Review on hydrogen production, storage and transport in the context of the energy transition

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Abstract. Hydrogen is considered a central element in the architecture of future sustainable energy systems, due to its versatility and potential for integration with renewable sources. However, despite the growing interest, the development of a functional hydrogen-based economy faces numerous technological, economic and logistical obstacles. The production of hydrogen from clean sources still involves significant costs and requires high energy consumption, which limits competitiveness compared to conventional methods. Efficient storage is hampered by the physical properties of hydrogen, which impose special handling conditions. In addition, the transport infrastructure is insufficient, which affects scaling at regional and global levels. This article aims to examine the main issues surrounding the use of hydrogen in the context of energy transition, with a focus on the crucial steps of production, storage, and transportation. They are considered, together with potential directions for technological and organizational advancement, without excluding elements related to public politics, investments, and international initiatives, where analysis is permitted. The overall goal is to help understand the role of hydrogen in future sustainable energy systems by highlighting both current challenges and potential solutions.

1. Introduction

Hydrogen can complement direct electrification by enabling deep decarbonisation in sectors where electrons alone are impractical, such as steel, chemicals, fertilisers, long-haul mobility and long-duration energy storage [1]. In the European Union (EU), policy initiatives and market instruments are accelerating early projects while standardisation bodies converge on common technical bases for quality, metrology and safety. Despite this momentum, industry still faces binding constraints: the cost of renewable hydrogen under European electricity prices; limited volumes of geological storage; uncertainty around pipeline repurposing at scale; and the need for interoperable safety rules that maintain public confidence. This article

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responds to these challenges with a structured synthesis of recent evidence and practice [1, 2, 3].

The review foregrounds the EU context and integrates global perspectives where useful for comparison. The analysis is organised around production, storage and transport, with a dedicated section on safety and regulation. To keep the discussion actionable, each major section identifies dominant cost and risk drivers, practical engineering trade-offs and their implications for deployment in 2025–2035. Three case studies provide concrete examples of the European roll-out.

2. Policy and market context in Europe

The EU's decarbonisation strategy anticipates a material role for renewable fuels of non-biological origin (RFNBOs), with hydrogen expected to serve both as energy carrier and as chemical feedstock. The policy architecture combines target-setting with bankability tools: updated renewable energy legislation defines conditions for RFNBO eligibility, while competitive premium-based auctions for renewable hydrogen support offtake during the scale-up phase [6].

Alongside, Member States advance Important Projects of Common European Interest (IPCEI) waves to develop manufacturing capacity and infrastructure. On the market side, offtake is clustering around industrial hubs, steel, ammonia, methanol and refuelling networks,where aggregation and infrastructure sharing provide early economies of scale [3]. European transmission system operators (TSOs) are translating this demand into plans for a European Hydrogen Backbone (EHB) that mixes repurposed and new-build pipelines connected to storage and import nodes [2].

3. Production

3.1 Terminology beyond colour labels

While public discourse often uses "grey", "blue" and "green", the European policy regime instead emphasises lifecycle greenhouse-gas intensity and electricity sourcing rules. Renewable hydrogen in the EU context refers to RFNBO hydrogen meeting temporal and geographical correlation and additionality criteria for the electricity used. Low-carbon hydrogen generally refers to fossil-based routes with carbon capture that comply with defined intensity thresholds.

3.2 Technology options and performance

Electrolysis is the main route to RFNBO hydrogen. Alkaline electrolysers (AEL) are robust and cost-effective at scale; proton-exchange membrane (PEM) electrolysers tolerate flexible operation and higher current densities; and solid-oxide electrolysers (SOEC) can achieve high electrical efficiencies when coupled to suitable heat sources [4]. System-level performance depends on stack design, balance-of-plant optimisation, water quality, and operating regime. In parallel, steam-methane reforming (SMR) and autothermal reforming (ATR) with high-capture carbon storage can deliver large volumes at competitive equipment cost, provided that suitable CO_2 transport and storage are available and that upstream methane emissions are effectively mitigated [1, 3].

3.3 Cost drivers and bankability

Levelised cost is primarily a function of electricity price, capacity factor and capital expenditure for electrolysis; and of gas price, capture rate and transport/storage cost for blue routes [1, 5]. In both cases, utilisation and offtake certainty strongly influence financing terms and therefore the cost of delivered hydrogen. European premium-based auctions, long-term offtake contracts for industrial products (e.g., green steel) and access to low-cost renewable power are the levers most often associated with bankable project pipelines [3]. Careful siting near renewable generation or process-heat sources improves overall efficiency and reduces curtailment [4].

3.4 RFNBO compliance and carbon-intensity accounting (EU)

In the EU regulatory context, renewable hydrogen (a renewable fuel of non-biological origin, RFNBO) must satisfy additionality, temporal correlation and geographical correlation for the electricity input. Additionality limits the use of existing renewable capacity to avoid cannibalising decarbonisation elsewhere; temporal correlation seeks alignment between electrolyser consumption and renewable generation windows; geographical correlation constrains sourcing to the same bidding zone or an interconnected area. Lifecycle greenhouse-gas (GHG) intensity depends on these sourcing rules, electrolyser efficiency and upstream emissions.

From a project-design perspective, co-location with renewable plants, flexible operation against day-ahead and intraday prices, and credible data collection for Guarantees of Origin (GOs) are key to compliance and bankability [1, 2, 5].

3.5 Electrolyser performance metrics and degradation

System efficiency (η_sys) is commonly expressed on a lower-heating-value (LHV) basis. A practical metric is the specific energy consumption (SEC, $kWh \cdot kg^{-1}$ H_2):

$$SEC = E\_in / m\_H2 \qquad (1)$$

where E_in is net electrical input and m_H2 is produced hydrogen mass. At the system level, balance-of-plant (compression, drying, cooling, power conversion) increases SEC versus stack values. Dynamic performance matters for grid-following operation: PEM (proton-exchange membrane) stacks tolerate fast ramps, while AEL (alkaline) stacks favour steady operation; SOEC (solid-oxide) systems achieve high electrical efficiency when adequate high-temperature heat is available, but ramping must respect thermal constraints. Degradation (e.g., catalyst thinning, membrane pinholes) manifests as rising cell voltage; periodic stack replacement can be a material OPEX line. Water treatment (deionisation and low-total-organic-carbon polishing) and heat-recovery loops materially impact SEC and uptime [4, 5].

4. Storage

4.1 Compressed gaseous hydrogen

Compressed hydrogen at 350–700 bar remains the default for mobility and for early market logistics using tube-trailers or multi-element gas containers. Composite Type-IV vessels minimise weight but require rigorous control of permeation and material compatibility [4, 6].

At the installation level, safety is ensured through appropriate separation distances, ventilation and leak detection, coupled with overpressure protection and controlled venting.

4.2 Liquid hydrogen

Liquefaction raises volumetric density and reduces footprint but at the price of significant energy consumption for cryogenic handling and the need to manage boil-off losses [1, 4]. Liquid hydrogen is therefore best suited to applications where energy density is at a premium or where specific logistics chains justify the investment, including aerospace and selected maritime routes. Thermal integration and boil-off re-liquefaction strategies reduce losses at scale.

4.3 Material-based options

Liquid organic hydrogen carriers (LOHCs) enable ambient-condition logistics using conventional liquid-fuel infrastructure [3]. They impose dehydrogenation energy penalties and require catalyst management and carrier handling protocols, yet they are attractive where flexible storage time and compatibility with existing assets dominate. Metal-hydride systems offer high volumetric density and intrinsic safety advantages, with kinetics and thermal management dictating practical deployment in stationary or niche mobile use [4].

Sorbent-based approaches achieve high capacities at cryogenic temperatures but remain less competitive at ambient conditions [4].

4.4 Underground hydrogen storage

Salt caverns combine large working gas volumes with high injection/withdrawal rates and favourable geochemistry; they are the leading option for seasonal hydrogen storage in Europe. Aquifers and depleted fields are being evaluated but face challenges in gas quality management and microbiological activity. Engineering considerations include cushion gas requirements, well integrity under hydrogen service, monitoring for leakage and quality control aligned with end-use specifications. As Europe develops a backbone, cavern clusters near industrial hubs are likely to become strategic for system balancing [8].

Figure 1 provides an overview of the hydrogen value chain discussed in this article. Figure 2 compares indicative volumetric storage densities at the system level. Practical logistics trade-offs are illustrated conceptually in Figure 3.

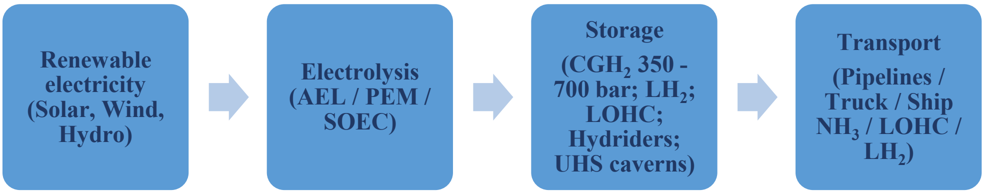

Fig. 1. Hydrogen value chain from production to storage and transport, indicating the main options discussed in the text

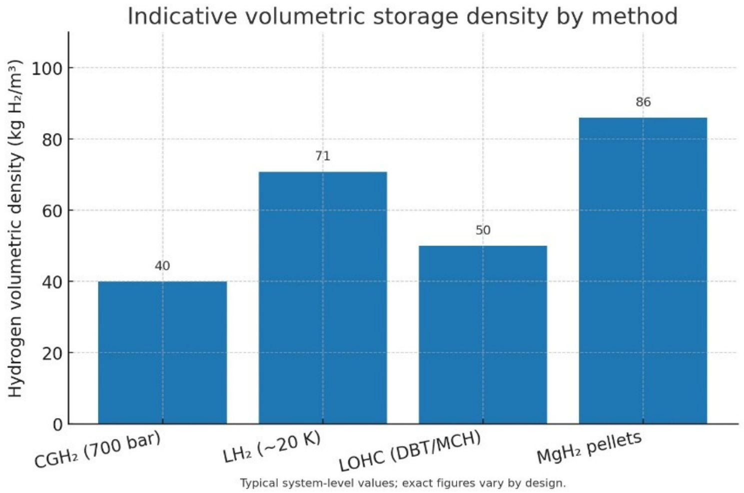

Fig. 2. Indicative system-level volumetric hydrogen storage densities for representative options (CGH_2 at 700 bar, LH_2, LOHC, metal hydrides). Exact values are design-dependent

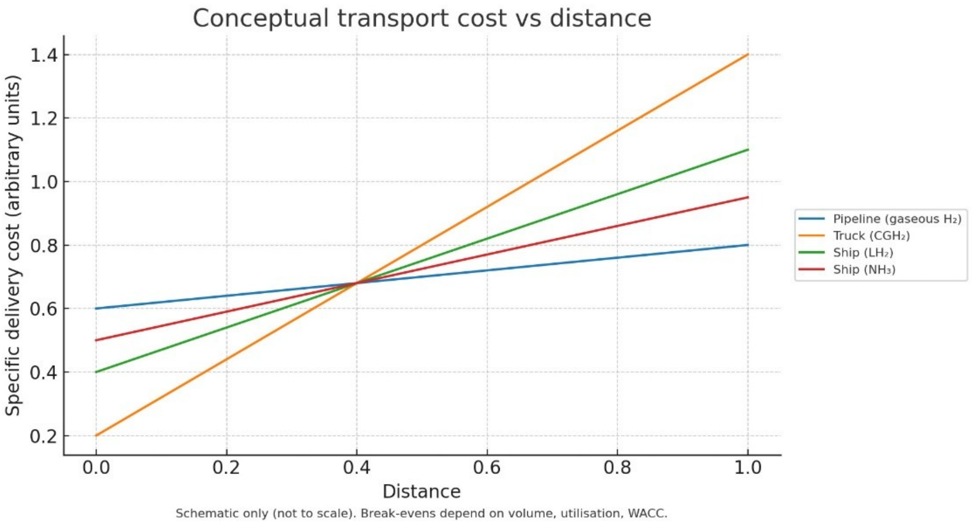

Fig. 3. Conceptual comparison of specific delivery cost versus distance for pipeline, compressed-gas trucking and maritime vectors (liquid hydrogen and ammonia). Schematic, not to scale

5. Transport

5.1 Pipelines and the European Hydrogen Backbone

Dedicated hydrogen pipelines offer the lowest long-run marginal cost for high-volume transport. Repurposing parts of the natural-gas grid is central to early network formation where materials and compressor stations can be adapted to hydrogen service. Technical issues include fracture toughness and crack growth in legacy steels, hydrogen compatibility of valves and seals, and the treatment of linepack as an operational buffer. Interoperability will depend on harmonised gas-quality specifications and metrology so that downstream end-uses, especially fuel cells, are protected [2, 3, 9].

5.2 Blending as a transitional measure

Injecting limited fractions of hydrogen into existing gas grids can enable early volumes and learning without the immediate need for dedicated infrastructure. However, appliance compatibility, energy billing, and cross-border market rules place practical limits on blending. For these reasons, blending is best treated as an interim option rather than a structural end-state for European hydrogen transport [3].

5.3 Road and rail modules

Tube-trailers carrying compressed hydrogen and cryogenic tanks for liquid hydrogen provide flexible point-to-point deliveries. Their deployment is governed by international dangerous-goods rules and national tunnel restrictions [10]. Rail can transport pressurised vessels efficiently where terminals are equipped for fast loading and unloading.

5.4 Maritime vectors

For intercontinental trade, hydrogen can be shipped as liquid hydrogen, as ammonia or as an LOHC. Ammonia benefits from existing infrastructure and high volumetric energy density but requires careful toxicity management and, where pure hydrogen is needed, efficient cracking units at destination. LOHCs trade off additional conversion energy for logistics simplicity. Liquid hydrogen shipping eliminates conversion chemistry but demands advanced cryogenic engineering and boil-off control [1, 7]. Major European ports are developing import terminals and onshore conversion logistics to serve inland pipelines and industrial users. Figure 4 sketches Europe's emerging corridors and nodes.

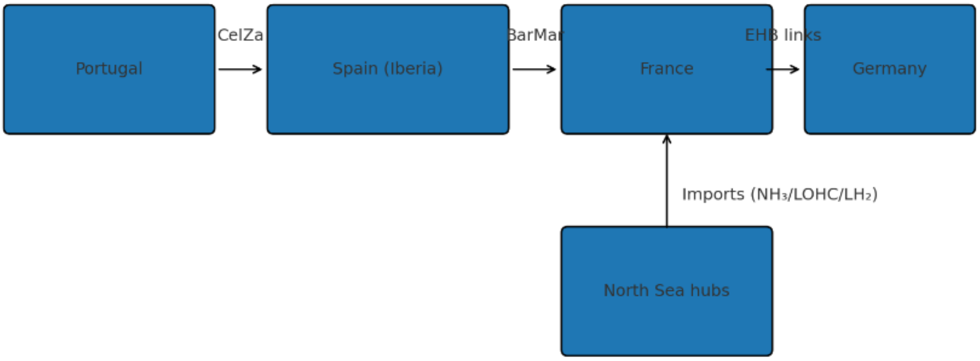

Fig. 4. Schematic EU hydrogen corridors emphasising H2Med (BarMar and CelZa) and links into the European Hydrogen Backbone

5.5 Pipeline hydraulics and compression (concepts)

Hydrogen's low molecular mass increases velocity for a given mass flow and pipe diameter, thereby raising frictional losses. Throughput in a given line depends on pressure ratio, compressibility factor (Z) and friction factor; higher compression energy is required per unit of energy delivered compared with natural gas, particularly where multiple booster stations are needed.

Linepack (the energy stored as pressure in the pipeline) provides short-term balancing but depends on material limits and allowable maximum operating pressure. Repurposed pipelines require verification of fracture toughness, weld quality, and compatibility of seals and valves under hydrogen service; dry, particulate-free gas reduces wear and protects downstream fuel-cell applications [2, 3].

6. Safety and regulation (EU focus)

6.1 Materials selection and embrittlement mechanisms

Hydrogen embrittlement can reduce ductility and fracture toughness in susceptible steels and alloys via mechanisms such as hydrogen-enhanced decohesion and localised plasticity. Mitigations include material selection (e.g., lower-strength steels for legacy assets), surface treatments, control of residual stresses, and design for crack-growth tolerance. Qualification testing under representative pressures and cyclic loads is recommended for repurposed infrastructure.

6.2 Gas-quality management and purity control

End-use purity requirements differ: proton-exchange-membrane fuel cells are sensitive to sulphur-bearing species and particulates at parts-per-billion levels, whereas industrial burners are more tolerant. Gas drying, filtration and polishing, together with contamination monitoring, are standard measures to ensure compliance with ISO and EN specifications referenced in this paper [11, 12].

6.3 Functional safety and operability

Functional safety layers (sensor redundancy, interlocks, emergency shutdown) complement passive measures (separation distances, ventilation). Safety-integrity-level targets may apply in process-control systems; while detailed standards are outside this paper's scope, the principle is to align detection and shutdown logic with credible hazard scenarios. Regular HAZOP (hazard and operability) reviews help maintain safety-by-design over asset life. In Europe, a layered framework governs equipment, workplaces and transport.

The ATEX Directives address explosive-atmosphere equipment and workplace classification; the Pressure Equipment Directive (and the Transportable Pressure Equipment framework) ensure integrity of pressure-bearing components; the Seveso regime manages establishments with significant inventories; and the ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road), RID (Regulations concerning the International Carriage of Dangerous Goods by Rail), IMDG (International Maritime Dangerous Goods Code) and IATA DGR (International Air Transport Association Dangerous Goods Regulations) govern carriage by road, rail, sea and air.
Hydrogen-specific quality and refuelling standards provide the additional precision required for fuel cells and for purity-critical industrial uses [6, 9, 11, 12].

Implementation combines hazard identification and operability review, quantitative risk assessments (QRA) and computational fluid dynamics (CFD) support for dispersion and jet-fire scenarios. Practical measures include engineered ventilation, gas-detection networks with graded alarm set-points, flame-proofing of electricals in zoned areas, passive and active fire protection, and clean-service protocols to achieve the fuel-quality limits needed for proton-exchange-membrane systems. Figure 5 maps the principal regulatory touch-points along the value chain.

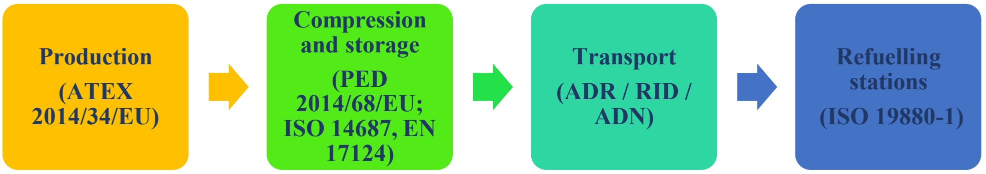

Fig. 5. Indicative mapping of key EU safety and quality frameworks along the hydrogen value chain (ATEX; PED/TPED; ADR/RID; ISO 14687; EN 17124; ISO 19880-1)

7. Case studies (EU)

7.1 H2Med/BarMar: connecting Iberia to core EU demand

Iberia's renewable resources make it a strong candidate for large-scale RFNBO production. H2Med proposes a dedicated hydrogen corridor with an offshore link between Barcelona and Marseille (BarMar) and an onshore link connecting Portugal and Spain (often referred to as CelZa). The project aims to integrate Iberian supply into the continental backbone and to facilitate flows toward industrial centres in France and beyond [2]. Its success will depend on coordinated network codes, gas-quality harmonisation and timely permitting.

7.2 Port of Rotterdam: gateway for imports

Rotterdam is positioning itself as a European gateway for hydrogen carriers, ammonia, LOHC and liquid hydrogen, while also building local electrolysis capacity [1]. The port's strategy combines import terminals, onshore conversion facilities, quality-control laboratories and pipeline links to Northwest European industrial clusters. This integrated approach illustrates how ports can anchor both maritime and inland value chains.

7.3 Underground hydrogen storage pilots in DE/NL

Pilot and demonstration projects in Germany and the Netherlands are progressively validating the design and operation of salt-cavern storage for hydrogen. The programmes focus on deliverability, integrity under cycling and gas-quality management for downstream users. As core hydrogen networks mature, cavern clusters near industrial demand are likely to play a central role in seasonal balancing and security of supply [8].

8. Discussion: integration issues and priorities

Three themes recur across the value chain. First, utilisation is decisive: whether electrolysers, pipelines or storage caverns, high-load operation and aggregated demand reduce delivered-cost volatility and improve bankability. Second, interoperability matters: common purity specifications, metrology and billing standards lower transaction costs and protect sensitive end-uses. Third, a disciplined sequencing of infrastructure, industrial clusters first, then interconnectors and storage, helps avoid stranded assets while creating credible offtake for upstream projects. Together, these priorities shape a pragmatic path for 2025–2035 [1-3, 5, 9].

8.1 Research gaps 2025–2035

- Electrolyser durability under flexible operation: Quantify lifetime impacts of frequent ramping and start–stop cycles at the system level, including balance-of-plant components (valves, compressors, power electronics).
- High-purity gas handling at scale: Cost-effective polishing and continuous monitoring to achieve stringent fuel-cell limits across long supply chains; development of common EN/ISO conformity assessment for hydrogen purity in pipelines.
- Materials compatibility and repurposing protocols: Standardised test methods and acceptance criteria for legacy steels and welds in hydrogen service, including fracture-mechanics-based fitness-for-service approaches.
- Underground storage microbiology and gas quality: Better modelling of microbial kinetics, sulphur chemistry and mitigation strategies in non-salt formations; robust interfaces between storage output and downstream purity-critical users.
- Carrier pathways TEA: Transparent benchmarks for ammonia, LOHC and LH_2 chains under EU carbon and power-market conditions, with explicit assumptions on capacity factors, WACC and end-use reconversion efficiencies.
- Operational integration with power systems: Co-optimisation of hydrogen production with congestion management and renewable curtailment, including network-code interactions and RFNBO compliance under temporal correlation rules.

9. Conclusions

Europe now has the contours of a hydrogen economy, but the credible contribution of hydrogen to decarbonisation depends on disciplined execution across the value chain. First, renewable hydrogen must become reliably affordable at sites where it is actually needed. That outcome is most sensitive to electricity price and utilisation, which in turn are shaped by the co-location of electrolysers with low-cost renewables and by bankable offtake anchored in industry and e-fuels. Premium-based auctions and long-term contracts should therefore be calibrated to deliver high load factors and predictable revenue while keeping competition for public support rigorous [1, 3, 5].

Second, Europe should sequence infrastructure in a way that creates optionality without locking in sub-optimal pathways. Dedicated hydrogen corridors around industrial clusters, connected through cross-border interconnectors, provide the backbone for scale; blending can play a transitional role where it accelerates demand aggregation but should not substitute for network formation. Storage in salt caverns deserves priority near demand centres to provide seasonal balancing and security of supply [2, 3, 8].

Third, interoperability and safety are preconditions for market trust. Harmonised gas-quality specifications, metrology and billing standards protect sensitive end-uses and facilitate cross-border trade, while consistent implementation of ATEX, PED/TPED and ADR ensures that hydrogen facilities meet the same safety bar across Member States [7, 8, 9, 10, 11, 12, 13, 14].

Looking to 2025–2035, the most resilient deployment pathway is one that focuses hydrogen where molecules are indispensable, feedstocks, high-temperature heat, long-duration storage and specific mobility use cases,while avoiding unnecessary detours that increase system losses. If policy keeps targeting the real cost and risk drivers, and if infrastructure is sequenced around bankable offtake, hydrogen can progress from promising pilots to reliable, scalable assets that enhance Europe's net-zero transition [1, 2, 3].

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References

1. International Energy Agency (IEA), Global Hydrogen Review 2024 (2024).
2. Z. Said, P. Sharma, B.J. Bora, V.N. Nguyen, T.A.E. Bui, D.T. Nguyen, X.T. Dinh, X.P. Nguyen, Modeling-optimization of performance and emission characteristics of dual-fuel engine powered with pilot diesel and agricultural-food waste-derived biogas, Int. J. Hydrogen Energy **48**, 31476–31490 (2023). https://doi.org/10.1016/j.ijhydene.2022.07.150
3. L. Xiong, C. Liang, B. Ma, F. Shah, W. Wu, Carbon footprint and yield performance assessment under plastic film mulching for winter wheat production, J. Clean. Prod. **270**, 122468 (2020). doi:10.1016/j.jclepro.2020.122468 https://doi.org/10.1016/j.jclepro.2020.122468
4. A. Buttler, H. Spliethoff, Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review, Renew. Sustain. Energy Rev. **82**, 2440–2454 (2018). https://doi.org/10.1016/j.rser.2017.09.003
5. G. Glenk, S. Reichelstein, Economics of converting renewable power to hydrogen, Nat. Energy **4**, 216–222 (2019). https://doi.org/10.1038/s41560-019-0326-1
6. ISO 19880-1:2020, Gaseous hydrogen - Fuelling stations - Part 1: General requirements.
7. J. Andersson, S. Grönkvist, Large-scale storage of hydrogen: LOHC as an option, Int. J. Hydrogen Energy **44**, 11901–11919 (2019). https://doi.org/10.1016/j.ijhydene.2019.03.063
8. S.J. McPhail, Hydrogen energy: State of the art and perspectives, Current Trends and Future Developments on (Bio-) Membranes, New Perspectives on Hydrogen Production, Separation, and Utilization, 3-19 (2020). https://doi.org/10.1016/B978-0-12-817384-8.00001-7
9. CEN/TS 17977:2023, Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems.
10. ADR 2025 (UNECE), European Agreement concerning the International Carriage of Dangerous Goods by Road, UN 1049 Hydrogen, compressed.
11. ISO 14687:2025, Hydrogen fuel quality - Product specification.
12. EN 17124:2022, Hydrogen fuel - Product specification and quality assurance - Proton exchange membrane (PEM) fuel cell applications for road vehicles.
13. Directive 2014/34/EU (ATEX) and Directive 1999/92/EC (ATEX workplace), equipment and protective systems intended for use in potentially explosive atmospheres.
14. Directive 2014/68/EU (Pressure Equipment Directive) and related Transportable Pressure Equipment provisions.