implement projects, hydrogen valleys, workforce development and local supply-chain initiatives	Monitor regional economic impacts, deployment progress and industry growth
Industry, PPPs	Provide market intelligence, technology insights and investment signals	Commit capital, partnerships and deployment decisions	Deliver projects, manufacturing capacity, infrastructure and commercial operations	Share performance data, disseminate lessons learned and demonstrate competitiveness impacts

Europe already has strong delivery mechanisms through innovation programmes, hydrogen valleys and industrial projects. Future governance challenges are therefore likely to be concentrated around strategic direction and assurance.

Future governance evolution should focus on direction and assurance

Many competitiveness barriers identified in this study sit beyond technology development and require coordinated action across European, national and regional actors. Challenges such as infrastructure deployment, supply chain development and investment span multiple stakeholders and cannot be addressed by any single organisation or level of government in isolation. As the hydrogen sector matures, governance must increasingly focus on ensuring innovation support is aligned with long-term competitiveness objectives and ensuring that interventions deliver measurable outcomes.

Direction

Current challenge

- Innovation, industrial, energy and infrastructure planning often operate separately.
- Competitiveness objectives are distributed across multiple programmes and policy frameworks.

Future focus

- Establish competitiveness objectives across programmes and policies.
- Align innovation, infrastructure and market development priorities.
- Coordinate actions across EU, national and regional levels.
- Focus support on deployment, scale and supply-chain growth.

Assurance

Current challenge

- Success is often measured through project delivery and technology progress and KPIs.
- Limited focus on wider competitiveness outcomes.

Future focus

- Monitor deployment, scale up and supply chain growth.
- Assess return on public spending.
- Track whether innovation is translating into industrial competitiveness.
- Identify and address fragmentation across Member States.

Key governance takeaways from this study:

1 Shift from project support to ecosystem development

Hydrogen competitiveness increasingly depends on integrated ecosystems combining production, infrastructure, end-use demand and supply chains rather than individual project/technology developments.

2 Stronger alignment of innovation, industrial and energy policy

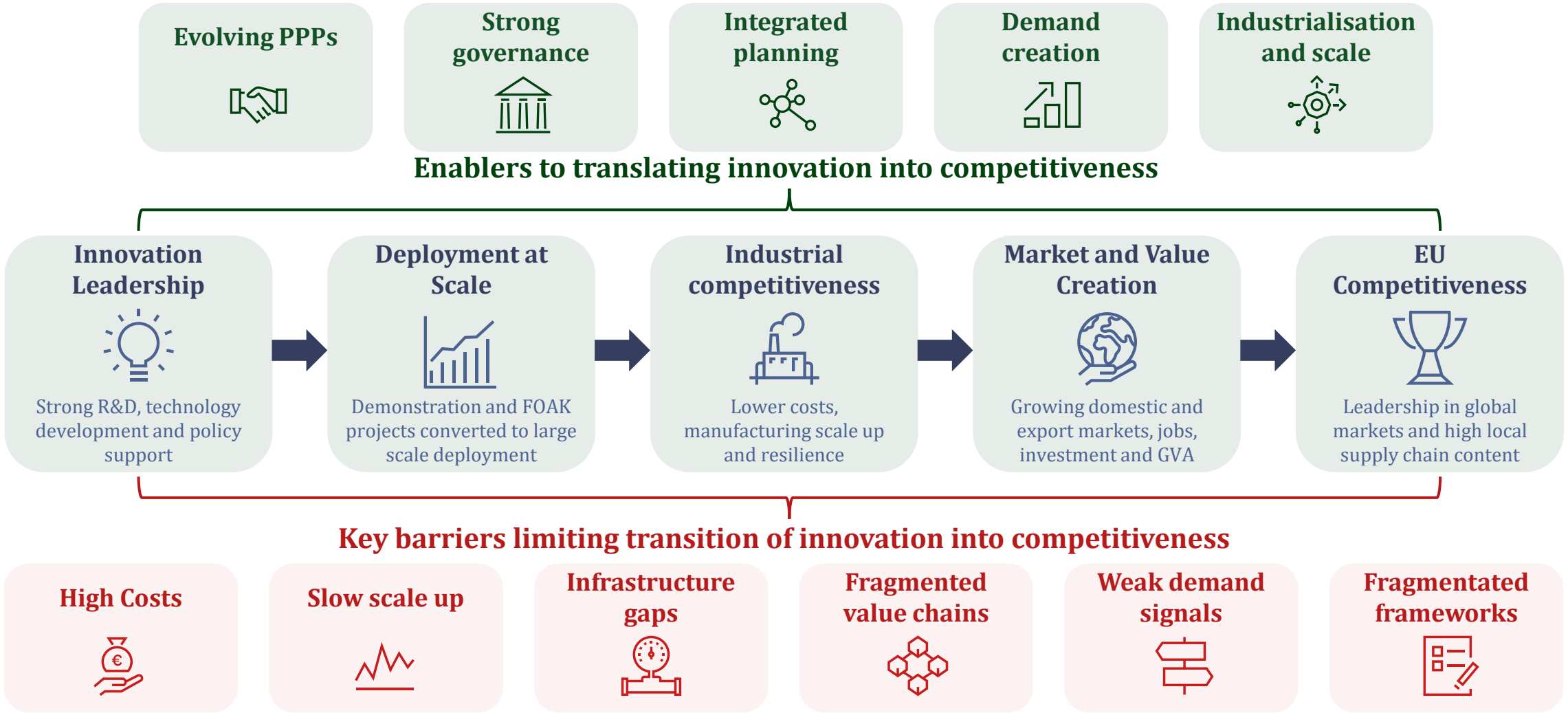
Many competitiveness barriers identified in this study sit outside technology development. Innovation support should continue here, but ensure focus be coordinated with infrastructure planning, industrial strategy and market creation measures.

3 Reduce fragmentation and improve coordination

Differences in permitting, support mechanisms, certification and infrastructure planning can slow deployment and increase costs. Stronger alignment across Member States can accelerate delivery, improve interoperability and support integrated value chains.

Translating innovation leadership into competitiveness

Europe's challenge is less about generating innovations across the sector. It's converting these innovative ideas into lower costs, larger markets and stronger domestic value chains



Thank you

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Appendix

Long list of innovation opportunities (1/13)

Innovation name	Innovation theme	Description
Manufacturing at scale	Manufacturing at scale	**Justification**: While manufacturing scale-up and automation is widely recognised as a long-term requirement for the EU hydrogen sector, it is not yet an area with a clear or coordinated strategic focus. The core opportunity lies in overcoming early-stage production constraints that currently keep costs high and lead times long. Electrolyser and fuel cell manufacturing remains characterised by low production volumes, limited automation, and fragmented designs across OEMs, which restrict the achievement of economies of scale and slow deployment against EU capacity targets. **Innovation need:** Experience from modular clean-energy technologies such as solar PV and lithium-ion batteries demonstrates that manufacturing learning rates of ~18–23% per doubling of cumulative production can translate into cost reductions of 70–90% over multiple scale-up cycles, driven less by breakthrough technology than by factory scale, standardisation and automation. By contrast, electrolysers are still largely produced at sub-GW annual manufacturing scale, well below the thresholds at which semi-automated and fully automated production lines become economically viable. For hydrogen technologies, manufacturing learning-by-doing rates in the range of 15–21% per doubling of cumulative capacity have been reported for alkaline and PEM electrolysers [1]*, implying that scaling cumulative deployment by one order of magnitude could reduce stack and system CAPEX by approximately 30–50%, excluding electricity costs. However, these reductions are contingent on addressing structural manufacturing barriers rather than relying solely on deployment-led learning [2]. **Specific innovation areas:** Increased automation Gigascale production lines Increased standardisation (see next point) Innovation to reduce complexity: design for manufacture
Advancing hydrogen valleys	Supporting hydrogen ecosystems	**Justification**: A cluster-based approach to the deployment of hydrogen technologies is a useful vehicle for mitigating several risks commonly found with hydrogen deployment, such as the proximity to demand and the availability of distribution infrastructure. However, there are still hurdles such as technology risks, integration challenges and the availability of financing for the distinct elements of the Valleys that still need to be addressed to ensure that the model can be scaled further. **Innovation need:** In hydrogen valleys, innovation could build on the clustering of hydrogen producers and users to ensure that there is free flow of information among them. Although several hydrogen valleys have received subsidy support, innovation is needed to ensure that there is continued financial and knowledge management support to enable the valleys' sustainable scale up [3,4]. **Specific innovation areas:** Formation of clusters of demand and supply: This could be through tendering platforms and digital marketplaces that prioritise geographical proximity. Trust-based supplier networks: certified supplier lists and audited services, which can mitigate risks, especially for the early adopters of the technology. Centralised independent valley support: The valleys will likely require support beyond the funded project lifetime, and there could be innovation in determining the type of agency that will be needed to maintain a centralised knowledge platform and mobilise public and private investment in the regions. Prioritisation of high maturity products while encouraging innovation: Having valleys as a testbed for early TRL deployments can provide a pathway to these technologies' demonstration while ensuring that valleys prioritise deployment of a selection of demonstrated technologies at scale.

*Appendix references are collated on the last slide

Long list of innovation opportunities (2/13)

Innovation name	Innovation theme	Description
Improving the reliability and affordability of electricity supply to hydrogen production and processing	Improving the reliability and affordability of electricity supply to hydrogen production and processing	**Justification:** The reliability and affordability of the renewable electricity system is a crucial contributor to the competitiveness of the hydrogen sector. The ability of hydrogen production projects especially to source sufficient renewable energy depends on the capacity of the system through which the electricity is transmitted. Renewable energy is intermittent and different combinations of supply may be needed for each project to ensure its viability. Additionally, hydrogen production and processing are currently significantly electricity-intensive. While innovations are needed to improve the efficiencies of these processes and thus the energy requirements, innovations are also needed to reduce the cost of electricity [6]. **Innovation areas:** Innovation in ensuring that electrolyser systems are capable of adjusting their operation will enable electrolyser projects to support the stability of the grid through providing grid balancing services in the short, medium and long term [6]. Innovations could also ensure that Europe offers cost-competitive electricity prices to large-scale electricity consumers. **Specific innovation areas:** Innovations in reversible Solid Oxide Cells can also increase hydrogen's role in longer term energy system management. Reducing the cost contribution of electricity to hydrogen production could involve regulatory innovation in grid capacity connection fees or policy innovations in the price of electricity to be supplied to electrolysis projects, e.g. as done in the UK through its British Industrial Competitiveness Scheme (BICS).
Enabling hydrogen carriers and supply chains	Enabling hydrogen carriers and supply chains	**Justification**: Under REPowerEU Strategy (2022), 10 million tonnes of imported hydrogen is targeted by 2030 (an equal amount is targeted for production). This is set to grow: by 2050, around 10% of Europes energy needs is expected to be met by renewable hydrogen. While European production will also grow, innovation in carriers will be necessary to ensure that imported hydrogen is cost-competitive and technologically feasible at the required scale. **Innovation need:** LOHC - Various liquid organic hydrogen carriers are available, each with slightly different performance benefits (toluene, BT, and DBT are most commonly used today). The dehydrogenation step (release of hydrogen from storage) is energy intensive (~300 degC), reducing round trip efficiency. Liquid carriers are currently mostly used as heat transfer fluids, with limited production capacity [7]. Ammonia - Commercial-scale ammonia crackers are approaching deployment, and while the underlying process is well understood, large-scale demonstration is still required. Cracking is high-temperature and energy-intensive, creating opportunities for efficiency improvements. Terminal/port infrastructure to handle large volume of ammonia also require development [8]. Liquid hydrogen - Liquefaction is highly energy intensive, requiring energy equivalent to about 30% of hydrogen's LHV to liquefy it. Liquefiers are mature technology but wide deployment has not been required by the market. Given its very low liquefaction temperature (-253 degC at atmospheric pressure), boil-off during transport and storage can lead to losses, decreasing round trip efficiency [9]. **Specific innovation areas:** LOHC - Innovative or new carrier liquids could reduce the energy intensity of the dehydrogenation process, while retaining or improving upon storage properties (wt% of hydrogen stored). Reactor catalyst developments may further reduce energy requirements by improving conversion efficiencies. Development of innovative business models may enable LOHCs to provide long duration, stationary hydrogen storage. Ammonia - Following commercial demonstration at scale, improvements in cracker efficiency to reduce energy requirements would reduce operating costs. Liquid hydrogen - Improvements to liquefaction efficiency through novel cycles would reduce energy requirements (early research demonstrates opportunity to reduce energy requirements by around 50%). Material, insulation or boil-off management innovation could reduce efficiency losses from boil-off.

Long list of innovation opportunities (3/13)

Innovation name	Innovation theme	Description
Clustering of supply chain and manufacturing	Supporting hydrogen ecosystems	**Justification:** Europe's hydrogen supply chain is fragmented, with dispersed suppliers, uneven skills availability and long lead times for critical components. Purpose-built manufacturing clusters (akin to hydrogen valleys on the demand side) can accelerate scale-up by concentrating suppliers, shared services, testing and logistics, while anchoring investment and skilled jobs close to end markets. Clustering also improves resilience (dual sourcing, local spares), raises quality through common standards and reduces unit costs via learning effects. **Innovation need:** Establish governance, shared infrastructure and incentives that enable geographically concentrated "make" ecosystems for stacks, BoP and storage/distribution equipment. This will help in linking OEMs, Tier-1/2 suppliers, recyclers, skills providers and test labs. The objective is faster time-to-market, higher yields, lower costs and a robust, EU-based supply chain [10]. **Specific innovation areas:** Cluster governance & incentives: dedicated SPV/authority, simplified permitting, targeted tax/land incentives and "one-stop shop" services. Shared industrial infrastructure: pilot/prototyping lines, metrology & reliability labs, environmental test chambers, cleanrooms, hydrogen safety training sites. Standards & QA/QC: common specifications, supplier qualification frameworks, PPAP/APQP-style gates adapted for electrolysers/fuel cells. Supplier development: Tier-2/3 capability uplift programs, vendor-managed inventory, joint purchasing of scarce inputs. Skills pipeline: regional academies and apprenticeships aligned to stack assembly, automation, NDE and H_2 safety. Circularity hubs: end-of-life take-back, PGM and membrane recycling facilities integrated into the cluster. Anchor demand: framework agreements with public buyers/utilities; lighthouse projects that offtake cluster output. Digital backbone: shared data standards and secure platforms for yield tracking, traceability and product passports.
Business model and financing innovations	Supporting hydrogen ecosystems	**Justification:** Hydrogen technology is currently capital intensive because most equipment is not manufactured at scale. Therefore, the deployment of these technologies often requires multiple routes of investment as well as financing. Sourcing financing is challenging for hydrogen projects compared to capital projects in other more mature technology sectors. This increased risk perception is due to offtake uncertainty, technology risks, limited financing track records, among other factors that draw into question the feasibility of deployment [11]. **Innovation need:** Innovation is needed to address the distribution of risks among stakeholders in the value chain. This could help lower the barriers to entry and encourage investment in the sector. Innovation is also needed in the portfolio of financing instruments, to ensure that sufficient financing options are available for different business and deployment models while ensuring long-term viability. **Specific innovation areas:** Increasing the risk borne by the public sector in the near to medium term, through contracts for difference, government-secured last-resort demand, regulated asset base models. Government support through Export Credit Agencies to bridge the financing gap for equipment manufacturers exporting goods. Business model innovation could redistribute the investment and risks borned by interacting players in the value chain, e.g. different iterations of hydrogen supply, power and mobility as a service models. Insurance products suited to hydrogen sector to mitigate the risks to the users over the course of the hydrogen asset's lifetime. Developing a second market for hydrogen assets through leasing models for PGMs

Long list of innovation opportunities (4/13)

Innovation name	Innovation theme	Description
Sub surface geological storage: salt cavern, oil & gas storage	Enabling hydrogen carriers and supply chains	**Justification:** The EU has recognised the central role that will be played from large scale underground hydrogen storage to support the intermittent production of electrolytic hydrogen. Although there isn't an official target capcity, studies estimate that by 2030 45 TWh of UHS is needed. In contrast, the planned capacity currently sits at only 9 TWh by 2030 [12]. This gap creates a clear innovation opportunity as UHS capacity grows (salt caverns, depleted oil and gas stores, lined rock caverns, acquifers). The gap between estimated need and planned capacity creates a clear bottleneck, driven by site selection complexity, subsurface uncertainty, and long development lead times [13]. **Innovation need:** Innovation should focus on accelerating development while reducing subsurface risk and improving operational confidence, including purity management and cycling optimisation. **Specific innovation areas:** Site selection acceleration: improved screening approaches, standardised survey methodologies, and better early-stage uncertainty reduction. Monitoring and integrity: subsurface integrity scans, continuous monitoring approaches, and performance verification frameworks. Operational optimisation: cycling strategies that align storage operation with variable renewable production. As noted by flagship EU projects such as HyPSTER, cavern usage optimisation will also need to be further studied, to help optimise cycling of the storage facility alongside the intermittent renewable production. Purity management: mitigation and monitoring of microbial reactions that can reduce hydrogen purity. Brine management
Engineered (Above and below ground) storage	Enabling hydrogen carriers and supply chains	**Justification:** Large-scale hydrogen storage is essential for system balancing, yet both above-ground and geological storage options face cost, efficiency, safety and lead-time challenges. **Innovation need:** Innovation should focus on reducing energy losses, improving safety and shortening development timelines to enable storage to scale alongside hydrogen production. **Specific innovation areas:** Liquefaction is a major cost barrier for high capacity storage designs and remains one of the highest OPEX contributors for liquid hydrogen systems, with liquefaction requiring ~40% of the energy content of hydrogen [14[. Improvements in pre-cooling cycles, compressor efficiency, and heat-exchanger materials can materially lower energy use and reduce liquid hydrogen unit cost. Large scale above ground hydrogen storage has a critical role across project development, system balancing, and early-stage market creation. Some of the main challenges with current technology are centred around design and materials. Minimising boil off and improving insulation are two key areas which contribute to the efficiency challenges and high OPEX. Also safety and hydrogen embrittlement. Optimisation of cycling strategies for intermittent supply is also a key areas to avoid curtailment.

Long list of innovation opportunities (5/13)

Innovation name	Innovation theme	Description
Pipeline repurposing	Enabling hydrogen carriers and supply chains	**Justification:** Repurposing existing gas pipelines is central to EU hydrogen infrastructure plans and can reduce both cost and time relative to new-build. The main constraints are integrity assurance, asset condition uncertainty, certification requirements, and the need for targeted retrofits to make legacy systems hydrogen-safe. The 60% of EHB pipelines that are set to be repurposed from existing natural gas pipelines offer a clear opportunity for innovation in the materials, seals and valves that are used to make these hydrogen-safe. Innovation in testing and certification may enable the use of existing equipment, lowering pipeline conversion costs [15]. **Innovation need:** Innovation should shorten repurposing lead times and lower conversion costs by providing faster, standardised pathways to assess, qualify and retrofit assets for hydrogen service. **Specific innovation areas:** Accelerated assessment: integrity testing and inspection methods focused on embritttlement susceptibility and fatigue performance. Retrofit solutions: cost-effective upgrades for seals, valves and interfaces most sensitive to hydrogen. Certification frameworks: standardised re-qualification approaches that are recognised across jurisdictions. Digital asset management: tools to manage lifetime assurance, maintenance scheduling, and evidence packs for regulators.
Reduce dependencies on electrolyser CRMs	Electrolytic hydrogen production	**Justification**: Significant scale up of renewable hydrogen production is required to meet European (and global) targets. PEM is a common technology, increasing in market share, which requires iridium and platinum. In order to meet global hydrogen production targets through electrolysis, a major scale up of PGM production would be required (PGMs are also used in other energy transition technologies that are likely to scale, creating competition) [16, 17]. **Innovation need** PGMs in electrolysers are expensive and extraction and production is energy intensive, and concentrated in few geographies. Existing supply chains could constrain scale-up of electrolyser production, to the detriment of hydrogen deployment targets. Reducing reliance on PGMs is necessary to support scale-up that aligns with hydrogen targets. **Innovation areas** Technologies - AEM electrolysers are likely to offer similar performance to PEM electrolysers but with little or no requirement for PGMs. But this technology is yet to reach full commercial maturity and deployment, and has durability issues. Supporting development in this technology could offer a route to reduce PGM reliance. Manufacturing techniques and thrifting - Advanced manufacturing techniques can reduce the quantity of PGMs required by PEM electrolysers. Recycling - as electrolyser stacks reach end of life, innovative recycling processes with high recovery of PGMs would reduce demand for new production. Together, these can reduce long-term material demand, aiming to avoid the PGM supply chain constraining required growth to meet hydrogen deployment targets.

Long list of innovation opportunities (6/13)

Innovation name	Innovation theme	Description
Demand side support measures	Enabling hydrogen end use	**Justification:** European hydrogen offtakers have not signed sufficient binding offtake agreements to meet EU targets, with offtaker demand currently too weak and uncertain to unlock large-scale investment. While supply side incentives are accelerating early electrolyser deployment, industrial consumers face high switching costs, long asset lifetimes, and concerns over availability and pricing of low-carbon hydrogen. There is a large current market for fossil-derived 'grey' hydrogen offtakers, however these currently have limited appetite to pay a green premium.The last five years of innovation funding from CHP has focussed on production, storage & distribution and hydrogen valleys; with stationary end-use recieving ~7% of total funding. Applications such as burners for industrial users or hydrogen ready turbines for power generation could represent a significant fraction of future hydrogen demand, but there does not appear to be much support to help deploy these technologies [18]. **Innovation need:** Demand side innovations need to focus on reduce cost and risk to offtakers in order to increase the number of binding offtake agreements. Reducing upfront conversion costs for industrial offtakers, particularly in ammonia, refining, methanol, and chemicals where grey hydrogen is already deeply embedded would avoid some of the challenge with switching to hydrogen in novel use cases and could help stimulate early demand. **Specific innovation areas**: CAPEX support for hydrogen offtakers helps reduce upfront costs for industrial users adopting hydrogen ready equipment, improving switching economics in early markets. Targeted support for existing grey hydrogen users closes the cost gap to green hydrogen and accelerates decarbonisation in large, concentrated demand centres. A matchmaking and demand-aggregation platform pools offtake needs, standardises contracting, and creates scale that improves bankability for new hydrogen projects. Using blending as an offtaker of last resort provides a flexible demand sink that stabilises early project economics and mitigates volume-risk for producers.
Role of AI	Other enablers	**Justification:** Hydrogen assets and supply chains are complex, capital-intensive and data-rich, with performance and cost hinging on thousands of variables (renewable intermittency, stack health, compression/refrigeration duty, logistics). AI can unlock step-changes in reliability, OPEX, throughput and safety, from gigafactory quality control to grid-responsive electrolyser dispatch and MRV of “clean” attributes [19, 20]. **Innovation need:** Build the data foundations (high-quality, tagged datasets; interoperability; cyber-secure pipelines) and deploy trustworthy, explainable AI that operators and regulators accept. Focus on use-cases that demonstrably lower LCOH/TCO, increase availability, and de-risk permitting and safety. **Specific innovation areas:** Manufacturing: machine-vision for cell/MEA defects, inline EIS-informed process control, predictive yield optimisation, scheduling of robotic assembly. Plant operations: AI-assisted set-point control (incl. reinforcement learning) for efficiency vs degradation trade-offs; anomaly detection for compressors, chillers, dispensers. Grid & market: short-term price/renewables forecasting, automated bidding/curtailment harvesting, co-optimisation of hydrogen output with grid services. Safety & integrity: continuous leak detection from sensor fusion; risk-aware maintenance planning; alarm rationalisation. Siting & logistics: AI for pipeline routing/linepack management, trailer fleet optimisation, HRS reliability and spare-parts positioning. MRV & provenance: automated hourly matching of GOs/RECs; emissions and water-use accounting with audit-ready trails. Materials discovery: AI-guided catalyst/membrane screening to reduce CRMs and boost durability (bridge to low-TRL work). Permitting & knowledge: copilots that generate/validate submissions and surface precedent conditions from prior projects.

Long list of innovation opportunities (7/13)

Innovation name	Innovation theme	Description
Performance improvement gains (electrolysers)	Electrolytic hydrogen production	**Justification**: Electricity prices are high in Europe. Electricity makes up a significant proportion of electrolyser project operating costs and may be prohibitively expensive in some scenarios. Improvements to efficiency will reduce project operating costs. **Innovation needs:** The European context of high power prices, means that higher efficiency in electrolyser stacks can have larger returns on lowering LCOH. Developing higher efficiency electrolyser technologies in Europe for European market could provide greater market share to European manufacturers, by making their products better performing (and able to deliver lower TCO) than foreign electrolysers. To reach higher efficiency, more development of membrane designs, materials and assembly methods can be achieved. Although efficiencies of some established technologies such as PEM and ALK are already above international market standards, SOEC and other emerging technologies including AEM continue to have room for growth [21]. Higher efficiency can also be obtained through improved system design, reducing losses frm BoP and other interfaces the electrolyser stack has. Furthermore, an increasing area of innovation is the design of systems that have multiple stacks of different technologies (e.g. one ALK and one PEM stack) to best follow a flexible renewable electricity generation profile. This can increase the system eficiency (rather than at stack level), thus reducing LCOH. This is perhaps more of a 'must meet a minimum standard to be competitive on the market' (which it is already acheiving), rather than 'European manufacturers must be the best', given that the benefit is relatively small in the context of overal European sector competitiveness [22]. **Specific innovation areas:** Improving membrane materials, catalysts and cell design can increase stack efficiency and durability while reducing overall energy consumption. Enhancing the interface between the stack and balance of plant can reduce system losses and support more reliable and flexible operation. Using novel project configurations such as combining more than one stack technology can improve overall system efficiency by better matching renewable generation profiles.
Component standardisation	Manufacturing at scale	**Justification:** A critical bottleneck in the scaling up of manufacturing is the lack of modular, standardised component architectures. Current electrolyser designs exhibit high levels of part variability in stacks, balance of plant (BoP) and control systems, limiting repeatability and automation potential [23]. **Innovation need:** Targeted innovation in modular stack design, standardised interfaces and BoP could support best practiuce manufacturing approaches similar to those seen in solar PV and batteries, where standardisation was a key enabler of mass automation and supply-chain depth. Finally, investment in gigafactories (GWs per year), supported by standardisation could unlock step-change economies of scale. IRENA and NREL analyses suggest that reaching GW-scale annual production with a 20-fold increase in electrolyser plant size can reduce system costs by over one third,with further reductions achievable through cumulative learning and BoP optimisation. This would support more predictable lead times, lower costs, and improved bankability across EU hydrogen projects [24]. **Specific innovation areas:** Developing standardised PEM stack designs can increase interoperability and enable automated, repeatable manufacturing at scale. Standardising balance of plant components across OEMs can also reduce system complexity and lower costs by simplifying integration and supply chains.

Long list of innovation opportunities (8/13)

Innovation name	Innovation theme	Description
CCS-enabled hydrogen	Other enablers	**Justification:** CCS-enabled hydrogen production (typically via SMR or ATR with CO2 capture) is technically mature relative to renewable hydrogen, with core process units and capture technologies already deployed at commercial scale. As a result, the primary barriers to deployment are not fundamental technology readiness but the coordination and delivery of enabling infrastructure, regulatory clarity, and commercial de-risking [25]. Projects are highly dependent on the timely availability of CO2 transport and storage networks, permitting certainty, and credible long-term commercial frameworks. Where these elements are absent or misaligned, projects are delayed or fail to reach final investment decision. The experience from LNG, ammonia and other large-scale process infrastructure suggests that repeatable designs and coordinated infrastructure rollout, rather than incremental process improvements, are the dominant drivers of cost reduction and scale. **Innovation need:** Innovation is required to accelerate coordinated deployment of CCS-enabled hydrogen by reducing first-mover risk, improving integration with shared CO2 networks, and standardising delivery models. The focus should be on system-level and commercial innovation that improves bankability and pace of rollout, rather than pursuing marginal process efficiency gains in isolation. At the same time, incremental technical innovation remains important to ensure compliance with tightening low-carbon certification standards and to maintain competitiveness against renewable hydrogen as appropriate as policy thresholds evolve [26]. **Specific innovation areas:** Standardised, modular plant designs: repeatable ATR/SMR + CCS configurations that reduce engineering effort, shorten delivery timelines, and enable learning effects across multiple projects, similar to modular LNG and ammonia facilities. CO2 transport and storage integration: technical and commercial interfaces that enable seamless connection to shared CO2 networks, including standard specifications for CO2 quality, pressure and flow, and clear allocation of risk across the value chain. Cluster-based delivery models: coordinated development of hydrogen production, CO2 transport and storage within industrial clusters to address underutilisation risk and enable anchor projects to proceed ahead of full network build-out. Permitting and regulatory streamlining: clearer, faster permitting pathways for integrated hydrogen-CCS projects, including tie-in of hydrogen, CCS and industrial regulations to avoid sequential approval delays. Incremental performance improvements: targeted innovation to improve capture rates, hydrogen yield, energy efficiency and operational flexibility, particularly to maintain eligibility under evolving EU low-carbon hydrogen certification and emissions thresholds.
Addressing regulatory barriers to hydrogen projects	Other enablers	**Justification:** Industrial permitting can take a long time and lead to delays in hydrogen projects' realisation. The long timescales for permitting could be due to a lack of regulations and standards to govern the production, distribution and use of hydrogen. It could also arise due to inefficiencies in the governing body's permitting processes [27, 28]. **Innovation need:** Innovation in permitting should reduce timelines and thus lower the costs involved in their realisation. It should also ensure that the regulatory requirements and standards for hydrogen supply allow for interoperability of equipment and international hydrogen supply between regions. **Specific innovation areas:** Advances in permitting could address the following problems: Preferential permitting for hydrogen infrastructure compared to fossil fuel infrastructure. Regulatory alignment for technical requirements, and hydrogen quality and operational standards across Member States across which hydrogen pipelines will be constructed. Overall acceleration of permitting timelines through digitalization and standardization of an approach to hydrogen.

Long list of innovation opportunities (9/13)

Innovation name	Innovation theme	Description
Hydrogen ready pipelines	Enabling hydrogen carriers and supply chains	**Justification:** Planned new-build hydrogen pipelines represent a major share of future EU infrastructure, the European hydrogen backbone plans to build ~53,000km of hydrogen pipelines by 2040 and 40% of these are expected to be new-build dedicated hydrogen pipelines [29]. Building these at scale creates an opportunity for innovation in pipeline components, sensing and materials to improve reliability and reduce lifecycle costs, while ensuring interoperability across Member States. Furthermore, as hydrogen is extracted from the pipelines, particularly where it is blended with NG, there is room for innovation in the purification technologies that can be used to purify the hydrogen for end use. **Innovation need:** Innovation should reduce capital intensity and delivery risk through standardised designs, component qualification, and embedded monitoring approaches that provide confidence in safe operation over long lifetimes. **Specific innovation areas:** Using seals, valves and fittings designed specifically for hydrogen service can improve integrity under high cycling and reduce failure risk. Integrating distributed sensing, leak detection and integrity monitoring into the original pipeline design through composite pipe manufacture is another method to significantly improve safety and operational assurance. Applying common technical requirements and hydrogen quality expectations can support interoperability across borders and simplify system integration. Designing the interface with offtake to allow for purification where hydrogen is extracted can ensure reliable delivery, particularly when operating blended networks.
Hydrogen refuelling stations (HRS)	Enabling hydrogen end use	**Justification:** As the EU reaches aims to work towards the target of having a hydrogen refueling station (HRS) evert 200km on major networks and urban nodes, as per the Alternative Fuels Infrastructure Regulation, there is room for innovation in both the technical delivery of these HRS as well as the commercial models for their operation [30]. HRS roll-out requires not only infrastructure deployment but also consistent operational availability and acceptable OPEX. In Europe, station reliability and performance issues have created a credibility gap that slows market uptake, even where policy ambition exists. **Innovation need:** Innovation should priorities a shift from build-only targets to performance outcomes, with station designs and operating models that maximise uptime, simplify maintenance, and build user confidence [31]. **Specific innovation areas:** Improved station design using modular layouts and built in redundancy can increase reliability and reduce downtime. Standardising key equipment components such as nozzles and compressor valves together with integrated software and consistent testing can simplify deployment whilst reducing failure rates. Increasing the availability of spare parts through standardisation shortens repair times and can improve operational continuity. Clustering refuelling stations with centralised hydrogen production and multiple supply options can strengthen resilience and support higher utilisation. Contracting frameworks that link support to actual throughput rather than construction alone are a strong mode to incentivise performance and accelerate market development.

Long list of innovation opportunities (10/13)

Innovation name	Innovation theme	Description
Exploiting linepack in pipelines for storage and flexibility	Enabling hydrogen carriers and supply chains	**Justification:** Gas networks currently heavily rely on linepack storage to help meet peaks in demand. This form of storage is supplemented by external seasonal storage through geological formations such as salt caverns, however remains central to how the gas network is able to operate on a daily basis. As the gas network begins to transmit hydrogen, at an increasingly large rate, this use of linepack will need to be re-calibrated. Due to hydrogen's much lower density than natural gas, the same volume of pipes will store a lower quantity of linepack storage, hence reducing the amount of demand that the gas network could meet. This not only means that the amount of external (beyond linepack) storage will need to increase to support the gas network, but also leaves room for innovation in how daily and hourly peaks/troughs in demand are met by gas network operators [32, 33]. **Innovation need:** Innovation should address both operational approaches and commercial incentives so that hydrogen networks can manage peaks and troughs reliably, minimising the need for over-build of infrastructure. **Specific innovation areas:** Hydrogen-specific network modelling: tools to quantify linepack capability and constraints under varying blends and operating conditions. Operational strategies: new dispatch and pressure management approaches to maximise usable linepack. Integration with other flexibility: coordinated operation with above-ground storage, underground storage, and demand response mechanisms. Market design: incentives for network users to provide flexibility (for example through tariff structures and balancing product design).
Fuel agnostic hydrogen technologies	Enabling hydrogen end use	**Justification:** As the market for production and imports for hydrogen derivative fuels grows in Europe (see point on hydrogen carriers), there is a clear innovation opportunity to develop technologies that can use these fuels directly for power generation. Power Generation is a key end use identified for the hydrogen sector, in line with the EU hydrogen strategy, but doesn't need to be confined to pure hydrogen use. Manufacturers are developing fuel agnostic turbines, fuel cells and engines, all of which can be used with a range of hydrogen derivatives (most notably ammonia and methanol). These technologies de-risk hydrogen infrastructure build-out by avoiding early fuel-availability constraints can unlock early projects to test their operation in field [34, 35]. **Innovation need:** Innovation should accelerate demonstration and standardisation of fuel-flexible turbines, engines and fuel cells, ensuring they can be deployed credibly in power and industrial applications without creating undue certification barriers. **Specific innovation areas:** Multi-fuel combustion and conversion: development and qualification of equipment able to use hydrogen, ammonia and methanol. Controls and operability: control systems that manage fuel switching, ramping and emissions performance across fuels. Certification and MRV alignment: emissions accounting and standards that recognise multi-fuel operation. Field demonstrations: lighthouse projects that prove availability, maintainability and lifecycle cost performance.

Long list of innovation opportunities (11/13)

Innovation name	Innovation theme	Description
Low TRL technologies development	Other enablers	**Justification:** While near-term competitiveness depends on deployment-ready solutions, long-run leadership requires a pipeline of breakthroughs that bend cost, performance and sustainability curves (e.g., CRM thrifting, efficiency gains, storage density, safety). Without continued low-TRL investment, Europe risks lock-in to today's technologies and erosion of strategic autonomy [36]. **Innovation need:** Maintain a balanced portfolio that deliberately links TRL 2–6 research to demonstration pathways: translational funding, open testbeds, standardised IP/consortia models, and "stage-gate" milestones tied to real deployment metrics (durability under cycling, manufacturability, recyclability, CRM intensity) [37]. **Specific innovation areas:** Electrolysis materials: iridium-lean/PGM-free catalysts, durable membranes for start-stop, high-pressure stacks. SOEC & high-temperature systems: integration with industrial waste heat; degradation mitigation. Storage carriers: safer, lower-temperature LOHC catalysts; metal hydrides for specific niches; cryo-compressed concepts. Advanced sensing & safety: robust H2 sensors, embrittlement monitoring, passive safety features. Design-for-manufacture & recycling: architectures optimised for automation and high-recovery end-of-life. Alternative production routes: where compatible with sustainability goals and lifecycle performance.
Increasing knowledge sharing/dissemination/public awareness	Other enablers	**Justification:** Decades of EU and Clean Hydrogen Partnership projects have produced extensive technical and operational knowledge. Too often, lessons sit in PDFs or individual teams, leading to repeated mistakes, slower permitting and inconsistent public understanding. Systematic knowledge capture, access and use can materially shorten project timelines, improve safety and strengthen social license [38]. **Innovation need:** Create a living, user-centered knowledge system with mandatory uptake: standardised outputs, searchable best-practice, training/credentialing, and feedback loops that propagate what worked (and what didn't) into new projects and funding calls [31, 39]. **Specific innovation areas:** Best-practice databank: curated, searchable library (design patterns, typical pitfalls, HAZOP/LOPA templates, commissioning checklists, reliability stats). Open test data: non-sensitive datasets from pilots (load profiles, failure modes) to benchmark tools and models. Mandatory uptake: require applicants/grantees to complete short modules and "go/no-go" checklists based on prior lessons; tie to funding milestones. Post-project impact tracking: simple, standard KPIs reported 12–36 months after completion to capture real-world outcomes. Communities of practice: regular clinics across developers, OEMs, TSOs/DSOs, regulators and emergency services. Communications toolkit: plain-language assets (visuals, FAQs, safety narratives) for communities and policymakers; localisation/translation. Knowledge brokers: funded roles to help SMEs and new developers apply guidance to their contexts.

Long list of innovation opportunities (12/13)

Innovation name	Innovation theme	Description
e-fuels (Aviation and Maritime)	Enabling hydrogen end use	**Justification:** Hydrogen-derived e-fuels are strategically important for aviation and maritime, where direct electrification is challenging. The production of e-fuels for marine and aviation sectors has significant overlap with hydrogen innovation, as hydrogen related costs typically dominate overall production costs for hydrogen derived synthetic aviation fuel (SAF) costs, making the economics highly sensitive to electrolyser efficiency and electricity pricing. Fischer-Tropsch (FT) and syngas-based SAF plants typically require steady, baseload hydrogen supply, yet innovations in flexible, ramp-capable electrolysers could allow these facilities to draw on lower-cost, variable renewable power and correspondingly lower hydrogen costs—unlocking new operating models not currently feasible [40]. **Innovation need:** Innovation should target the "bankability stack" for e-fuels: improving integrated process performance, enabling flexible hydrogen supply strategies, and ensuring policy and support mechanisms reduce revenue risk rather than creating additional complexity. **Specific innovation areas:** Flexible hydrogen supply: ramp-capable electrolysers and operational strategies that can use variable renewable power while meeting synthesis plant needs. Integrated plant optimisation: better integration of hydrogen production, CO2 handling, syngas generation and synthesis to reduce efficiency losses and improve utilisation. Commercial and policy design: mechanisms that reduce revenue risk and avoid fragmented incentives across hydrogen and e-fuels. Allowing double-stacking of hydrogen and SAF subsidies would directly improve deliverability by enabling developers to access renewable hydrogen support and e-fuel incentives, which would revenue risk and narrowing the cost gap with conventional fuels. Scale-up demonstrations: large-scale demonstrations that prove operability, reliability, and replication potential in EU contexts.
Deblending	Enabling hydrogen carriers and supply chains	**Justification:** While hydrogen deblending is not a clear EU strategic focus, it offers the opportunity to overcome early infrastructure challenges and ensure minimise offtaker risk for sectors with tight fuel tolerances such as glass, chemicals and steel. Hydrogen deblending faces well-defined technical and economic barriers: current technologies are costly, often adding significant additional €/kg H2 (as much as €0.70-€2.50/kgH2 using current non-domestic electricity prices) and are sensitive to low hydrogen concentrations, odorants, multi-product specifications, and flow conditions. These constraints limit deliverability and make deblending a bottleneck for early blending-enabled hydrogen deployment. However, there are clear innovation opportunities focused on cost reduction and barrier removal [41, 42]. **Innovation need:** Innovation is required to reduce costs and expand the operating envelope of deblending technologies, while recognising fundamental economic limits. **Specific innovation areas:** Hybrid separation configurations (e.g. membrane and PSA systems) show potential to materially reduce purification costs compared with cryogenic methods, especially for industrial-scale applications, and enable higher-pressure outputs without extra compression Odorant-tolerant membranes, new odorant formulations, and improved recovery efficiencies could remove one of the most fundamental operational barriers, as existing technologies are easily poisoned or require downstream re-odorisation. Electrochemical hydrogen separation offers future cost-down potential at mobility scale if low-maintenance assumptions materialise, and is less sensitive to low hydrogen concentrations, presenting a pathway to deblend even lean blends. Systems-level advances, such as optimised network siting, scaling to achieve economies of scale, and matching deblending technologies to end-use purity/pressure requirements, could unlock more viable business cases for hydrogen offtake from early blended networks.

Long list of innovation opportunities (13/13)

Innovation name	Innovation theme	Description
Oxygen valorisation	Enabling hydrogen end use	**Justification:** Hydrogen production via water electrolysis generates 8 tonnes of oxygen for every tonne of hydrogen. This oxygen is typically vented because its value is low relative to hydrogen and purity requirements vary by sector. However, as electrolysis scales, these associated oxygen streams become large, continuous, and low-cost. This creates a clear innovation opportunity centred on capturing, upgrading, and utilising electrolytic oxygen to improve project economics and reduce emissions across adjacent industries. Offtake opportunities such as water treatment or oxy-fuel combustion require significant oxygen volumes, and co-location of electrolysers in these locations can reduce levelised costs of hydrogen by as much as 7% [43]. **Innovation need:** Innovation should focus on making oxygen utilisation practical and replicable, primarily through integration with nearby demand, low-cost upgrading, and standardised offtake and specification approaches. **Specific innovation areas:** Upgrading and handling: purification, compression and storage solutions appropriate for large continuous flows. Industrial symbiosis models: co-location approaches with sectors that can absorb volume reliably, supported by contractual structures that reduce offtake risk. Standard specifications: simplifying oxygen quality requirements where possible and standardising interfaces. Project design integration: ensuring oxygen valorisation is considered early in FEED, not retrofitted after commissioning.

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