BE-HyFE

# HYDROGEN: A VIABLE SOLUTION TO SUPPORT THE BELGIAN ENERGY TRANSITION?

White paper

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# Hydrogen in Belgium:
## From Hype to Realistic Pathways

A pragmatic roadmap for Making -Moving -Using low-carbon hydrogen

### MAKING

Low-carbon, diversified, realistic

- Limited renewables
- High cost
- Material constraints

**SOLUTIONS**

- ✓ Renewables + Nuclear + CCUS
- ✓ Cut electrolyser costs
- ✓ Focus on carbon intensity
- ✓ Support early projects

**OUTCOME**

Affordable, secure $H_2$ supply
Boosts industrial competitiveness

### MOVING

Robust & economically viable

- $H_2$ embrittlement
- Low utilisation
- Costly storage

**SOLUTIONS**

- ✓ Hydrogen-resistant alloys
- ✓ Repurpose pipelines
- ✓ $H_2$ + $CO_2$ planning
- ✓ Targeted subsidies

**OUTCOME**

Resilient $H_2$ infrastructure
Enhances EU energy security

### USING

Priority for hard-to-abate sectors

- High energy demand
- Retrofit challenges
- High $H_2$ costs

**SOLUTIONS**

- ✓ Decarbonise existing $H_2$
- ✓ Improve efficiency first
- ✓ Hydrogen-ready technology
- ✓ Heavy industry focus

**OUTCOME**

Targeted hydrogen use
Avoids wasteful applications

## The Policy Compass

- Focus on carbon intensity, not labels
- Combine production pathways
- Coordinate hydrogen & $CO_2$ networks
- De-risk early investments
- Protect energy security & industry

> **"The future is not purely electric. It is eclectic."**

# CONTEXT

This white paper was written by the PhD researchers of the BE-HyFE project, a Belgian academic collaboration, funded by the federal Energy Transition Fund of FPS Economy and coordinated by Ghent University. BE-HyFE brings together all the knowledge institutes in Belgium to conduct fundamental research on hydrogen. Project duration: 01/10/2021 - 31/03/2026.

The project includes 16 researchers working across the full hydrogen value chain, from production and infrastructure to end use. It is embedded in the wider Belgian hydrogen research community and maintains strong connections with industry and policy partners in a triple-helix collaboration. The team is multidisciplinary and combines engineering and technological expertise with socio-economic and policy perspectives.

This white paper reflects the ambition of the researchers to create impact beyond academic publications. Instead of limiting their work to individual PhD dissertations, they joined forces to translate their insights into a clear and accessible overview for policymakers and industry. Their complementary expertise and system-level perspective place them in a strong position to provide this balanced assessment of hydrogen's role in Belgium's energy transition.

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# TEAM

Marie Dejonghe
Ghent University

*Research focus: The energy security implications of large-scale imports of sustainable fuels*

Antoine Dechany
UCLouvain

*Research focus: Process implications for electrifying ammonia production*

Samuel Jottrand
ULB

*Research focus: Study of low-cost compressors for GH2 storage at high pressure*

Maria José Mendoza
UMONS / VUB

*Research focus: Impact of H2, H2-based fuels and their mixtures on the thermodynamic performance of gas turbines of different sizes*

Mauro Daese
KU Leuven / UCLouvain

*Research focus: An experimental and numerical investigation of CO2 diluted, oxy-fuel combustion in a reciprocating engine using mixtures of natural gas & H2*

Bryan Carré
ULiège

*Research focus: Optimized carbon supports for durable and high performance PEMFC electrodes*

Elisa Stendardo
VUB / UMONS

*Research focus: Towards fuel-flexible industrial combustion: investigation of the combustion performances of H2 and H2-based fuels*

Sohrab Pahlavan
IMEC / ULiège

*Research focus: Alternative electrocatalytic strategies for alkaline-based water electrolyzers & fuel cells*

# TEAM

## Lorenzo Vallisa
VKI / UGent

*Research focus: Advanced characterization of densified cryogenic hydrogen*

## Negar Namazifard
VITO / KU Leuven

*Research focus: Hydrogen policy and infrastructure modeling for industrial decarbonization*

## Digvijay Ghogare
UHasselt / VITO

*Research focus: Next generation of conductive and stable electrocatalysts for CO2/H2 conversion and H2 production*

## Joren Vanlaere
ULB / VUB

*Research focus: Safety of operations and logistics using GH2 and LH2*

## Robbe Jacops
UHasselt / UAntwerpen

*Research focus: Photo-electrochemical (PEC) water splitting for hydrogen generation*

## Foteini Lappa
ULiège / KU Leuven

*Research focus: CCU routes: Experimental study of catalysts and process designs for chemical synthesis using H2 and CO2*

## Ali Nabizada
UGent / UCLouvain

*Research focus: Developing hydrogen-resistant materials by innovative alloy design*

## Marijke Mahieu
Ghent University

*BE-HyFE Project Coördinator*

# INTENDED AUDIENCE

***Who:*** *Policymakers and industry leaders deciding on Belgium's energy future.*
***Why:*** *To separate realistic opportunities for hydrogen from hype and false promises.*
***What we ask:*** *Use this paper as a reference when weighing investments and policies.*

## POLICY MAKERS

If you are a **policymaker at the local or regional level,** you should read this because your decisions on planning, permitting, and guidelines will determine hydrogen's place in Belgium's energy mix. This paper offers a clear view of opportunities and limitations.

If you are a **national policymaker**, you should read this because your role is to balance climate goals, energy security, and affordability. Here you will find a factual basis for judging where hydrogen is necessary or useful, and where resources are better spent elsewhere.

If you are active in the **European policy arena,** you should read this to see how Belgium's choices fit into EU strategies. This paper highlights where alignment is possible and where risks of overlap or inefficiency may arise.

## INDUSTRY

If you are part of the **industrial community** -producing, transporting, using, or financing hydrogen- you should read this because your investment choices will decide whether hydrogen remains a niche or develops into a viable pathway. This paper provides a realistic overview of which applications are feasible and which are not.

***This document separates sense from nonsense, avoids hype and dogma, and provides a compass for choices that will shape Belgium's energy future.***

# INTRODUCTION

The Belgian energy transition is entering a decisive phase. Ambitious climate targets, rising energy demand, and growing concerns about security of supply force policymakers, industry, and society to rethink the way we produce, store, and use energy. In this debate, hydrogen has long been presented as a potential cornerstone technology. It promises flexibility, seasonal storage, and pathways to decarbonize sectors that are otherwise difficult to electrify. Yet, recent developments show that hydrogen has lost much of its initial momentum. Investments have slowed, several demonstration projects are on hold, and public discourse has shifted from enthusiasm to skepticism.

This white paper addresses the central question: **How can hydrogen realistically and feasibly become part of the Belgian energy system?** The aim is not to reinforce hype, but to take a sober look at where hydrogen makes sense, where it does not, and under what conditions it can provide real value for the energy transition.

Several benefits are clear. Hydrogen infrastructure can serve as a backbone for long-term energy storage and cross-sector integration. Strategic investments today can prepare Belgium for future import, transport, and industrial applications. Such decisions, if made wisely, will be future-proof and support resilience in an increasingly uncertain energy landscape. However, separating sense from nonsense is crucial: hydrogen will not solve every problem, nor should it compete with electrification in areas where direct electricity use is cheaper and more efficient.

At the same time, challenges must be acknowledged. The initial hype has faded, and with it came hesitation. Hydrogen projects are often considered too costly, access to the resource remains limited, and economic feasibility is questioned. Many actors are "desperately electrifying everything," while fearing that this strategy alone is insufficient. Without a balanced perspective, Belgium risks losing time, credibility, and opportunities.

This white paper, therefore, seeks to provide guidance. It will highlight the domains where hydrogen is a strategic asset, dismiss solutions that are technically or economically unrealistic, and discuss policy instruments that can help overcome the investment gap. The purpose is not to choose hydrogen over other technologies, but to embed it in a broader, eclectic vision of the energy transition. The future will not be purely electric; it will be eclectic, requiring a mix of solutions, with hydrogen playing an important, but carefully defined, role.

# STRUCTURE

This white paper is structured along three core segments of the hydrogen value chain: **making, moving, and using**. This distinction reflects the natural flow of hydrogen through the energy system, from production to transport and storage, and finally to end-use applications. By organizing the document in this way, the researchers aim to provide clarity in what is often a complex and highly interconnected debate.

Each section analyzes the main technological, economic, and systemic challenges within that segment and identifies realistic pathways forward. At the same time, the structure allows for highlighting the interdependencies among production choices, infrastructure development, and application priorities. The making–moving–using framework, therefore, allows for both focused analysis and a coherent system-wide perspective, ensuring that hydrogen is assessed not as isolated technologies, but as an integrated value chain within Belgium’s broader energy transition.

# 1 MAKING


## SUMMARY

Belgium's limited renewable energy potential makes exclusive reliance on renewable hydrogen production challenging; a resilient and cost-competitive hydrogen supply may therefore require a diversified set of low-carbon production pathways, subject to systematic techno-economic assessment.

- **Key technical barriers:** limited renewable energy land and grid capacity, costly, material-intensive electrolysers, and difficult industrial integration into existing plants.
- **Economic challenge:** low-carbon hydrogen costs 2–3 times as much as fossil hydrogen; reducing CAPEX and electricity costs, and using blue hydrogen as a bridge, are essential.
- **Emissions focus:** the priority is low carbon-intensity, not color labels; combining renewables, CCUS, and nuclear offers the fastest path to genuine emission cuts.
- **Policy actions:** enable early projects through grants, CCUS incentives, and streamlined permitting, and build frameworks for carbon tracking and responsible sourcing.
- **Outcome:** a pragmatic, technology-neutral strategy secures affordable supply, energy security, and industrial competitiveness, positioning Belgium as a European hydrogen leader.


## 1.1 THE STRATEGIC ROLE OF HYDROGEN PRODUCTION

The objective is to assess how hydrogen production can be integrated into the Belgian energy transition in a feasible and sustainable manner. Hydrogen's versatility enables its use in steelmaking, chemical industries, heavy transport, and seasonal energy storage. To support these applications, a robust hydrogen production system is required—one that can balance demand while enhancing energy and chemical security and reducing external dependencies. Such a system would play a key role in decarbonizing industrial processes and energy systems.

However, Belgium faces structural constraints, notably its limited domestic renewable energy potential and relatively high cost base. As a result, the feasibility of hydrogen production is not solely a technical challenge but also an economic one.

The objective is therefore not simply to promote hydrogen production within Belgium, but to identify the most cost-competitive and technically feasible hydrogen production pathways for the Belgian context, taking into account challenges such as limited renewable resources, high grid fees, taxes and levies, and a strong reliance on electricity imports from neighbouring countries.

## 1.2 TECHNOLOGICAL BARRIERS AND SOLUTIONS

Belgium's pathway to low-carbon hydrogen production is constrained not by a single obstacle, but by a combination of technological and structural limitations. Achieving large-scale deployment requires addressing three interconnected challenges: limited domestic renewable energy potential, material and efficiency bottlenecks in electrolyser technologies, and the integration of new hydrogen systems into existing industrial infrastructure. In addition, electrolyser-based hydrogen production is highly capital-intensive. Each of these barriers directly affects cost, scalability, and the pace of deployment.

Rather than assuming a predefined technology mix, the key question is to identify the most optimal pathway for low-carbon hydrogen production in Belgium, one that ensures cost competitiveness and security of supply, while avoiding the inefficient reallocation of scarce renewable electricity from direct electrification to hydrogen production. This requires a systematic assessment of alternative hydrogen production routes and energy sources within the specific constraints of the Belgian energy system.

### RENEWABLE ENERGY SHORTAGE

**Barrier**

Belgium's renewable energy potential is insufficient to support large-scale green hydrogen production. In optimistic scenarios, total onshore wind and rooftop solar capacity could yield about 132 TWh per year, matching today's electricity demand (≈ 80 TWh) but falling short of the projected 155–170 TWh electricity needed by 2050 as electrification accelerates [1, 2]. Slow permitting, grid congestion, and public acceptance further constrain deployment. Claims of abundant "surplus" renewable power for electrolysis are therefore not supported by evidence [3, 4].

## Solution

A purely renewable electrolysis-hydrogen strategy is not realistic for Belgium. To ensure energy security and a scalable low-carbon hydrogen supply, production must combine several complementary pathways [5, 6]. This balanced approach also helps overcome the early “chicken-and-egg” challenge, in which limited hydrogen demand and infrastructure constraints hinder investment in new production capacity.

- **Maximize domestic renewables** through continued onshore and offshore wind and solar investment, while streamlining permitting for suitable sites [1,2].
- **Leveraging CCUS in existing fossil-based hydrogen production** can enable the near-term supply of low-carbon hydrogen by building on established technologies and infrastructure, thereby maintaining industrial continuity. This approach can support early market formation and help alleviate the chicken-and-egg problem between hydrogen demand and infrastructure investment [7–9]. In the Belgian context, where most fossil-based hydrogen is currently produced in decentralised steam-methane reforming units at industrial sites (e.g., the fertiliser sector) or supplied by nearby industries (e.g., refineries), such an approach can reduce uncertainty around initial hydrogen infrastructure deployment. However, this pathway critically depends on a robust $CO_2$ value chain and transport network to enable the safe sequestration or utilisation of captured $CO_2$.
- **Expand nuclear-powered electrolysis** (“pink hydrogen”), which offers among the lowest lifecycle emissions and reliable baseload generation [10]. The stable electricity output of nuclear power allows continuous production of low-carbon hydrogen, providing a dependable base supply for industry that complements variable and limited renewable hydrogen production.
- **Explore natural (“white”) hydrogen** as a long-term option, recognizing that geological production is still at a research stage [11, 12].

Belgium’s hydrogen policy should shift focus from dogmatic color labels to measurable carbon intensity for each production pathway [13, 14]. A balanced mix of renewable, nuclear, and fossil with-CCUS hydrogen can deliver near-term volumes, support industrial decarbonization, and provide energy security while renewable capacity gradually expands.

## MATERIALS EFFICIENCY AND STABILITY PROBLEM

### Barrier

Current electrolyser technologies (PEM, alkaline, and SOEC) are technically mature but still face limitations in efficiency, durability, and material supply. Catalysts depend on platinum-group metals (PGMs) such as platinum, iridium, and ruthenium, which are scarce, costly, and geographically concentrated [15–17]. These critical raw materials are vulnerable to supply disruptions and raise ethical and environmental concerns linked to mining and refining. System components, such as membranes and bipolar plates, also degrade over time, reducing performance and increasing replacement costs.

### Solution

Improving electrolyser sustainability requires **research and innovation across materials, design, and supply chains:**

- **Reduce dependence on PGMs** by lowering catalyst loadings and exploring relatively earth-abundant substitutes such as nickel, iron, cobalt, and molybdenum [16, 17].
- **Enhance efficiency and lifetime** by advancing membrane stability, corrosion resistance, and stack architecture [15].
- **Develop recycling and circular supply systems** to recover valuable metals from spent stacks and process residues.
- **Strengthen supply security via EU-level coordination,** local refining capacity, and strategic partnerships with producing countries, aligned with the EU Critical Raw Materials Act.
- **Support research on emerging technologies,** such as anion exchange membranes (AEMs), solid oxide (SOEC) systems, and photoelectrochemical (PEC) systems, which may offer long-term cost and efficiency gains.

Reducing material intensity and diversifying supply chains are essential for scaling low-carbon hydrogen. Belgium can play a strategic role by fostering research partnerships, recycling initiatives, and responsible sourcing standards, aligned with the EU Critical Raw Materials Act.

## SYSTEM INTEGRATION CHALLENGES

### Barrier

**Integrating electrolysis into existing industrial processes is technically complex and capital-intensive.** Most hydrogen in Belgium is produced from natural gas, tightly linked to refinery, ammonia, and methanol systems that recover and reuse process heat. Electrolysers, by contrast, generate hydrogen without usable process heat and require new auxiliary systems for power conversion, water treatment, and safety. Retrofitting existing sites, therefore, demands major redesigns of utilities and control systems, making the transition gradual and costly.

### Solution

A phased integration strategy is needed to maintain industrial continuity while decarbonizing.

- **Short term: Apply carbon capture, utilization, and storage (CCUS)** to existing steam methane reformers to cut emissions rapidly without disrupting production.
- **Medium to long term: Deploy electrolysers in new or fully electrified facilities,** designed from the outset for renewable or nuclear power integration and optimal heat and water management.
- **Encourage pilot projects** and hybrid configurations that combine electrolysis with existing units, allowing gradual adaptation of process infrastructure and workforce skills.

Industrial hydrogen decarbonization must proceed in an evolutionary, not disruptive, manner. CCUS offers immediate emission reductions from existing assets, while next-generation plants can adopt electrolysis as the technology matures and electricity supply becomes cleaner and more abundant.

## 1.3 ECONOMIC BARRIERS AND MEASURES

While technology defines what is possible, economics determines what is scalable. Even with viable production pathways, high capital and electricity costs remain the main barriers to competitive low-carbon hydrogen in Belgium. Addressing these structural cost drivers while using transitional solutions and targeted policy support will be essential to close the price gap with fossil-based hydrogen and accelerate market adoption.

## Barrier

**Renewable low-carbon hydrogen remains two to three times more expensive than fossil-based hydrogen in Belgium.** Current estimates place costs at roughly EUR 6.4/kg for grid-based electrolysis, EUR 9/kg for renewable-powered electrolysis, EUR 3.5/kg for natural gas with carbon capture (CCUS), and EUR 2.8/kg for unabated steam methane reforming [18]. The main cost drivers differ by technology:

- **Electrolysis (grid or renewable):** dominated by CAPEX (40–55%) and electricity (30–45%), with taxes and fees adding 10–15%.

- **Fossil-based hydrogen:** driven primarily by fuel cost (60–70%), with low capital intensity. High electricity prices and limited availability of renewable energy in Belgium further inflate costs.

## Solution

Reducing hydrogen production costs requires **targeted action on capital and energy costs**:

- **Lower CAPEX** through material innovation and manufacturing improvements. Electrolyser stacks account for about 20% of the total investment. Balance-of-plant and EPC costs represent the remaining 80%, offering savings through standardized design, streamlined permitting, and supply-chain scaling [5].
- Reduce electricity costs via increased renewable energy generation, long-term power contracts, and integration of nuclear energy as a stable, low-cost baseload source [19].
- **Bridge the transition using natural gas with CCUS**, which halves production costs compared to electrolysis and can leverage existing assets while renewable and nuclear supply expands.
- **Support early projects** with targeted grants and state-backed contracts to overcome first-mover barriers.

Hydrogen affordability hinges on CAPEX reduction, cheaper low-carbon electricity, and transitional blue hydrogen deployment. Sustained policy support, research, and investment coordination can narrow the cost gap, enabling Belgium to develop a competitive and secure domestic hydrogen market.

## 1.4 ENVIRONMENTAL AND ETHICAL BARRIERS

Economic feasibility alone is not enough for a sustainable hydrogen strategy. Production pathways must also meet environmental and ethical standards to ensure that decarbonization efforts genuinely reduce emissions without creating new ecological or social risks. The challenge lies in managing life-cycle emissions, material sourcing, and nuclear responsibility so that hydrogen expansion strengthens -not undermines- Belgium's broader sustainability goals.

**Barrier**

**Hydrogen's climate impact varies widely depending on its production pathway**. Conventional hydrogen from natural gas emits 10–12 kg $CO_2$-eq/kg $H_2$, and from coal 22–26 kg, while adding CCUS can reduce this to 2–4 kg if methane leakage is well managed. Electrolysis is emissions-free at the point of use but ranges from near-zero (with renewables or nuclear) to over 30 kg $CO_2$-eq/kg when powered by fossil-based grid electricity [10]. Nuclear-powered electrolysis has among the lowest life-cycle emissions (0.1–0.3 kg $CO_2$-eq/kg). Beyond $CO_2$ emissions, the manufacturing of electrolysers, renewable infrastructure, and critical minerals introduces additional environmental pressures and ethical concerns linked to mining, labor conditions, and supply-chain transparency.

**Solution**

True **decarbonization depends** not on color labels but on **verified carbon intensity and responsible sourcing.**

- **Prioritize low-carbon pathways:** renewable electrolysis, fossil hydrogen with CCUS, and nuclear-powered electrolysis.
- **Reduce embedded emissions** through cleaner manufacturing, material recycling, and circular economy practices.
- **Ensure ethical supply chains** by enforcing due diligence standards for critical materials and promoting sustainable mining partnerships.
- **Improve nuclear governance** by maintaining strict safety standards and investing in transparent, long-term waste management.
- **Develop robust policy frameworks** for carbon-intensity certification, material traceability, and life-cycle assessment of hydrogen technologies.

A credible hydrogen strategy must balance climate integrity with ethical responsibility. By tracking carbon intensity, enforcing responsible sourcing, and maintaining public trust in nuclear safety, Belgium can ensure that its hydrogen economy is both environmentally sustainable and socially legitimate.

## 1.5 POLITICAL BARRIERS TO HYDROGEN IMPORTS

Although most hydrogen production and consumption currently occur on-site, hydrogen is often anticipated to become a globally traded energy commodity as decarbonization efforts accelerate. Despite hydrogen's low volumetric energy density—making it significantly more costly and technically complex to transport than fossil fuels or electricity—a proliferation of bilateral agreements since 2018 suggests a growing momentum toward establishing a global hydrogen market [20].

The emergence of such a market raises questions about **energy security, geopolitical dynamics, and socio-environmental justice.** These political barriers challenge the notion that hydrogen imports are a straightforward and technical solution to regional decarbonization efforts. Rather, they expose governments to a spectrum of risks that must be balanced judiciously [21].

**First, hydrogen imports risk creating new strategic dependencies** that could replicate past fossil fuel vulnerabilities. As early hydrogen markets are likely to be dominated by a limited number of producer countries, importers may face supply disruptions, market concentration, and geopolitical pressure. To mitigate these risks, governments increasingly emphasize diversifying supply partners and partnering with politically aligned countries [22].

**Second, hydrogen imports are essential to maintain industrial competitiveness** in regions with limited renewable energy potential, such as Northwestern Europe and Belgium. Without access to affordable green hydrogen, energy-intensive industries may relocate to areas with cheaper renewable resources—a phenomenon known as the **"renewables-pull"** effect [23]. Hydrogen imports, therefore, function as both an energy strategy and a defensive industrial policy to prevent deindustrialization.

**Third, environmental sustainability concerns persist,** particularly regarding continued support for blue hydrogen. Relying on hydrogen derived from natural gas with carbon capture could possibly risk carbon lock-in and long-term dependence on fossil infrastructure [24]. Moreover, hydrogen exports may undermine domestic decarbonization in producer countries if their own energy systems remain carbon-intensive.

**Fourth, hydrogen imports raise global justice concerns.** Many projected trade flows follow a North–South pattern in which benefits accrue primarily to importing countries, while adverse impacts—such as land-use pressure, limited local energy access, or environmental degradation—may be externalized to producing regions. Value creation also tends to concentrate in technology-intensive segments dominated by industrialized economies, limiting development opportunities elsewhere [25].

Taken together, these risks underscore the **deeply political nature** of hydrogen imports. Governments must carefully evaluate which risks they are willing to accept and design policies that balance national energy objectives with broader considerations of security, sustainability, and global justice.

## 1.6 BENEFITS OF A BALANCED APPROACH

A balanced hydrogen strategy can deliver real advantages for Belgium's economy and energy system. By combining renewable, nuclear, and fossil-based hydrogen production with carbon capture, utilization, and storage (CCUS), Belgium can secure **affordable hydrogen** for industry, strengthen energy security, and **stimulate technological innovation**. Developing expertise across diverse production pathways would **enhance industrial competitiveness,** drive new **economic growth**, **reduce dependence on imported fossil fuels, and address social justice concerns**. Through sustained investment, research collaboration, and responsible sourcing, Belgium could position itself as a knowledge hub and industrial leader in Europe's low-carbon energy transition.

# 2 MOVING

## SUMMARY


A well-integrated low-carbon hydrogen transport network in Belgium would unlock the flexibility of the EU hydrogen supply chain. However, it should be robustly designed based on a scenario-based bottom-up industrial demand estimation and its spatial distribution in the region.

- **Key technical barriers**: Hydrogen's low volumetric energy density, material challenges such as hydrogen embrittlement and permeation, limitations of surface storage technologies, and remaining uncertainties in large-scale underground storage (e.g., geochemical interactions and operational stability in salt caverns), as well as the low TRLs of emerging concepts such as slush hydrogen.
- **Economic challenges**: Early-stage low demand, limited capacity booking, high upfront investment for TSOs, uncertain tariff recovery, and the persistent cost gap between green hydrogen and fossil-based alternatives.
- **Environmental and ethical considerations**: High energy use for compression/liquefaction/slush production; material extraction impacts; leakage and safety risks; and uneven global access to advanced hydrogen technologies.
- **Policy actions**: Coordinated hydrogen–$CO_2$ infrastructure planning, targeted subsidies and de-risking mechanisms, streamlined permitting for central storage sites, and support for R&D in hydrogen-resistant materials and novel storage technologies.
- **Outcome**: A cost-effective, resilient hydrogen network that enhances system flexibility, reduces long-term risks, supports industrial uptake, and strengthens Belgium's and Europe's energy security.


## 2.1 THE IMPORTANCE OF PROVIDING ACCESS TO AFFORDABLE LOW-CARBON HYDROGEN

Like any other commodity in the energy system, low-carbon hydrogen requires a robust and well-connected transport infrastructure. Such infrastructure is essential not only to link production hubs and import terminals with major offtakers, but also to provide access to potential storage sites (e.g., salt caverns) [26–28]. This becomes particularly critical for electrolytic hydrogen, or more specifically, green hydrogen, which is expected to have an intermittent production profile. At the same time, most hydrogen demand will come from industry (see section 3), where consumption flexibility is limited. Focusing on Belgium, the country holds a strategic position to emerge as a key transport hub for low-carbon molecules and hydrogen within Europe [29]. Its deep-sea ports, Zeebrugge and Antwerp, have historically provided access to fossil-based energy flows. These ports can now be repositioned as gateways for importing clean molecules from renewable-rich regions worldwide. Moreover, Belgium serves as a natural link between southern Europe, where renewable potential is high, and north-west Europe, where industrial demand is concentrated. Developing a well-integrated low-carbon hydrogen transport network in Belgium could therefore unlock significant added value by enhancing the overall flexibility and resilience of the regional hydrogen supply chain.

## 2.2 TECHNOLOGICAL BARRIERS AND SOLUTIONS

The low density of hydrogen is the main reason why "moving" hydrogen is often regarded as a challenge in the hydrogen value chain. This is due to its low molecular weight, which affects many aspects of transport, storage, and compression.

### MATERIAL INTEGRITY AND HYDROGEN EMBRITTLEMENT

**Barrier**

**One of the key technological hurdles to a reliable hydrogen backbone is hydrogen embrittlement in existing metallic infrastructure**. As Belgium considers repurposing parts of its natural gas network, steel durability becomes critical because hydrogen exposure dictates allowable operating pressures, inspection frequency, and long-term safety.

Internal pipeline coatings are often seen as a practical, low-cost way to start transporting hydrogen, but are not a robust long-term solution. They can delaminate during pressure cycling, perform poorly in high-strain sections, and hinder inspections by obscuring the pipeline's true condition. They are also frequently ineffective for components with complex stress states, such as valves, compressors, metering equipment, and high-pressure storage vessels [30].

## Solution

**Innovative Hydrogen-Resistant Alloys** To ensure operational safety and continuity as Belgium repurposes parts of its gas network, conventional pipeline steels will need to be complemented by hydrogen-resistant alloys that retain mechanical integrity under long-term exposure to hydrogen and harsh thermal/mechanical loads. Emerging metallurgy research, in Belgian universities, industrial laboratories, and European partnerships, is increasingly focused on microstructural engineering: designing alloys that trap hydrogen in benign regions rather than allowing it to concentrate at crack-prone sites. Unlike coatings, which act only as an external barrier and can fail under pressure cycling or strain, these materials embed resistance in the metal itself and address degradation at its source.

If deployed at scale, such alloys could expand what is technically feasible across the hydrogen value chain: enabling higher pipeline operating pressures than today's conservative 66.2-bar limit, improving reliability for fatigue-sensitive components (compressors, valves, actuators), and sustaining performance in demanding storage conditions. The payoff is lower recompression needs, reduced maintenance burden, and stronger safety margins, particularly important in densely populated areas, while avoiding premature asset deterioration and pressure restrictions.

For policymakers, investing in hydrogen-compatible materials is a risk-management strategy: support alloy development, accelerate qualification procedures, and enable industrial-scale testing to align infrastructure lifetimes with economic planning. This can position Belgium as a materials-innovation leader in the European hydrogen economy, strengthening energy security, safety, and affordability.

# PRESSURE MANAGEMENT AND COMPRESSION CONSTRAINTS

## Barrier

**Pressure management and compression constraints under hydrogen service**. Although existing natural gas pipelines may be repurposed for hydrogen, operating pressure is constrained by hydrogen embrittlement, which currently limits the design pressure of Belgian hydrogen pipelines to about 66.2 bar. Yet higher pressure is desirable to reduce gas velocity and friction losses. This constraint shifts the burden to compression, but natural-gas compressor stations cannot simply be reused: hydrogen's different properties (density, compressibility, velocity) and the evolution of pressure along the line require redesigned hydrogen compression stations, especially over long distances. Moreover, the intermittency of green hydrogen production implies more variable pipeline utilisation and operating transients, further complicating compressor sizing and control and potentially increasing exposure to pressure cycling that can aggravate embrittlement and undermine coatings. Repurposing remains the lowest-cost pathway, but it hinges on material compatibility and a compression strategy tailored to hydrogen [31–33].

### Solution

**Deploy hydrogen-compatible materials and redesign compression for flexible operation.** Qualify repurposed pipelines segment-by-segment and upgrade the most exposed sections and components with hydrogen-resistant alloys to expand the safe pressure envelope and reduce sensitivity to cycling. Replace or retrofit natural-gas compressor stations with hydrogen compressors and add buffering control to smooth transients from variable green $H_2$, maintaining low losses and safety at higher utilisation.

## SCALING STORAGE

### Barrier

**Scaling hydrogen storage for industrial decarbonization and long-duration energy balancing.** Hydrogen storage is an important component of low-carbon energy systems because it enables temporal decoupling between renewable electricity production and energy demand, supporting industrial decarbonization and long-duration energy storage. Physical storage technologies mainly include compressed gaseous hydrogen, liquefied hydrogen, and underground geological storage [34].

Compressed gaseous hydrogen storage is currently the most mature technology and is commonly implemented at pressures between roughly 20–70 MPa (200–700 bar) using steel or composite pressure vessels [35]. However, hydrogen's low volumetric density means large storage volumes are required, which can increase infrastructure footprint and compression energy requirements.

Liquefied hydrogen (LH) storage significantly increases volumetric density by cooling hydrogen to its boiling point of approximately 253 °C, reducing the storage volume by about 800 times compared with gaseous hydrogen at ambient conditions. This higher density makes LH particularly attractive for large-scale transport and centralized storage, especially within port-based hydrogen supply chains. However, cryogenic storage introduces challenges related to boil-off losses, insulation requirements, and the energy demand of the liquefaction process [36].

For large-scale, long-duration storage, underground geological formations offer the most promising pathway. Salt caverns, depleted gas reservoirs, and deep saline aquifers can store very large quantities of hydrogen at relatively low cost per unit of energy and may enable seasonal storage to balance renewable electricity production. Key challenges include understanding hydrogen–rock interactions, microbial activity, gas purity management, and long-term containment performance [37].

Emerging concepts such as slush hydrogen, a mixture of liquid and solid hydrogen, aim to increase volumetric density beyond conventional liquefied hydrogen. While modelling studies suggest potential benefits for cryogenic storage and transport, the technology remains at low technology readiness levels and requires further experimental validation [38].

In addition, hydrogen may be converted into energy carriers such as ammonia or methanol, which can facilitate long-distance transport and serve as fuels for maritime shipping. However, these pathways introduce additional conversion steps and efficiency losses that must be considered when designing the hydrogen supply chain.

## Solution

**Developing a diversified hydrogen storage portfolio**. Scaling hydrogen storage requires the deployment of complementary storage technologies adapted to different roles in industrial and energy systems. For compressed hydrogen storage, advances in high-strength composite pressure vessels and improved compression technologies can improve durability and reduce energy losses, supporting flexible hydrogen buffering in industrial clusters. For liquefied hydrogen, improvements in liquefaction processes, cryogenic insulation, and boil-off management are necessary to increase efficiency and enable large-scale storage and transport. For long-duration storage, underground hydrogen storage in salt caverns and porous geological formations offers one of the most scalable options for storing large quantities of hydrogen and supporting renewable energy integration. Continued research is required to better understand geochemical interactions, microbial processes, and gas purity management in geological formations. Together, these technologies can form a robust hydrogen storage ecosystem capable of supporting industrial decarbonization, renewable energy integration, and large-scale energy system flexibility.

Hydrogen storage is a promising option for supporting industrial decarbonization and long-duration energy system balancing, particularly as renewable electricity generation increases. A portfolio of storage solutions is likely required, including compressed hydrogen for short-term buffering, liquefied hydrogen for higher-density storage and transport, and underground storage in salt caverns or porous formations for large-scale or seasonal energy storage. While salt caverns offer attractive storage capacities and relatively low costs, challenges remain related to geochemical interactions, microbial activity, and long-term operational stability. Emerging concepts such as slush hydrogen could further increase storage density, although they remain at an early stage of technological development.

## 2.3 ECONOMIC BARRIERS AND MEASURES

### UTILISATION RATES

#### Barrier

**The pipeline utilisation rates would remain limited in the early stages of an integrated hydrogen market.** While hydrogen transport through pipelines is generally viewed as a cost-effective means of moving energy—especially when existing natural gas infrastructure can be repurposed [32, 33], the initial capital investment represents only one aspect of the overall financial framework for developing a hydrogen network. In practice, the Belgian and wider European hydrogen backbone is expected to experience two distinct financial phases that closely mirror the evolution of the low-carbon hydrogen economy.

**The first phase corresponds to the market ramp-up period, characterized by limited hydrogen demand and low levels of capacity booking on the network.** Bookings during this stage may involve both short-term and long-term contracts, but overall utilization remains modest. **As the hydrogen market matures and demand scales up, the system is expected to transition into a more stable, fully developed market phase.**

In the long term, investments made by transmission system operators (TSOs) can become financially sustainable once the market reaches this second phase. However, the early developmental phase presents significant financial hurdles. During this period, TSOs may face challenges recovering their investments, as revenue from network tariffs could fall short of levels permitted under regulatory frameworks—most of which are still largely modeled on natural gas infrastructure. Because operational revenues are essential to cover construction and maintenance costs, insufficient tariff income due to low capacity bookings or uncertain willingness to pay among potential users can create financial pressure.

This situation may discourage TSOs from committing to large-scale network expansion, both within Belgium and across Europe. Consequently, the limited availability of transport capacity and access to affordable low-carbon hydrogen production or storage sites can deter potential offtakers, reinforcing a cycle of low demand and delayed investment—a classic "chicken-and-egg" dilemma in the hydrogen value chain.

### Solution

**Coordinated planning between the hydrogen, $CO_2$, and biofuel value chains.** To overcome the investment recovery challenges faced by transmission system operators (TSOs) and to reduce barriers to network expansion, a certain level of confidence in the future market interest of potential offtakers—particularly industrial clusters—will be crucial. Conducting a detailed bottom-up estimation of hydrogen demand and its spatial distribution would be an essential first step toward systematically assessing market potential. Coordinated planning across the $CO_2$ and hydrogen value chains, while accounting for the availability of other domestic green fuels (e.g., biofuels), is essential for accurate industrial demand estimation and effective network design. Such coordination is critical to mitigate the risk of underutilized pipeline infrastructure and stranded assets in future energy systems.

## MARKET UNCERTAINTY

### Barrier

**Uncertain market interest in the long-term.** Bottom-up industrial demand assessments and sector-coupled energy system analyses have shown that—even in the long term—the role of green hydrogen in industrial applications may remain limited [39, 40]. This depends on several factors, including the $CO_2$

allowance price reflected in the EU Emissions Trading System (ETS), the availability of biofuels for decarbonizing the chemical sector, and the feasibility of integrating carbon capture technologies into industrial processes, alongside sufficient EU-level $CO_2$ sequestration potential. As a result, there remains a risk of suboptimal development and underutilization of low-carbon hydrogen infrastructure if hydrogen and $CO_2$ network planning is not coordinated.

### Solution

**Combine regulatory flexibility with targeted subsidies to close the cost gap and de-risk early infrastructure.** Because green hydrogen remains cost-disadvantaged in the near term, boosting uptake requires reducing avoidable cost drivers while bridging the remaining price gap. This can be achieved by relaxing overly stringent EU production requirements that raise costs in the short term [41], accelerating innovation-driven cost reductions, and unlocking flexibility (e.g., faster permitting of central hydrogen storage) to lower system costs. In parallel, well-designed subsidy schemes are needed to close the residual gap relative to fossil alternatives [42]; part of the support should also de-risk network operators' upfront investments to provide early cost-recovery certainty and accelerate the rollout of low-carbon hydrogen transport infrastructure.

## INVESTMENT COST

### Barrier

**Higher upfront investment costs for hydrogen-resistant infrastructure**. Hydrogen-resistant alloys offer greater structural reliability and operational flexibility than conventional pipeline steels or internal coatings, but they require a significantly higher upfront investment. Advanced microstructural engineering, stricter manufacturing tolerances, enhanced quality control, and extended certification and qualification procedures increase capital expenditure (CAPEX) per kilometre of pipeline and for critical components such as compressors, valves, and high-pressure storage vessels. In early market phases with low utilisation rates, these higher capital costs can be difficult to recover through regulated tariffs, increasing financial risk for transmission system operators. Moreover, uncertainty regarding economies of scale, standardisation pathways, and regulatory approval timelines further amplifies perceived investment risk, potentially delaying deployment [30].

**Solution**

**Adopt lifecycle-based investment frameworks and targeted de-risking mechanisms.** Although hydrogen-compatible materials increase short-term CAPEX, they can reduce long-term operational expenditure (OPEX) and system risk. Higher allowable operating pressures reduce recompression needs and energy consumption; improved material resilience lowers inspection frequency and maintenance costs; and extended asset lifetimes decrease the likelihood of premature replacement or failure in densely populated areas. Policymakers can support affordability by promoting lifecycle-based cost assessment rather than relying solely on upfront cost comparisons. Regulatory frameworks that allow accelerated depreciation, cost pass-through mechanisms, innovation allowances, or targeted investment support can help bridge the early-stage cost premium. As production scales and material standards become harmonised at the European level, unit costs are expected to decline, improving long-term economic viability.

Early hydrogen pipeline networks face low utilisation and high investment risk, reinforcing a cycle of low demand and delayed infrastructure rollout. A detailed bottom-up assessment of industrial hydrogen demand and its spatial distribution is essential to guide effective system design. Strong coordinated planning across hydrogen, $CO_2$, and biofuel value chains is critical to avoid underused assets and ensure infrastructure readiness. Complementary regulatory flexibility and targeted subsidies can improve green hydrogen competitiveness and support timely network development.

## 2.4 ENVIRONMENTAL AND ETHICAL BARRIERS AND SOLUTIONS

### HIGH ENERGY DEMAND

**Barrier**

**High energy demand for compression, liquefaction, and slush hydrogen production, and advanced storage systems.** All major hydrogen storage pathways require significant energy inputs. Compression, liquefaction, and slush hydrogen production have substantial electricity requirements, with liquefaction alone consuming 30–40% of hydrogen’s energy content [43, 44]. Solid-state storage and hydride formation also require energy-intensive processing. When the electricity mix is not fully renewable, these steps materially increase lifecycle emissions and reduce the climate effectiveness of the hydrogen supply chain.

## Solution

**Prioritise low-emission transport modes and renewable-powered storage processes.** Favouring pipeline transport and compressed gaseous hydrogen, where feasible, can minimise energy losses. For cryogenic storage, renewable-powered liquefaction and slush production should be supported, particularly in industrial ports and hydrogen hubs. Lifecycle emissions from transport and storage should be integrated into Guarantees of Origin or carbon-intensity certification frameworks to prevent high-emission storage pathways from undermining climate targets.

# ENVIRONMENTAL FOOTPRINT

## Barrier

**Land-use, material demand, and environmental footprint of pipelines and advanced storage technologies.** Expanding hydrogen transport and storage infrastructure has direct impacts on land, ecosystems, and water resources. New pipelines, compressor stations, or underground storage facilities may disrupt local environments. Advanced storage technologies—such as metal hydrides, carbon-based sorbents, or composite high-pressure tanks—require significant quantities of critical minerals, raising concerns about resource depletion, mining impacts, and supply-chain sustainability.

## Solution

**Align hydrogen corridors and storage deployment with environmental planning and responsible material sourcing.** Infrastructure routes should be integrated into spatial planning frameworks, favouring existing industrial and natural gas corridors to minimise ecosystem disruption. Environmental impact assessments must be mandatory for major storage and transport installations. Policymakers should promote sustainable material sourcing, recycling strategies, and circularity in advanced storage systems to reduce upstream environmental burdens.

Hydrogen transport and storage can generate significant lifecycle emissions from energy-intensive compression and liquefaction, as well as land-use and material-extraction impacts. Prioritising low-emission transport modes, renewable-powered and more efficient storage processes, and responsible spatial and material planning is essential to reduce environmental burdens.

## 2.5 BENEFITS OF AN OPTIMIZED HYDROGEN INFRASTRUCTURE CAPACITY

The long-term planning of a low-carbon hydrogen infrastructure through techno-economic analysis of an integrated hydrogen supply chain—including production, transport, storage, and end-use—requires consideration of various macroeconomic and techno-environmental conditions. These include analyzing the impact of different energy vectors and CO2 allowance prices, biomass availability, and the feasibility of carbon capture, transport, and sequestration. Such an approach enables not only an optimized but also a robust hydrogen network design over the long term.

This analysis facilitates the identification of cost-competitive green hydrogen supply configurations (e.g., onshore vs offshore production, imports with dehydrogenation vs inland production in renewable-rich regions), demand-side connection points (e.g., fertilizers, refineries, primary steel), and appropriate storage strategies (e.g., decentralized hydrogen tanks vs centralized geological storage). As a result, it provides critical insights into where infrastructure investments are most justified across the hydrogen value chain and helps reduce uncertainty surrounding future deployment decisions.

By developing a socially optimal —rather than oversized— low-carbon hydrogen infrastructure in Belgium and its neighboring countries, and ensuring strategic interconnection with the broader EU network, it becomes possible to identify the most cost-effective layout for linking competitive production hubs across Europe with key industrial demand clusters. This approach not only enhances infrastructure efficiency but also strengthens the EU's energy security by mitigating the risks posed by potential disruptions to clean molecule imports from overseas.

## 2.6 CONCLUSION

Belgium holds a unique opportunity to become a central node in Europe's low-carbon hydrogen system, but realizing this potential requires substantial technological, economic, and regulatory progress. Technologically, the hydrogen value chain faces fundamental challenges related to low density, embrittlement, and immature storage solutions such as slush hydrogen. Material innovation and improved storage technologies are essential to ensure safety, performance, and reliability. Economically, early-stage market uncertainties create investment risks for TSOs and industrial users, making targeted support mechanisms indispensable for network rollout. Coordinated hydrogen–$CO_2$ infrastructure planning, combined with strategic subsidies and streamlined permitting, can accelerate market formation. Ultimately, Belgium's ability to integrate resilient transport infrastructure, advanced materials, and optimized storage will determine whether it can successfully anchor a competitive and secure European hydrogen backbone.

# 3 USING

## SUMMARY


Using hydrogen produced by different methods, as discussed previously, results in varying hydrogen quality or purity, and it should be allocated based on clear priorities for each application's needs. First, the focus should be on decarbonizing existing hydrogen demand and other hard-to-abate sectors before supporting new uses.

- **Key technical barriers:** application-specific, but typically related to system efficiency, material and durability limits, high energy demands, and balancing the development of new technologies with the retrofitting of existing assets.
- **Economic challenge:** a combination of unclear or overly stringent hydrogen regulation, limited market interest due to high costs, and the high cost of low-carbon hydrogen as both a feedstock and a fuel.
- **Environment and ethics:** direct end-use emissions are usually $CO_2$-free, but combustion-based applications still generate $NO_x$. The overall climate and ethical performance ultimately depend on the entire value chain, as well as on the responsible sourcing of materials and the fair distribution of impacts.
- **Policy actions:** hard-to-abate applications should be prioritized, and the focus should be on de-risking early adoption through targeted incentives and public procurement. That can be achieved through providing clear standards, retrofit support, and skills/advisory programs.
- **Outcome:** a targeted, standards-based hydrogen policy for end-users will accelerate decarbonisation in hard-to-abate sectors, avoid wasteful uses, and strengthen industrial competitiveness and energy security.


## 3.1 THE NEED FOR HYDROGEN

Hydrogen is a high-value industrial feedstock, but its availability, and especially the availability of low-emission hydrogen, will remain limited in the coming decades. At the same time, a growing number of applications have been proposed as candidates for "hydrogen-based" decarbonisation. This makes allocation a crucial question: not every use case can or should be supplied with low-emission hydrogen. Today, global hydrogen demand of almost 100 Mt is still dominated by long-standing uses in oil refining and the chemical sector (notably ammonia, methanol and fossil-based direct reduced iron), while new applications in transport, power and other emerging sectors account for less than 1% of total demand [5]. Belgium broadly mirrors this pattern, with most hydrogen consumed on-site in refineries and ammonia plants, and only limited low-emission supply and new end-uses at pilot scale [45].

In this context, **priority should be given to decarbonising existing hydrogen demand**. Substituting fossil-based hydrogen with low-emission hydrogen in refineries and ammonia plants offers a relatively straightforward lever to reduce $CO_2$ emissions, without fundamentally changing the underlying processes. Only once these “no-regret” uses are addressed does it make sense to expand low-emission hydrogen towards new applications in high-temperature industrial heat, long-duration energy storage, selected transport modes, or as a feedstock for e-fuels via $CO_2$ hydrogenation and related routes [46].

## 3.2 TECHNOLOGICAL BARRIERS AND SOLUTIONS

### HIGH ENERGY DEMAND

**Barrier**

**Key industrial processes remain highly energy-intensive and often inflexible.** Industrial implementation remains a significant challenge due to the high energy demands of related processes. Conventionally, these processes were energetically supported by energy from other processes (usually exothermic ones), which will now have to be replaced. As a follow-up, industrial plants need to be modified and new equipment installed to support the demands of the new processes. One example is the decarbonization of synthetic ammonia production plants, where the replacement of steam methane reforming (fossil-based hydrogen) with low-severity alkaline electrolyzers powered by renewable electricity (green hydrogen) can reduce $CO_2$ emissions by 96-99% —with ammonia synthesis currently responsible for 1.2% of global $CO_2$ emissions—but increases overall energy consumption by a factor of 2.2. This transition also introduces substantial process implications, such as the replacement of the steam system and a reconfiguration of the plant’s heat management [47].

It is often detrimental to combine many new technologies (with varying TRLs). For instance, to utilize hydrogenation of $CO_2$ as a decarbonization effort for the production of added-value products such as olefins or fuels, the high reliance on the TRLs of carbon capture technologies creates uncertainty, lowering the TRL of the overall process [46].

Hydrogen can increase the efficiency of systems such as gas turbines when only direct energy flows are considered [48]. However, once losses on the hydrogen production side are accounted for, the overall efficiency of hydrogen-based power generation is significantly lower than that of other electricity generation technologies.

### Solution

**Reduce and reshape the processes' energy demand before supplying with hydrogen.**

Measures that reduce and reshape the energy demand in energy-intensive processes should be prioritised before implementing these processes in industrial environments. This can be done through efficiency improvements (development of better catalytic systems, optimization of existing ones, etc.), better heat integration (creating plants with the objective of enhancing energy integration and waste heat recovery), and careful technology choices. With research focused in that direction, it would be promising to support large-scale use of low-carbon hydrogen in these applications.

## RETROFITTING AND MATERIALS COMPATIBILITY

### Barrier

**Existing combustion systems and related equipment must be redesigned.** When using hydrogen as a fuel, several specific challenges must be addressed. Its combustion behaviour differs from that of conventional hydrocarbon fuels, requiring that the combustion chambers of internal combustion engines and gas turbines be adapted, along with the materials and designs of components in direct contact with hydrogen, such as fuel injectors [49]. In addition, for the same energy content at identical operating conditions, hydrogen occupies at least three times the volume of conventional fuels. As a result, pipelines and storage tanks must either operate under different conditions (e.g., higher pressure) or be significantly larger, both of which imply higher investment and operating costs.

## Solution

**We need a step-by-step retrofit approach, guided by clear technical and safety standards.** Priority should be given to deploying "hydrogen-ready" equipment (burners, turbines, boilers, engines) that can safely operate on blends and progressively higher hydrogen shares, in accordance with clear design and safety standards. Targeted retrofits should combine upgraded materials and coatings, redesigned injectors and mixing systems, and improved monitoring and control. Co-firing hydrogen blends in existing units, supported by rigorous testing and certification, can reduce technical risk and upfront costs while building the operational experience necessary for full hydrogen conversion, where it is both technically and economically justified.

Support a gradual retrofit of existing combustion and fuel-handling systems by prioritising hydrogen-ready equipment, funding materials, and component upgrades (burners, injectors, coatings, storage), and backing blend-based demonstration projects and certification schemes that safely build experience and reduce costs before committing to full hydrogen conversion.

# SCALABILITY OF PROCESSES AND SYSTEMS

## Barrier

**Fuel cells are still difficult to scale from pilot projects to large, cost-competitive deployments.** They rely on expensive materials, complex manufacturing, and very high hydrogen purity, which increases costs and limits lifetime. At the same time, global production capacity for stacks and balance-of-plant components remains limited, slowing down large-scale roll-out [50].

## Solution

**Scaling fuel cells requires both technological improvement and industrialisation.** This means reducing or substituting critical materials, extending system lifetime, and relaxing purity constraints where possible, while in parallel standardising designs, ramping up high-volume manufacturing, and focusing early deployment in applications where fuel cells offer a clear advantage (such as heavy-duty transport), so that learning effects can gradually drive costs down.

Support the scale-up of fuel cells by targeting material substitution and lifetime improvements, boosting high-volume manufacturing, and concentrating early deployment in applications where fuel cells have a clear advantage (e.g., heavy-duty transport), so that learning effects and stable demand can drive costs down over time.

## 3.3 ECONOMIC BARRIERS AND MEASURES

Beyond the technological hurdles, the deployment of hydrogen use-cases is primarily constrained by economics. Even when solutions are technically mature, high hydrogen prices, the cost of dedicated equipment, and an uncertain regulatory framework often make hydrogen less attractive than conventional fossil options.

### HIGH COST OF LOW-CARBON HYDROGEN

#### Barrier

**Low-carbon hydrogen remains significantly more expensive than fossil alternatives.** Even before accounting for infrastructure or end-use technologies, hydrogen as a feedstock or fuel is still priced well above conventional options. This cost gap limits market interest, delays investment decisions, and makes it difficult for hydrogen-based routes to compete with conventional processes or fossil-based electricity generation.

#### Solution

**Narrow the cost gap while targeting the most valuable uses first.** Policy support should focus on reducing production costs (e.g., cheaper low-carbon electricity, scale-up of electrolysers, transitional use of blue hydrogen) and on directing limited low-carbon hydrogen towards high-value, hard-to-abate applications where it can displace the most emissions per euro spent [51].

Low-carbon hydrogen remains significantly more expensive than fossil options, so policy and industry should focus on reducing its production costs and allocating the limited supply to high-value, hard-to-abate applications where it delivers the most emissions reductions per euro.

## REGULATORY UNCERTAINTY AND FRAGMENTED RULES

**Barrier**

**Unclear and stringent regulations dampen market interest.** E-fuels, although promising drop-in replacements for conventional fuels, still lack clear, stable regulatory frameworks, creating uncertainty for investors and end users. At the same time, strict, sometimes fragmented rules on what qualifies as "green" hydrogen can restrict demand rather than enabling an orderly scale-up [52].

**Solution**

**Provide clear, predictable, and harmonised regulatory signals.** Policymakers should define stable sustainability criteria for hydrogen and e-fuels, streamline certification and reporting, and align regulations across sectors and jurisdictions so that developers and end-users can invest with confidence in low-carbon hydrogen value chains.

Unclear and fragmented rules on "green" hydrogen and e-fuels discourage investment, so policymakers should clarify and harmonise criteria and certification to give industry the confidence to scale low-carbon solutions.

## COST AND REQUIREMENTS OF END-USE TECHNOLOGIES

**Barrier**

**Fuel cells and other hydrogen end-use technologies remain expensive and demanding.** Using low-carbon hydrogen for chemical and fuel production remains a costly option compared to established fossil-based processes. Fuel cells add another layer of expense: they depend on high-purity hydrogen that must meet ISO 14687:2025 specifications and on stacks that rely on platinum-based catalysts and specialised manufacturing, with costs that are not yet competitive at scale [53].

**Solution**

**Support innovation and targeted deployment of hydrogen end-use technologies.** Research and industrial policy should prioritise reducing noble metal loadings, extending system lifetimes, and simplifying balance-of-plant while early deployment is concentrated in applications where fuel cells and other hydrogen technologies offer a clear advantage. Well-designed support schemes can help bridge the cost gap until economies of scale and learning effects bring costs closer to competing fossil-based options.

Fuel cells and other hydrogen end-use technologies are still expensive and demanding, so policy and industry should back innovation to cut material and system costs, and focus on early deployment where these technologies have a clear advantage, using targeted support to bridge the cost gap to fossil-based options.

## 3.4 ENVIRONMENTAL AND ETHICAL BARRIERS

The deployment of low-carbon hydrogen in end-use applications raises environmental and ethical challenges that extend beyond technical feasibility and economic cost. While hydrogen conversion at the point of use is typically $CO_2$-free, the overall sustainability of hydrogen-based end-use technologies depends on upstream factors, how hydrogen is produced and with which energy sources, as well as technology-specific factors such as material demand, safety, and system efficiency.

Assessing these impacts is particularly challenging because hydrogen end-use technologies are at different stages of technological maturity. As a result, uncertainties remain regarding their full life-cycle emissions, material requirements, and broader societal implications. A robust evaluation of hydrogen use therefore requires a life-cycle and system-level perspective, including consideration of what hydrogen-based solutions replace in the energy system.

### DEPENDENCE ON UPSTREAM HYDROGEN PRODUCTION

Barrier

**The climate performance of hydrogen end-use technologies is strongly dependent on upstream hydrogen production.** Hydrogen-based applications such as electricity generation, industrial heat, or chemical synthesis can only be considered low-carbon if the hydrogen itself is produced with low emissions. Hydrogen production pathways vary widely in carbon intensity depending on the energy source and production method. Without explicit accounting of upstream emissions, hydrogen end-use technologies risk shifting emissions along the value chain rather than reducing them.

In addition, there is currently no global surplus of renewable electricity. Hydrogen produced today may therefore rely on electricity that could otherwise have been used for direct electrification. From a system-wide perspective, this opportunity cost complicates claims of "green" hydrogen and requires careful comparison with alternative decarbonisation pathways.

### Solution

**Assess and regulate hydrogen end-use emissions on a full life-cycle basis.** Emissions from hydrogen-based end-use technologies should be assessed and reported on a life-cycle basis, clearly distinguishing between direct emissions at the point of use and indirect emissions associated with hydrogen production. Robust tracking of hydrogen origin and its associated emission factor is essential, particularly as public support schemes increasingly incentivise hydrogen deployment. Certification frameworks and Guarantees of Origin should transparently integrate upstream emissions to ensure that hydrogen use delivers genuine climate benefits rather than redistributing emissions within the energy system.

## MATERIAL INTENSITY

### Barrier

**Hydrogen end-use technologies often have higher material intensity than conventional alternatives.** Compared to fossil-based or directly electrified options, many hydrogen end-use technologies require larger or more complex systems and rely on specialised materials. Fuel cells depend on platinum-group metals for catalysts, hydrogen turbines require advanced alloys and coatings, and novel chemical pathways rely on high-performance catalytic materials. This increased material intensity raises embedded emissions, supply-chain risks, and ethical concerns related to the sourcing of critical raw materials [54, 55].

Many of these materials are scarce, geographically concentrated, and sourced from regions with weak environmental regulation, poor labour conditions, or geopolitical instability [56]. Scaling hydrogen end-use technologies without addressing these constraints risks creating new strategic dependencies and ethical trade-offs. In addition, when hydrogen replaces efficient electrified or fossil-based systems, overall energy use and indirect emissions may increase, undermining decarbonisation objectives.

## Solution

**Prioritise high-value uses, reduce material intensity, and ensure traceability**. Hydrogen deployment should prioritise applications where it provides clear system value and where material requirements are proportionate to the climate benefits achieved. Life-cycle assessments should explicitly account for embedded material emissions and supply-chain risks alongside operational emissions.

Policymakers should strengthen due diligence and traceability requirements for critical materials, enabling assessment of environmental, ethical, and geopolitical impacts. In parallel, sustained research and innovation are needed to reduce reliance on scarce materials, lower catalyst loadings, develop alternative materials, and improve the durability of end-use technologies.

# HYDROGEN LEAKAGES

## Barrier

**Hydrogen leakage represents an integrated environmental, safety, and ethical challenge that affects deployment and public acceptance.** Hydrogen has physical properties, such as high diffusivity, low ignition energy, and wide flammability limits, that require safety approaches fundamentally different from those used for conventional fossil fuels. While hydrogen is not inherently unsafe, it cannot be treated as equivalent to fossil fuels in terms of safety measures and risk management.

Even small, persistent hydrogen losses can (i) erode the net climate benefit of hydrogen through indirect atmospheric effects, (ii) increase hazard potential, and (iii) undermine stakeholder confidence if risks are perceived as being managed informally or communicated selectively. In practice, this manifests as “deployment friction” for end users: permitting and insurer scrutiny increase, operating procedures become more complex, and community acceptance can deteriorate if there is ambiguity about how leaks are prevented, detected, and addressed.

Hydrogen safety therefore requires a dedicated, multi-level approach, spanning construction practices, material selection, component design, process safety, and personnel training. At present, safety-related knowledge and guidance remain partially decentralised, and not all relevant standards and regulations are fully adapted to hydrogen-specific risks.

**Solution**

Systematically translate existing hydrogen safety knowledge into industry standards and governance frameworks. Over the past 15 years, significant efforts have focused on practical research into hydrogen safety. These efforts have led to the establishment of working groups and platforms to consolidate and disseminate safety-related knowledge. Examples include HySafe, which organises biennial workshops and academic conferences, and international initiatives such as the H2tools platform developed by the United States Department of Energy.

While the academic and research communities provide a strong foundation, the next critical step is to translate this knowledge into the codes, standards, and operational practices used by industry. In Europe, the European Hydrogen Observatory provides an overview of hydrogen-related policies, standards, and codes, supporting alignment across jurisdictions and applications. Embedding this accumulated knowledge into harmonised regulation, certification schemes, and workforce training is essential to reduce uncertainty, improve safety performance, and maintain public trust as hydrogen end-use technologies scale.

Hydrogen end-use technologies can only deliver genuine environmental and ethical benefits if assessed from a full life-cycle and system perspective. Their performance depends on upstream hydrogen production, material intensity, safety governance, and what technologies they replace. Addressing hydrogen-specific safety and leakage risks through clear standards, responsibilities, and transparent risk communication is essential to avoid deployment delays and ensure that hydrogen use contributes to sustainable decarbonisation rather than shifting emissions, risks, or dependencies.

## 3.5 TECHNOLOGICAL OPTIONS

Recent technological advances have provided solutions to the above-discussed challenges, but some remain at lower TRLs. It has become clear that even though further R&D is essential, decisions need to be made, starting with adding flexibility to the energy grid and accepting the combination of technologies rather than a universal solution, which is not realistic for all applications. Blue hydrogen might be implemented as a temporary, low-emissions hydrogen production solution, with a long-term shift toward renewable methods of producing it. Moreover, not all hydrogen production methods provide the same purity standards of the final product, so a careful distribution of that needs to be made among the usage technologies. Synthetic fuels, such as diesel, gasoline, and kerosene, can be produced with zero emissions and used directly in existing engines. It is, however, suggested to make the right choice of the most suitable fuel for each application. While hydrogen can be an attractive fuel for larger vehicles, such as boats or trucks, it cannot replace conventional aviation fuels and is unlikely to be a better alternative than electrification for particular vehicles. It is essential to emphasize that the scale of hydrogen use technologies is one of the most significant challenges; however, it is suggested that the focus and resources be shifted to those that are more mature and can scale up more quickly.

Finally, at this stage, it is essential to conduct a thorough analysis of the entire interconnected hydrogen chain across energy, emissions, and economic factors.

## 3.6 BENEFITS OF A BALANCED APPROACH

Implementing such a detailed approach to address low-emission challenges can benefit many industrial and social sectors. Such solutions can help strategically distribute hydrogen and effectively utilize various hydrogen energy sources. In addition, decarbonization has a direct impact not only on electricity production but also on the transportation sector. Such solutions can boost the hydrogen value chain and create certainty in the demand. At the same time, the industry remains competitive, and there is independence for resources and energy at the national or European level.

## 3.7 CONCLUSION

Hydrogen use offers many potential benefits for replacing high-emission technologies. Although many challenges remain and various technologies from different fields need to be connected, today's advances suggest this is not a utopian scenario. With a clear choice of the right distribution of hydrogen and development of the right technologies, the no-emission goals of the EU and Belgium can be realistically met.

# DISCLAIMER

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# NOTES

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