

HYDROGEN'S ROLE IN THE ENERGY ECOSYSTEM

An End-to-End Perspective on its Potentials and Limitations

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An End-to-End Perspective on its Potentials and Limitations



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Foreword

Our society is at a turning point. The need to achieve climate goals while ensuring prosperity, jobs and quality of life presents a major challenge for governments, businesses and communities alike. In the face of rising global greenhouse gas emissions, the hydrogen economy emerges as a promising path and additional solution to drive sustainable change.

At accilium, we are committed to shape the energy ecosystem of tomorrow. We believe that innovation, combined with modern digital tools and collaborative approaches, is essential to overcoming today's pressing challenges. Drawing from our expertise working with energy providers, manufacturers and public institutions, we develop strategies to address these issues while carefully evaluating their practicality and potential impact.

In our efforts to support the transition to a low-carbon future, we see hydrogen as a key enabler. Our focus is on five fundamental pillars of the hydrogen value chain: Production, Conversion, Storage, Transport and Utilization. By examining each of these areas, we aspire to create a roadmap that bridges the gaps between achieving climate goals and accelerating the transformation of the hydrogen economy.

This study is aimed at decision-makers and forward-thinking leaders, offering a concise overview of the long-term viability of different hydrogen value chain strategies. Our research is designed to provide a clear, evidence-based perspective on potential opportunities within the hydrogen sector.

We encourage you to explore the findings in this report, which we hope will inspire your efforts to build a sustainable and resilient future. By working together and taking informed, decisive action, we can unlock the potential of hydrogen to help meet global climate targets and ensure a better future for all.



A stylized, handwritten signature in black ink, appearing to read 'Peter Allan'.

Peter Allan
Managing Partner
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About accilium

accilium is a management and strategy consultancy founded on the core idea that nothing is built to last unless it is built to evolve. On this basis, accilium has been driving the mobility and energy transition for 7 years now by solving the problems of clients in the mobility and energy ecosystem (automotive & transport, public sector & infrastructure, energy & environment) by accelerating the digital transformation. With more than 130 consultants at seven European locations, accilium is already one of the top 10 management consultancies in the DACH-region.

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07 EUROPEAN OFFICE LOCATIONS



170 EMPLOYEES

130 strategy and
management
consultants

40 software
developers

ACCILIUM GROUP



Executive Summary

The global energy transition is redefining how we produce, transport, and consume energy. Hydrogen, as a versatile and scalable energy carrier, has emerged as a cornerstone of this transformation, offering pathways to decarbonize hard-to-abate sectors such as heavy industry, long-distance transport, and power generation. This study explores the potential and limitations of hydrogen and its derivatives through three end-to-end use cases: green steel production, power generation and heavy-duty mobility solutions.

The analysis leverages a **Methodology of Value Chain Building Blocks**, a structured framework that evaluates technological maturity, investment costs, geopolitical risks, CO₂ footprints, and supply chain resilience. This approach provides tangible insights into the viability of different hydrogen value chains, emphasizing the importance of prioritizing use cases where hydrogen delivers the greatest impact.

Despite its promise, hydrogen is not a universal solution. The **Hydrogen Ladder** emphasizes the need to focus resources on high-priority applications, such as steel, ammonia, and aviation, where alternatives are limited. Misallocating hydrogen to low-impact sectors, like domestic heating or passenger transport, risks inefficiencies and delays in achieving decarbonization goals.

Meeting future hydrogen demand, projected to rise from 94 million tons in 2021 to 450 million tons by 2050, requires scaling global electrolyzer capacity and developing robust supply chains. International collaboration, such as partnerships between the EU and regions with abundant renewable energy resources like Argentina, Saudi Arabia and Australia, will be essential to diversify sourcing and ensure resilience. These regions benefit from significant solar and wind energy potential, enabling large-scale green hydrogen production. Policymakers must align incentives, infrastructure investments, and R&D efforts to reduce efficiency losses across value chains and support the integration of these global partnerships.

Hydrogen is a crucial part of the energy mix, but its success depends on strategic deployment. By prioritizing high-impact sectors and addressing systemic inefficiencies, hydrogen can fulfill its transformative potential in driving meaningful global emissions reductions.

Key Findings:

- In **green steel production**, locally produced hydrogen offers low emissions and energy security but faces high investment costs for infrastructure and electrolysis. Imported hydrogen, while less capital-intensive, carries geopolitical risks and higher emissions from transport.
- For **power generation** in Europe, importing hydrogen in the form of ammonia presents a more viable option due to its well-established infrastructure compared to liquid hydrogen. The use of liquid hydrogen for global transport shows slightly better efficiency but remains constrained by high costs and limited scalability for long-distance shipments.
- For **heavy-duty mobility solutions**, hydrogen supports fuel cell electric trucks (FCETs), offering superior energy efficiency and zero tailpipe emissions. Conversely, e-fuels provide a transitional solution for existing internal combustion engine (ICE) fleets but suffer from inefficiencies in production and higher lifecycle emissions.

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1 Introduction

Hydrogen has emerged as a pivotal solution in the global energy transition, offering a scalable and versatile pathway to decarbonize sectors where direct electrification remains challenging. As a clean energy carrier, hydrogen holds immense potential to reduce greenhouse gas emissions, enhance energy independence, and drive innovation across industries such as the heavy industry, long-distance transport, and power generation.

Recognizing its transformative role, global stakeholders are accelerating investments in hydrogen technologies and infrastructure. Initiatives such as the EU's REPowerEU¹ plan, the U.S. Inflation Reduction Act², and large-scale projects in countries like Japan, South Korea, and Saudi Arabia highlight hydrogen's growing prominence in shaping the future energy landscape. Discussions at key international forums, including COP28 and COP29, have further cemented its importance in achieving net-zero targets.

1.1 Hydrogen Perspectives and its Challenges

The integration of hydrogen into the global energy mix is not without challenges. While its versatility offers significant opportunities, the journey to scale hydrogen adoption is complex and requires overcoming technical, economic, and geopolitical barriers. The development of a robust hydrogen economy depends on coordinated efforts from policymakers, industries, and technology providers to address these barriers systematically and sustainably.

This study provides a comprehensive overview of the hydrogen ecosystem, examining its value chain – including Production, Conversion, Storage, Transport, and Utilization – and its potential to reshape energy systems. By analyzing practical applications across key sectors, this report explores hydrogen's role in reducing emissions and achieving global climate goals. The findings emphasize the need for a targeted approach that prioritizes high-impact use cases, optimizes value chains, and aligns resources with the most promising applications.

However, unlocking the full potential of hydrogen requires addressing six fundamental challenges that currently hinder its widespread adoption:

High Production Costs

Green hydrogen, produced through electrolysis powered by renewable energy, remains significantly more expensive than grey hydrogen, which currently dominates the market. Grey hydrogen is produced from natural gas through processes like steam methane reforming, which emit large amounts of CO₂. Blue hydrogen is hydrogen produced from natural gas via steam methane reforming (SMR) with carbon capture and storage (CCS) to reduce CO₂ emissions. The high costs of green hydrogen are primarily driven by:

- Limited availability of low-cost renewable electricity.
- The high capital expenditures (CAPEX) of electrolyzers, which are not yet produced at scale. Achieving cost parity with grey and blue hydrogen requires substantial investments in renewable energy expansion, technological innovation, and production scale-up.

¹ European Commission. REPowerEU: Affordable, Secure and Sustainable Energy for Europe. European Commission

² U.S. Department of the Treasury. Inflation Reduction Act. U.S. Department of the Treasury

Infrastructure Gaps

The infrastructure required to produce, store, transport, and distribute hydrogen is underdeveloped. For example:

- › **Storage:** Hydrogen's low energy density by volume requires compression, liquefaction, or chemical conversion, all of which are costly and energy-intensive.
- › **Transport:** Current pipelines are limited and not designed for large-scale hydrogen transport, while shipping liquid hydrogen over long distances remains inefficient due to energy losses.
- › **Distribution:** Developing end-user infrastructure, such as fueling stations for hydrogen vehicles, is expensive and unevenly distributed across regions.

Market Uncertainty

Hydrogen markets are still in their infancy, with a lack of standardized pricing mechanisms and regulatory frameworks. Key challenges include:

- › Establishing transparent price benchmarks, such as the HYDRIX index, to promote investment and fair competition.
- › Addressing long-term demand uncertainty, as industries and governments are still evaluating hydrogen's role in the energy mix.

Financing and Risk

Short-to-medium-term project financing remains a significant hurdle due to high upfront costs, extended periods required to recover investments and technological uncertainties. While public funding and long-term private capital are helping to drive initial investments, many investors remain cautious about the associated risks, including:

- › Market volatility and fluctuating policy support.
- › Unclear breakeven points for green hydrogen, particularly in competitive markets.

Public Acceptance and Perception

Public opinion on hydrogen is mixed, with concerns about:

- › **Safety:** Hydrogen's flammability and risks associated with storage and transport require stringent safety measures, which can raise costs.
- › **Sustainability:** Skepticism remains about the reliance on grey hydrogen, which undermines climate goals.
- › **Cost:** Public awareness of hydrogen's high costs and infrastructure requirements may slow adoption. Clear communication from policymakers and industry leaders is essential to build trust and dispel misinformation about hydrogen's role and benefits.

Geopolitical and Trade Dependencies

Hydrogen's development is reshaping global energy dynamics, introducing new dependencies and rivalries:

- › Europe is investing heavily in green hydrogen to reduce reliance on Russian natural gas, but this might create new dependencies on regions like North Africa for cheap renewable electricity.
- › China dominates electrolyzer manufacturing, challenging Europe's efforts to lead the hydrogen value chain.
- › Competing national strategies may hinder international collaboration and trade standardization, slowing market development.

These interconnected challenges form the foundation of our analysis. By addressing them strategically, hydrogen can evolve from a promising energy carrier into a cornerstone of global energy systems, enabling a sustainable and resilient energy future.

2 Hydrogen Ecosystem and Value Chain

Before analyzing the hydrogen value chain, it is essential to understand hydrogen's unique properties and the challenges associated with its use. Hydrogen is the lightest and most abundant element in the universe, appearing as a colorless, odorless gas at room temperature and atmospheric pressure. Despite its simplicity in atomic structure, its practical use presents several challenges.

Hydrogen is highly volatile due to its reactivity, low molecular weight, and low boiling point, making it challenging to store and transport. When released, hydrogen disperses quickly and can mix with oxygen, creating a high risk of flammability and explosion. Its low volumetric energy density further complicates storage, requiring large volumes or specialized methods such as compression or liquefaction, both of which demand costly infrastructure.

From an economic perspective, hydrogen production, storage, and transport are significantly more expensive than traditional fossil fuels. This is due to the high energy input required for production and the need for advanced equipment and facilities. While hydrogen is non-toxic, its reactivity necessitates stringent safety protocols, especially in industrial and logistical contexts.

Green hydrogen, produced via electrolysis using renewable energy, represents the most sustainable form. However, its production is still in the early stages of development and has yet to reach the scale needed for widespread adoption. These factors highlight both the promise and challenges of integrating hydrogen into future energy systems.

The hydrogen value chain consists of five stages: production, conversion, storage, transport, and utilization.

Production involves generating hydrogen from sources such as natural gas, biomass, or water using methods like steam methane reforming, electrolysis, or biomass gasification. The choice of method depends on feedstock availability, costs, and Greenhouse Gas (GHG) emissions. **Conversion** transforms hydrogen into stable compounds like ammonia to simplify storage, transport, and usage. **Storage** includes compressed gas, liquefied gas, or solid-state methods, selected based on application and duration. **Transport** relies on pipelines, trucks, or ships, depending on quantity and distance. Finally, **utilization** involves using hydrogen as fuel in mobility, power generation and industrial processes. Each stage will be explored in more detail in the following chapters.

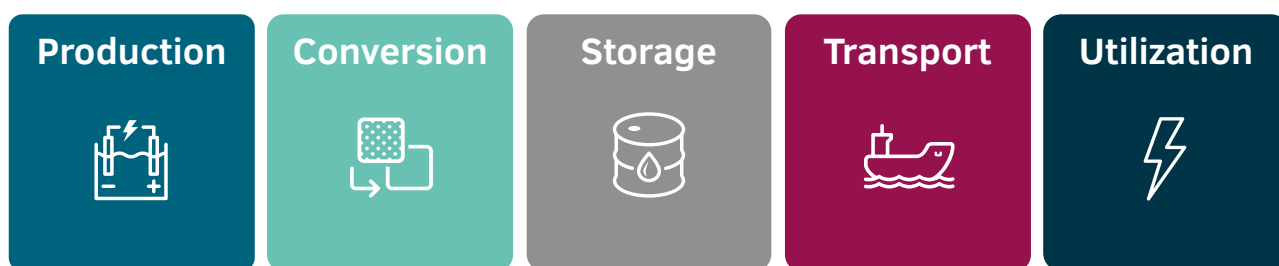


Figure 1: Hydrogen Value Chain

2.1 Hydrogen Production



Generation refers to the process of producing hydrogen gas from various sources. It is essential to closely examine hydrogen production, particularly the methodologies employed for its generation, since most GHG emissions in the value chain are created during the production process. In Figure 2, the different types of hydrogen generation are displayed. Hydrogen can be classified based on the methods used for its production and the sustainability of the generation process.

The assignment of different colours to each method is intended to provide quick information on the specific production methods used, the energy sources involved and the sustainability of the hydrogen produced.

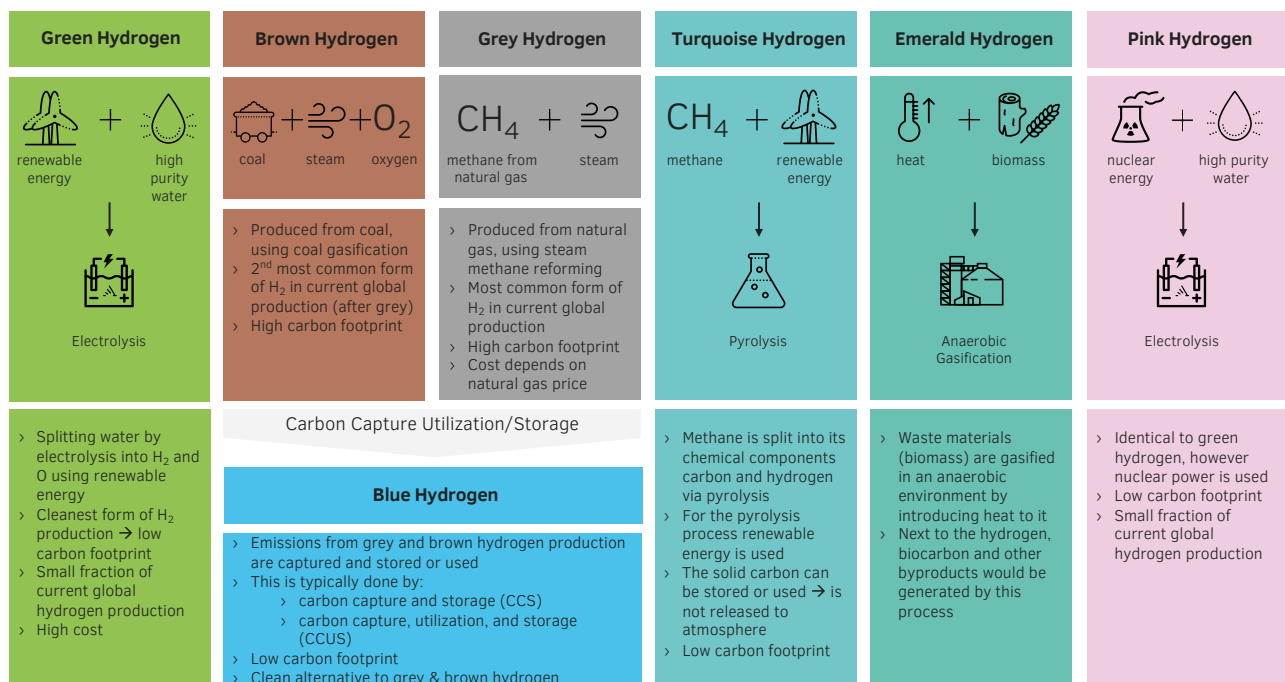


Figure 2: Overview Hydrogen Production Methods

Green Hydrogen Generation

This study focuses on green hydrogen, produced through the electrolysis of water using renewable energy. The process requires three key components: purified water, an electrolyzer, and renewable energy.

Water can be sourced from municipal systems, brackish groundwater, or seawater, which requires desalination and purification before use. Electrolyzers split water into hydrogen and oxygen using an electric current, with the most common types being alkaline, Proton Exchange Membrane (PEM) and solid oxide electrolyzers. Renewable energy sources such as wind, solar, and hydropower can drive the electrolysis process, making green hydrogen a sustainable alternative.

Figure 3 illustrates the green hydrogen generation process, showcasing the inputs (water and renewable energy), the electrolysis step, and the possible storage, transport, or utilization pathways for the hydrogen produced.

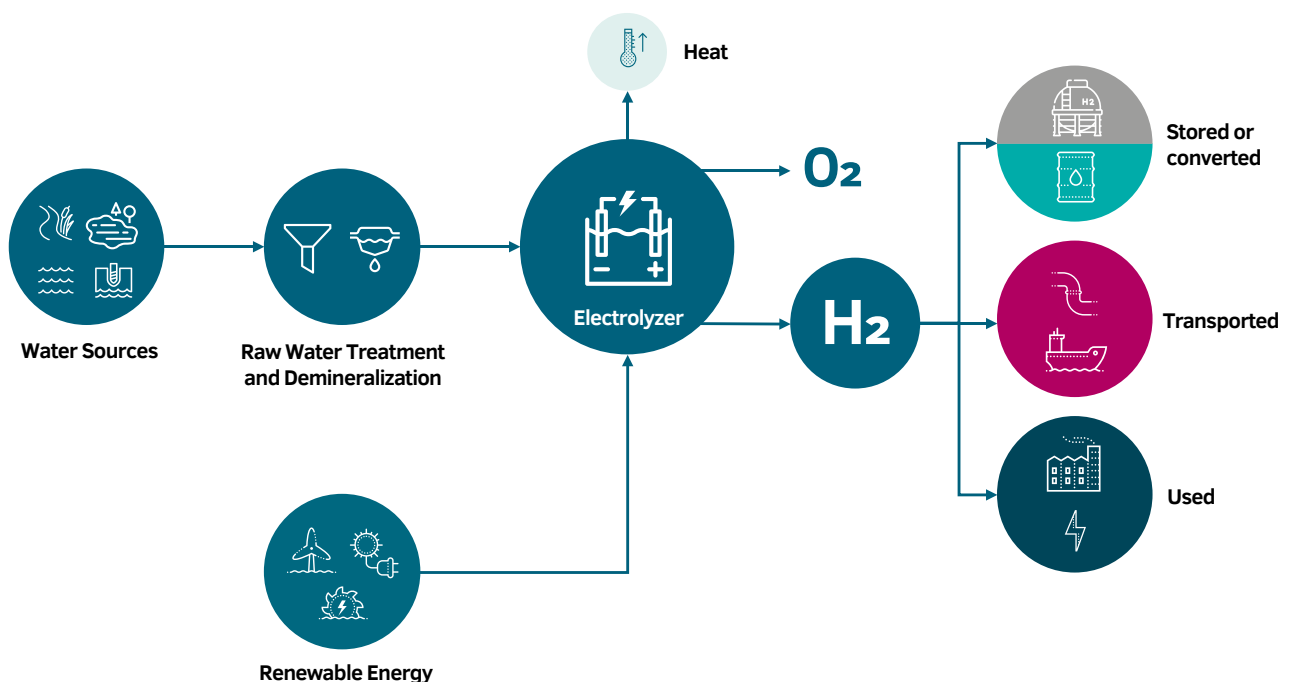


Figure 3: Green Hydrogen Generation

Green Hydrogen Production Spot Selection

Selecting an optimal site for green hydrogen production is a critical step in the value chain, requiring an evaluation of tactical and strategic factors. Key considerations include access to water, as electrolysis depends on reliable sources such as municipal water systems or desalinated seawater. The availability of renewable energy, such as wind, solar, or hydropower, is essential to power the process sustainably and affordably.

Transportation infrastructure, such as proximity to pipelines, tanker routes, or ports, is crucial for efficiently delivering hydrogen to end-users. Strategically locating facilities near high-demand areas, such as industrial hubs or transportation centers, helps reduce logistical challenges and costs. Favorable regulatory environments and policies, coupled with incentives, can significantly enhance the feasibility of hydrogen projects. Access to skilled labor for facility operation and maintenance is equally important. Finally, environmental impacts can be minimized by carefully selecting the site to compliance with ecological standards and sustainable practices.

Strategic Choice of Geography for Hydrogen Production

Selecting the ideal location for hydrogen production involves evaluating several strategic criteria. Long-term demand projections are essential to justify the significant capital investments and ensure the facility's profitability over time. Scalability is another key factor, allowing the site to accommodate future expansions or modifications to adapt to changing market conditions.

The competitive landscape and regulatory environment play a critical role in attracting investments and fostering innovation. Geopolitical stability and favorable trade policies ensure reliable access to global hydrogen markets and associated technologies. Additionally, proximity to strong research and development hubs enables the facility to stay at the forefront of technological innovation and maintain its competitiveness in the market.

Players in Generation and Supply

The large-scale production of green hydrogen relies on collaboration among several key players. EU- and national-level authorities establish policies and long-term energy strategies to support green hydrogen development. Financial institutions fund meaningful, long-term projects to ensure scalability.

The energy industry, encompassing utilities and green energy producers, fosters local hydrogen clusters while preparing for a long-term shift toward regions with lower production costs and abundant renewable energy. Meanwhile, technology and engineering manufacturers, specializing in electrolyzer design and development, work closely with energy companies to bring advanced hydrogen technologies to market.

Unlocking green hydrogen's full potential requires overcoming several challenges. Electrolyzer innovation is essential, as production efficiency hinges on achieving a balance between cost, performance, and sustainability. The selection of optimal production sites, factoring in tactical and strategic considerations, poses another significant hurdle.

Scaling up production to commercial levels remains expensive due to technological and infrastructural requirements, demanding cost-effective solutions to enhance economic viability. Finally, water availability must be ensured, with a focus on securing resources and minimizing environmental impacts.

Hurdles in Green Hydrogen Production

Green hydrogen production at scale faces several key challenges that must be addressed to achieve its potential. One of the primary hurdles is the cost and efficiency of electrolyzers, which are essential to the production process. Current technologies require significant advancements to improve performance, reduce energy use, and lower costs, making green hydrogen more competitive with fossil-based alternatives.

Another critical issue is the availability of water and renewable energy sources, both of which are vital for electrolysis. Access to purified water, particularly in arid regions, and reliable renewable energy such as wind or solar, limits site selection and scalability. Careful planning is needed to ensure these resources are sustainably utilized.

High capital investments present another obstacle, as scaling production requires substantial funding for infrastructure such as electrolyzer facilities, storage systems, and renewable power connections. These investments hinge on clear regulatory frameworks and long-term policy support to ensure economic viability.

Finally, the environmental impact of water extraction and energy-intensive processes must be managed to avoid ecological harm. Addressing these hurdles through innovation, strategic planning, and strong policy alignment will be essential to making green hydrogen a cornerstone of a sustainable energy future.

2.2 Hydrogen Conversion and Storage



Conversion and storage of hydrogen are critical for its scalability, enabling applications in mobility, power generation, and industrial heat. Due to its low density, hydrogen must be compressed or liquefied for efficient storage and transport.

Figures 4 and 5 illustrate some energy carriers – including gasoline, diesel, liquefied natural gas, natural gas, lithium-ion batteries, and hydrogen – focusing on hydrogen's energy properties. While hydrogen has a high gravimetric energy density, its volumetric energy density is extremely low (33.3 kWh/kg at atmospheric pressure). This characteristic makes hydrogen storage significantly more complex and costly compared to natural gas, which can be stored more easily in gaseous or liquefied form.

Hydrogen storage methods are typically divided into **physical-based** systems, such as pressure tanks or liquefied hydrogen, and **material-based**³ systems, including ammonia or metal hydrides. Figure 6 provides an overview of these methods, which will now be discussed in more detail.

Physical-based Storage

Physical-based hydrogen storage involves storing hydrogen in its pure form, without chemically bonding it to other elements. The three main methods include:

- › **Compressed hydrogen gas:** Stored in high-pressure tanks, typically for portable and mobile applications. These tanks must be made of specialized materials to withstand pressure and prevent leakage.
- › **Liquid hydrogen:** Stored in cryogenic tanks at -253°C , commonly used in aerospace applications. Cryogenic tanks require materials with low thermal conductivity to minimize heat transfer and prevent hydrogen boil-off.
- › **Underground storage:** Large-scale storage is feasible in salt caverns, depleted oil and gas fields, or aquifers. These sites, widely used for natural gas and crude oil, provide reserves for balancing supply-demand fluctuations or for emergencies.

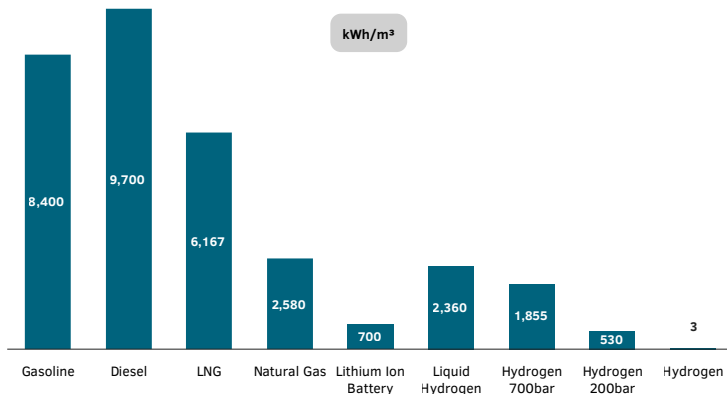


Figure 4: Volumetric Energy Density in kWh/m³

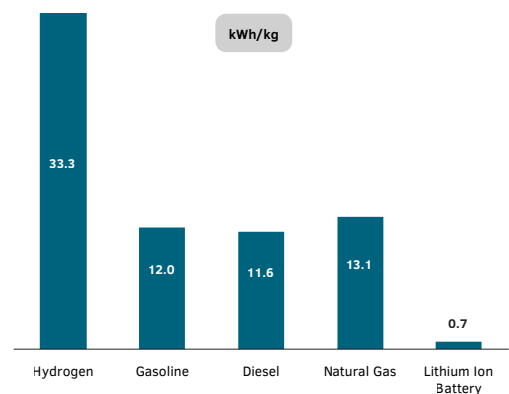


Figure 5: Gravimetric Energy Density in kWh/kg

³ U.S. Department of Energy. Hydrogen Storage. U.S. Department of Energy

Material-based Storage

Material-based hydrogen storage includes advanced methods such as metal hydrides, where hydrogen is absorbed and stored in metal alloys for portable and stationary applications, and chemical hydrides, where hydrogen is stored in chemical compounds and released upon heating, e.g. H_2 converted into Ammonia (NH_3). To ensure practicality and scalability, all material-based storage methods must meet strict criteria for safety, efficiency, and cost, making them viable for diverse applications.

Players in Storage and Conversion

Hydrogen storage requires collaboration between key stakeholders. EU- and National-level authorities play a pivotal role by promoting initiatives and identifying suitable storage sites. Energy companies, including natural gas SSOs (Storage System Operators), focus on developing large-scale storage systems and repurposing existing gas storage facilities. Meanwhile, technology companies specialize in designing advanced storage systems and work closely with energy firms and governments to commercialize innovative hydrogen solutions.

Despite the progress made, hydrogen storage and conversion face significant challenges. High compression pressures are necessary for storing large volumes, while hydrogen's flammability and explosiveness require advanced handling and storage facilities. Its low volumetric energy density makes it less practical for mobile applications, necessitating larger

tanks. Selecting underground storage sites also requires careful evaluation of security, geomorphology, logistics, and proximity to demand centers.

Figures 4 and 5 highlighting the differences in energy density between hydrogen and traditional fuels, emphasize the challenges of hydrogen storage for practical applications.

Hurdles in Hydrogen Conversion and Storage

Hydrogen conversion and storage face critical challenges that hinder scalability and practicality. One major hurdle is hydrogen's low volumetric energy density, requiring high compression pressures or liquefaction at $-253^\circ C$ for efficient storage. These processes demand significant energy and specialized infrastructure, increasing costs and reducing overall efficiency. Additionally, hydrogen's reactivity pose material challenges, necessitating advanced storage systems such as reinforced tanks or underground caverns. For material-based storage, conversion losses of up to 25% further complicate adoption.

Safety is another key issue, as hydrogen's flammability and explosiveness require stringent handling and storage protocols. Regulatory frameworks and robust standards are essential to ensure secure storage, especially in populated or industrial areas. Overcoming these hurdles requires innovation in storage technologies, strategic site selection, and collaboration between policymakers, energy firms, and technology providers. Without addressing these challenges, hydrogen's role as a scalable energy carrier will remain limited.

Physical-based Storage		Material-based Storage	
Pressure tank Tech: Steel (and carbon fiber) tanks Conversion-loss*: 13–18% ★★★★★★ ★★★★★★ Maturity Cost	Underground Cavern Tech: Reusing old underground caverns similar to natural gas storage No significant loss ★★★★★★ ★★★★★★ Maturity Cost	Ammonia Tech: H_2 converted to Ammonia (NH_3) via Haber-Bosch-Process Conversion-loss*: ~25% ★★★★★★ ★★★★★★ Maturity Cost	LOHC** Tech: H_2 converted to Liquid Organic Hydrogen Carrier, e.g. methylcyclohexane,... Conversion-loss*: ~25% ★★★★★★ ★★★★★★ Maturity Cost
Liquefied Hydrogen Tech: H_2 cooled to $-253^\circ C$ Conversion-loss*: ~25% ★★★★★★ ★★★★★★ Maturity Cost	Cryo-compressed H_2 Tech: H_2 cooled to $-253^\circ C$ and pressurized Conversion-loss*: ~25% ★★★★★★ ★★★★★★ Maturity Cost	Absorbents Tech: Metal Hydrides, Microspheres Conversion-loss*: ~20% ★★★★★★ ★★★★★★ Maturity Cost	Power-to-X Tech: H_2 converted to liquid fuel, e.g. methanol, ethanol,... Conversion-loss*: 20–40% ★★★★★★ ★★★★★★ Maturity Cost

Low ★☆☆☆☆ High ★★★★★★

* Conversion-loss refers to the relative amount of energy which is lost in the conversion process from $H_2 \rightarrow X$
 ** Liquid Organic Hydrogen Carrier

Figure 6: Hydrogen Storage Methods, Source: Created by the author based on their expertise

2.3 Hydrogen Transport and Distribution



Efficient transport and distribution systems are critical for hydrogen to compete with fossil fuels. Hydrogen storage, particularly in stationary facilities, plays a vital role in balancing production and demand, ensuring a stable supply for transport and industrial use. It also serves as a buffer for continuous production and distribution. Figure 7 illustrates three primary methods for transporting and distributing hydrogen:

Pipelines offer a cost-effective solution, particularly by repurposing existing natural gas infrastructure. However, modifications such as larger diameters, compressors, and pressure-maintaining equipment are necessary due to hydrogen's lower energy density. Countries like Germany, Japan, and the U.S. already operate hydrogen pipelines, and converting existing networks to hydrogen or hydrogen blends is an evolving solution.

Trucks and rail transport compressed hydrogen in tanks, making them ideal for short distances and smaller quantities. While flexible, this method is costly due to the need for specialized vehicles, training, and maintenance.

Ships enable large-scale, long-distance hydrogen transport by storing liquefied hydrogen in cryogenic tanks. This method requires specialized infrastructure, including loading and unloading facilities, making it suitable for international transport.

Despite progress, the technologies needed for safe, large-scale hydrogen transport are still under development, as hydrogen's properties pose unique challenges.

Players in Transport and Distribution

Hydrogen distribution at scale depends on collaboration between several key stakeholders. EU regulators and national public authorities play a vital role by creating policies and strategies to support investments in pipelines and infrastructure. Transmission System Operators (TSOs) and Distribution System Operators (DSOs), responsible for managing existing natural gas networks, must undertake significant capital projects to adapt pipelines for hydrogen transport or build entirely new networks.

European TSOs (Transmission System Operators), through the European Hydrogen Backbone initiative, are working together to establish a coordinated hydrogen transport ecosystem. Meanwhile, technology and engineering firms are tasked with innovating pipeline systems and ensuring the safe conversion of hydrogen for transport. Collaboration with truck manufacturers, shipyards, and tank producers is also critical for scaling road and sea transport systems.

Hurdles of Transport and Green Hydrogen Distribution

The transport and distribution of hydrogen face significant challenges that must be addressed to enable its widespread adoption. Pipelines, often considered the most cost-effective option, require extensive upgrades to handle hydrogen's unique properties, such as its lower energy density and higher diffusivity compared to natural gas. These upgrades include modifications like larger diameters, advanced compressors, and equipment to maintain pressure. While initiatives like the European Hydrogen Backbone aim to repurpose existing natural gas pipelines, the associated capital investments remain substantial.

For short distances, trucks and rail are flexible options for transporting compressed hydrogen, but high costs associated with specialized vehicles, infrastructure, and safety training make scaling difficult. International transport via ships, using liquefied hydrogen stored in cryogenic tanks, presents even greater hurdles. This method demands significant investment in port infrastructure and specialized loading facilities, further complicating efforts to scale global hydrogen trade.

Safety is another major concern. Hydrogen's flammability and small molecular size require stringent protocols and harmonized safety standards across regions to ensure secure storage and transport. Without these safeguards, public trust and large-scale adoption could be hindered. Additionally, regulatory alignment is critical, as inconsistent policies between countries create barriers cross-border hydrogen distribution.

Overcoming these hurdles requires a coordinated effort among policymakers, TSOs, DSOs and technology providers. Investments in infrastructure, innovative transport solutions, and a unified regulatory framework are essential to develop an efficient hydrogen distribution network. Without addressing these challenges, the potential of green hydrogen as a cornerstone of the global energy transition will remain unrealized.

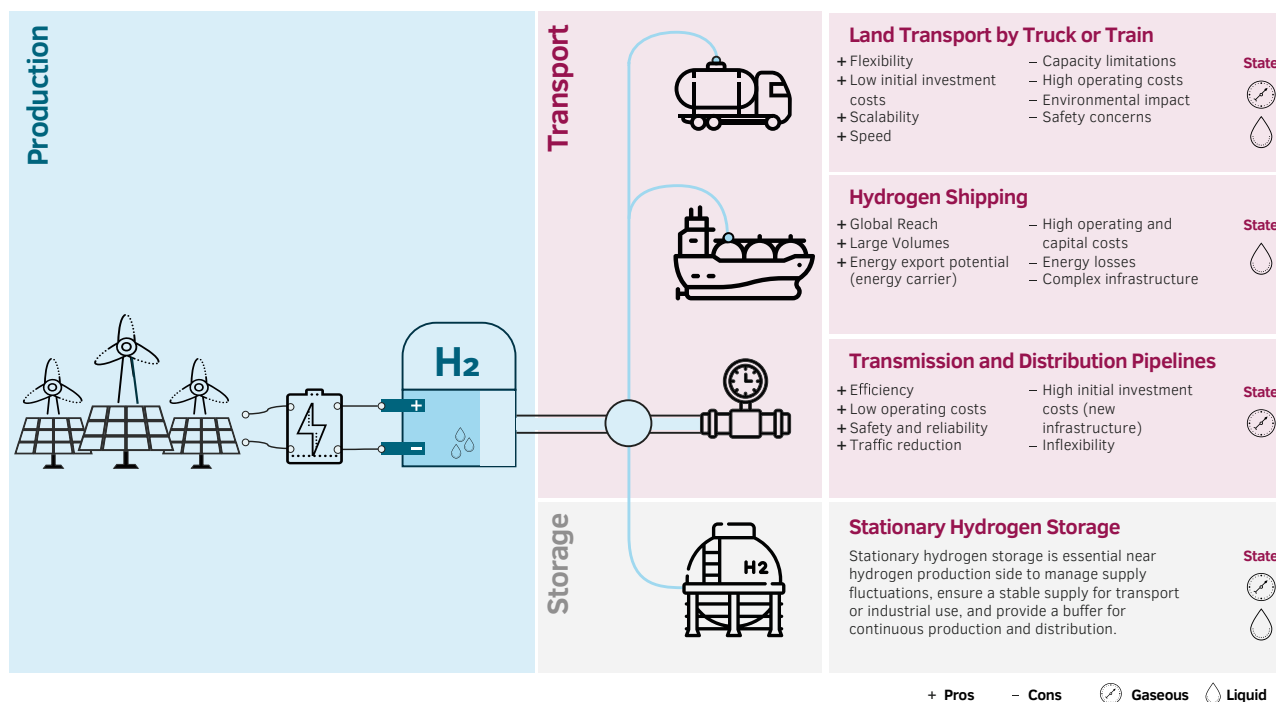
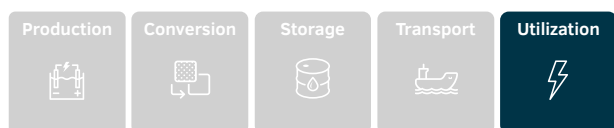


Figure 7: Hydrogen Transport Methods, Source: Created by the author based on their expertise

2.4 Hydrogen Utilization



The role of hydrogen in decarbonizing global energy systems varies widely depending on the application. Figure 8 illustrates Michael Liebreich's Hydrogen Ladder⁴, a framework that organizes use cases into categories based on their efficiency and competitiveness. By prioritizing sectors where hydrogen has the highest impact and avoiding applications where it is uncompetitive, the ladder serves as a critical tool for guiding investments and strategies in the transition to a low-carbon economy.

Understanding the Categories of the Hydrogen Ladder

The ladder categorizes hydrogen applications from Category A (most competitive) to Category G (least competitive), providing a framework to assess where hydrogen can be most effectively utilized.

Category A encompasses sectors where hydrogen is indispensable and lacks viable alternatives. This includes ammonia production for fertilizers, methanol synthesis, and processes like hydrocracking and desulfurization in refineries. In these areas, hydrogen is already integral, and transitioning to green hydrogen is the only option for reducing GHG emissions in the long run.

Category B includes applications such as shipping and jet aviation, where hydrogen-based fuels like ammonia or synthetic hydrocarbons are among the few feasible options for decarbonization. However, challenges related to cost and infrastructure development persist.

Category C covers sectors like coastal and river vessels, non-road mobile machinery, and biogas upgrading. These applications present potential for hydrogen adoption as technologies mature and costs decline.

As we move down the ladder to **Categories D through G**, the competitiveness of hydrogen decreases. In these categories, alternatives such as electrification or bioenergy are often more efficient and cost-effective. For instance, in Category G, applications like passenger cars and domestic heating are better suited to direct electrification, making hydrogen an uncompetitive choice.

The ladder also indicates the substitutability of hydrogen in various applications:

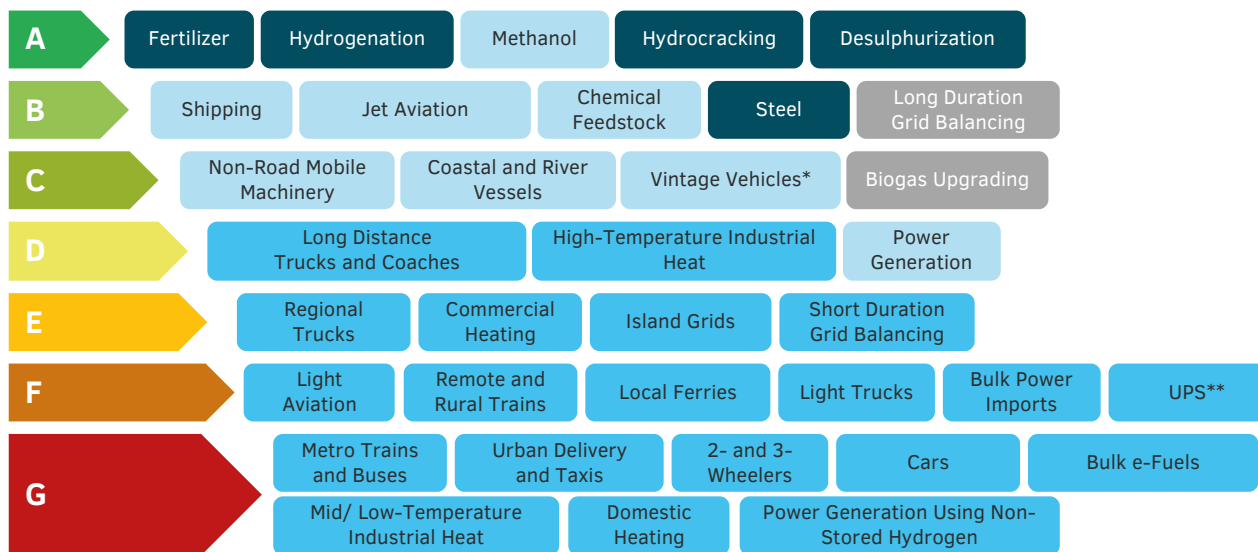
No real alternative: Sectors where hydrogen is essential, with no viable substitutes.

- **Electricity/batteries:** Applications where electrification is a more efficient alternative.
- **Biomass/biogas:** Areas where bio-based solutions can replace hydrogen.

By describing these categories and levels of substitutability, the Hydrogen Ladder guides stakeholders in prioritizing hydrogen deployment where it offers the most significant benefits and avoiding areas where other solutions are more appropriate. To bring this framework to life, three practical hydrogen utilization use cases from different categories, showcasing how hydrogen can effectively drive decarbonization in key sectors.

⁴ Liebreich, Michael. Hydrogen Ladder Version 5.0. Liebreich, 2023

unavoidable



uncompetitive

* powered by hydrogen-generated e-fuel/ammonia – Scope of study

** Uninterruptible Power Supplies

Substitutability:

No Alternatives

Biomass/Gas

Electricity/Battery

Other

Figure 8: Hydrogen Ladder

Hydrogen Utilization Use Case 1: Category A – Fertilizer

In the fertilizer industry, hydrogen is primarily used for ammonia production, which is a critical component of many fertilizers. This industry falls into Category A due to the high efficiency of hydrogen in the ammonia synthesis process through the Haber-Bosch method. The technology employed here is well-established and has been successfully utilized for decades, showcasing a high maturity level. Future advancements in this sector focus on enhancing the efficiency of hydrogen production, particularly through green hydrogen (produced via renewable energy sources). The development outlook is promising, with ongoing research aiming to reduce costs and improve the sustainability of hydrogen utilization in fertilizer production.

Hydrogen Utilization Use Case 2: Category D – Power Generation

Power generation for grid balancing is categorized under Category D of the Hydrogen Ladder. While green hydrogen competes with alternatives like natural gas or biomass, it offers a distinct sustainability advantage due to its carbon-free energy storage and conversion capabilities.

In comparison to fossil gas, green hydrogen can significantly reduce emissions, aligning with global decarbonization goals and providing a more sustainable long-term solution.

Its key strength lies in storing energy for extended periods and converting it back into electricity, making it an effective backup for intermittent renewables like wind and solar. While the technology is still maturing, existing gas turbines are already capable of using hydrogen blends, with ongoing advancements supporting the shift toward pure hydrogen utilization. This positions hydrogen as a viable, sustainable option for long-duration storage in regions transitioning away from fossil fuels. However, realizing its full potential will require substantial cost reductions and expanded green hydrogen infrastructure to improve competitiveness and scalability within grid solutions.

Hydrogen Utilization Use Case 3: Category G – Cars

Passenger cars fall into Category G of the Hydrogen Ladder, where hydrogen is deemed uncompetitive due to the clear superiority of alternatives like battery electric vehicles (BEVs).

Electric vehicles are far more efficient, as they avoid the energy losses associated with hydrogen production, compression, and conversion.

While hydrogen cars exist, their adoption is hindered by high costs, limited infrastructure, and the rapid advancement of battery technology. Charging networks for BEVs are expanding quickly, making them the preferred choice for decarbonizing personal transport. In this category, focusing on hydrogen would waste resources better directed toward sectors where it provides a unique advantage.

Players in Hydrogen Utilization

Hydrogen utilization at scale requires seamless integration into existing infrastructure, driven by collaboration among key stakeholders. Governments and policymakers, like those behind Germany's National Hydrogen Strategy (2020), set the framework through strategies and funding.⁵

Heavy industries, such as steel and chemical manufacturing, lead adoption efforts. Projects like Austria's H2FUTURE showcase hydrogen's potential to replace coal in steelmaking, while ammonia and methane producers transition to sustainable alternatives.⁶

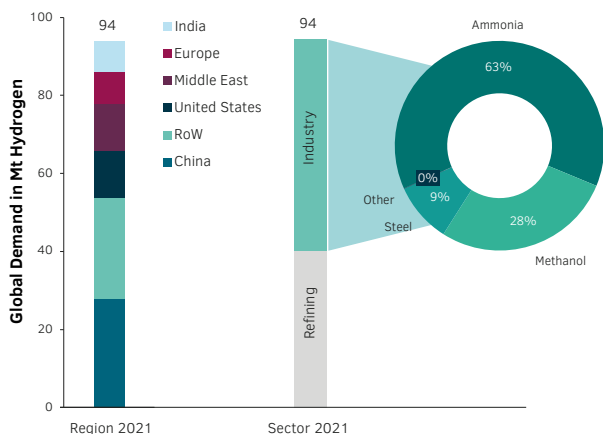


Figure 9: Global Hydrogen demand by region and sector in 2021

Energy companies are scaling green hydrogen production to meet industrial demand or as an energy storage option.

Engineering firms play a crucial role by building infrastructure, advancing technologies, and ensuring safety and system integration. Successful collaboration across industries, governments, and technology providers, such as pilot projects in the Netherlands and Japan, demonstrates the importance of partnerships in accelerating hydrogen's global deployment.

Hurdles of Meeting Future Hydrogen Utilization Needs

The global energy transition places immense expectations on hydrogen as a key enabler for decarbonizing industries, transport, and energy systems. Yet, the gap between projected hydrogen demand and sustainable supply is significant. As shown in Figure 9, demand reached 94 million tons (Mt) in 2021, largely driven by refining, ammonia, and methanol production. By 2050, this figure could rise to 450 Mt annually, fueled by heavy industry, long-distance transport, and renewable energy integration. However, hydrogen production, especially green hydrogen, remains far behind. Current global electrolyzer capacity of 1 GW must scale up to 3,000–4,000 GW to meet this demand.⁷

Addressing these challenges requires a coordinated effort to scale green hydrogen production, develop infrastructure, and align policies. However, it is not enough to simply increase supply, deploying hydrogen strategically in areas where it creates the most value is essential.

Hydrogen's versatility is both a strength and a challenge. Its applications span industries, yet prioritization is critical. As the Hydrogen Ladder highlights, resources should focus on high-impact sectors like ammonia, steel, and aviation (Categories A and B), where alternatives are limited. Conversely, low-priority applications like domestic heating or passenger cars risk misallocating resources and slowing progress toward decarbonization.

This underscores the critical need to prioritize value chains and focus resources where hydrogen is truly transformative. Without clear prioritization, the hydrogen economy risks inefficiency, undermining its potential to drive meaningful global emissions reductions.

⁵ Federal Government of Germany. Hydrogen Technology. Bundesrepublik Deutschland

⁶ Energy Innovation Austria. H2FUTURE. Energy Innovation Austria

⁷ International Energy Agency. World Energy Outlook 2022. 2022

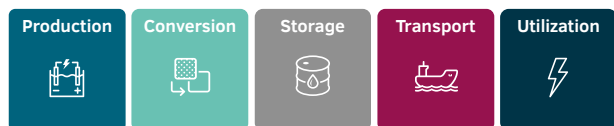


3 End-to-End Hydrogen Value Chains

Hydrogen's applications range from being an energy carrier to serving as feedstock for producing various chemicals and essential reactants in different industrial processes. In this chapter we want to demonstrate how important it is to analytically look at the whole value chain to test and evaluate hydrogen use cases.

Due to the physical characteristics of hydrogen, it can be considered that ideally the hydrogen value chain has minimal intermediary steps. In this chapter, three distinct use cases showcase how structured methodologies, and analytical tools can guide decision-making and maximize hydrogen's potential across industries.

3.1 Methodology of Value Chain Building Blocks



At accilium, we emphasize the importance of a structured methodology for analyzing the entire End-to-End (E2E) hydrogen value chain and its use cases. Expanding upon the previously introduced five key components, our methodology systematically identifies bottlenecks, assesses feasibility, and highlights both opportunities and challenges. This structured breakdown enables a detailed assessment of factors like process locations, system efficiency, and scalability, ensuring a targeted and effective analysis.

To complement this approach, we prioritize key performance indicators (KPIs), mainly cost (€/kWh hydrogen), and total energy efficiency (%) to evaluate the economic and environmental viability of each stage. Our proprietary tool, integrating a comprehensive database of industry standards, academic research, and internally derived assumptions, enables simulations and transparent comparisons across the entire E2E hydrogen value chain.

This methodology has been applied to three industrial and mobility-focused use cases to demonstrate its practical application across complete hydrogen value chains. These use cases

represent different sectors with potential for green hydrogen deployment, analyzed comprehensively from production to utilization:

- 1 End-to-End Value Chain for Green Steel Production
- 2 End-to-End Value Chain for Power Generation
- 3 End-to-End Value Chain for Heavy-Duty Mobility Solutions

For each use case, two distinct value chains were modeled to compare cost and efficiency differences. The approach to defining the use cases began with an assessment of hydrogen demand within each use case, factoring in losses across the entire previously defined value chain steps. This demand assessment served as the foundation for determining the required size of the electrolyzer, ensuring alignment with real-world operational conditions. By analyzing factors such as production-location and conversion options, insights are provided to optimize hydrogen value chains for real-world applications. The focus remains on balancing cost, energy efficiency, and social impact to identify the most effective solutions for advancing the hydrogen transition.

At accilium, we aim to support researchers, policymakers and industry stakeholders by delivering a clear, data-driven understanding of the hydrogen ecosystem. By applying our methodology, we contribute to accelerating the adoption of hydrogen as a clean energy carrier and unlocking its full potential in the global energy transition.

3.2 End-to-End Value Chain for Green Steel Production

As of 2023, the European Union (EU27) was the third-largest steel producer in the world, after China and India, with a total crude steel production of approximately 126.2 million tons.⁸ Achieving its 2050 climate neutrality goal will require replacing emission-intensive steel with green steel. Steel and iron production account for roughly 7% of global greenhouse gas emissions, depending on the methodology used to include indirect emissions. Figure 10 shows the distribution of global CO₂ emissions by sector, with the energy sector making the largest contribution at 54%, including emissions from aviation, for example, which account for around 2.5% of global emissions.

A significant portion of these emissions comes from coal-fired blast furnaces, where iron ore is traditionally reduced to iron using coal or natural gas as a reducing agent. Hydrogen offers a cleaner alternative through a process called Direct Reduced Iron (DRI). By utilizing green hydrogen, produced using renewable energy sources, DRI enables effectively zero-emission steel production. This transition is not only vital for achieving global sustainability targets but also strengthens regional energy independence, as it reduces reliance on imported fossil fuels like coal or natural gas.

Transitioning to hydrogen-based steel production offers a promising pathway to drastically reduce emissions while supporting energy security and aligning the sector with EU's climate goals.

Assumptions: Figures 11 and 12 illustrate two potential value chains for the supply of hydrogen for green steel production. The first value chain considers the production of hydrogen in Austria, while the second considers its production in North Africa and its subsequent pipeline transport to Austria via the Netherlands.

For our calculations, we assume a demand of 1 million tons of green steel per year in Austria. Providing the need of 50kg hydrogen per ton of green steel, we would need a total of ~50,000 tons of hydrogen per year. According to our assumptions, and the various losses across the two value chains, a Proton Exchange Membrane (PEM) of 750 MW was considered for both value chains in this use case.

Value Chain A (Figure 11)

In this value chain, hydrogen is produced near a steel production facility in Austria, using locally sourced renewable electricity. The electrolyzer is sized to meet the annual demand

of hydrogen, with underground storage (e.g. salt caverns) providing 10% of the yearly demand as a buffer. A 50 km pipeline connects the storage to the steel plant, minimizing transport losses.

The total efficiency of the chain is 77%, with 23% efficiency losses occurring mainly during compression and storage. These losses impact the cost competitiveness of green hydrogen, contributing to higher production costs compared to conventional methods. However, local production and short transport distances help reduce logistics costs, making this setup viable for Austria's green steel ambitions.

Value Chain B (Figure 12)

In this value chain, hydrogen is produced in North Africa (e.g. Morocco) using low-cost renewable energy. After production, the hydrogen is liquefied and shipped to the Netherlands, then transported via gas pipelines to Austria. To balance supply and demand, underground storage holds 10% of the annual hydrogen demand, and a 50 km pipeline connects the storage to the steel plant.

The total efficiency of this chain is 59%, with 41% efficiency losses occurring mainly during liquefaction, shipping, and regasification. While hydrogen production costs in North Africa are as low as 0.07 €/kWh, transport and conversion processes increase the total cost to 0.285 €/kWh, highlighting the challenges of long-distance hydrogen logistics.

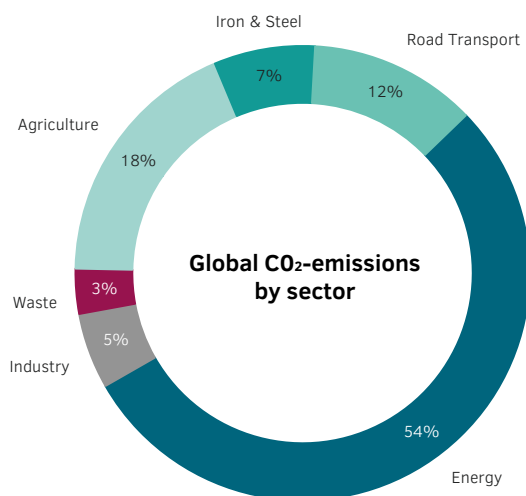


Figure 10: Global Greenhouse Gas Emissions by Sector, Source: GHG Emissions by Sector

⁸ World Steel Association. World Steel in Figures 2024. World Steel Association

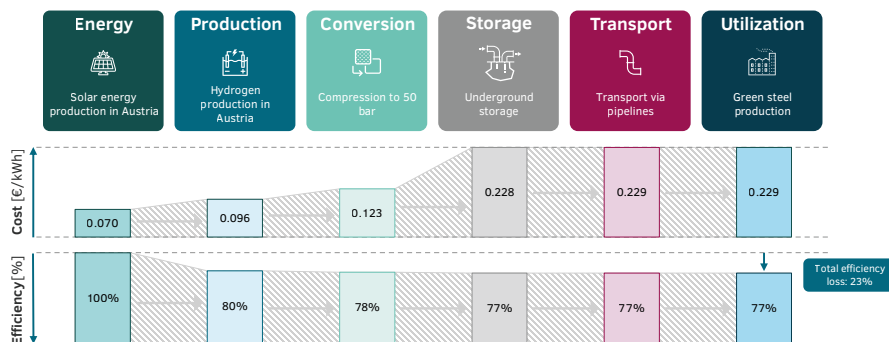


Figure 11: Value Chain A – Green steel production with hydrogen production in Europe

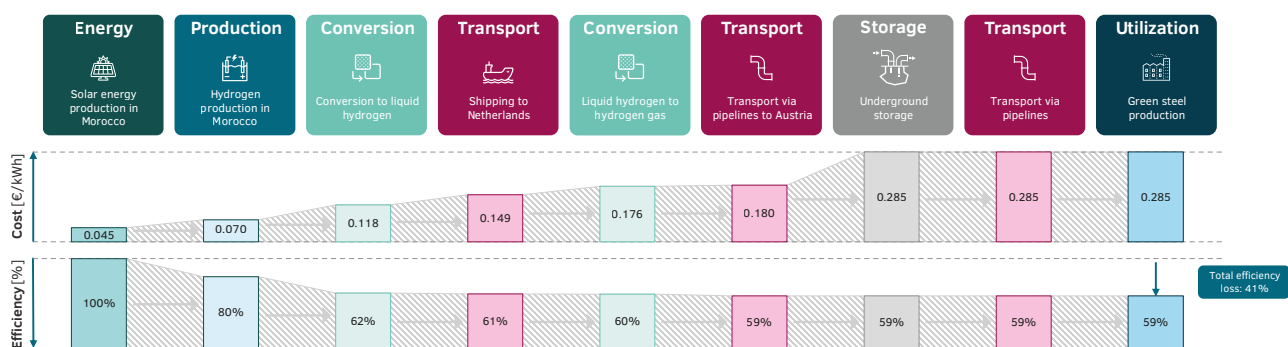


Figure 12: Value Chain B – Green steel production with hydrogen production in North Africa

Conclusion

Analyzing the cost and efficiency trends of both value chains reveals distinct strengths and challenges. Value Chain A, with hydrogen produced locally in Austria, has a total cost of 0.229 €/kWh and benefits from minimal transport requirements and lower efficiency losses (23%). This makes it the more cost-efficient option overall, despite higher production costs for renewable hydrogen.

In contrast, Value Chain B leverages the low-cost renewable energy potential of North Africa, where hydrogen production costs are as low as 0.07 €/kWh. However, the additional expenses for liquefaction, shipping, and regasification increase the total cost to 0.285 €/kWh and lead to higher efficiency losses (41%).

Overall, Value Chain A is better suited for regions with access to local renewable energy, offering a more streamlined and cost-effective solution for green steel production. Value Chain B, while less efficient and more costly, could complement local production by scaling hydrogen supply through international partnerships.

3.3 End-to-End Value Chain for Power Generation

The integration of hydrogen into power generation requires a comprehensive evaluation of end-to-end value chains to identify the most viable pathways for large-scale implementation. Ammonia, in particular, can play a critical role as a hydrogen carrier due to its ability to leverage existing infrastructure for transport and storage. Despite the challenges associated with ammonia's toxicity and energy-intensive conversion processes, its mature infrastructure and established production methods make it a promising option for global hydrogen transport.

This chapter examines two potential approaches for supplying hydrogen as a fuel for gas power plants, focusing on their cost structures, efficiency losses, and technological requirements. By analysing these value chains, we highlight the trade-offs between efficiency and cost in transporting hydrogen over long distances and the role of green ammonia and liquid hydrogen in enabling sustainable energy transitions.

Assumptions: Figures 13 and 14 illustrate two potential value chains for supplying hydrogen as a fuel for a gas power plant in Germany. The first value chain examines the transport of green ammonia, while the second considers the transport of hydrogen without conversion, apart from liquefaction and regasification.

For our calculations, we assume a gas-fired power plant with heat recovery in Germany that produces 500 MW of electric power and operates for 3,000 hours per year, resulting in a total electricity output of 1.5 TWh annually. The plant operates as a combined cycle gas turbine (CCGT) facility with an efficiency of 60%, requiring 2.5 TWh of fuel input. This corresponds to an annual hydrogen demand of approximately 75,000 tons.

In these two comparisons, green hydrogen is produced via water electrolysis in a region with very low renewable energy costs, specifically the Middle East, with Saudi Arabia selected as the production location. Due to the different intermediate stages of each value chain, and their efficiency losses, an electrolyzer of 1,500 MW is considered for the first value chain, and a 1,300 MW electrolyzer for the second value chain.

Value Chain A (Figure 13)

In this value chain, green hydrogen is produced in Saudi Arabia via water electrolysis and converted into ammonia using the Haber-Bosch process. The ammonia is then shipped to Italy, where it is stored in ammonia tanks before being cracked back into hydrogen. After the cracking process, the hydrogen is transported via pipelines to the power plant in Germany for utilization.

The total efficiency of this value chain is 30%, with 70% efficiency losses occurring primarily during ammonia conversion, cracking and transport. The delivered hydrogen costs 0.193 €/kWh, reflecting the energy-intensive nature of this pathway.

Value Chain B (Figure 14)

In this value chain, green hydrogen is produced in Saudi Arabia via water electrolysis and directly liquefied instead of being converted to ammonia. The liquefied hydrogen is then shipped to Italy, where it is regasified into its gaseous state.

After regasification, the hydrogen follows the same steps as in Value Chain A, where it is transported via pipelines to Germany, and stored in underground facilities near the power plant before utilization.

The total efficiency of this value chain is 33%, with 67% efficiency losses occurring mainly during the liquefaction, shipping, and regasification processes. These steps also result in a higher hydrogen cost of 0.287 €/kWh, making this option less efficient than ammonia-based transport for long distances.

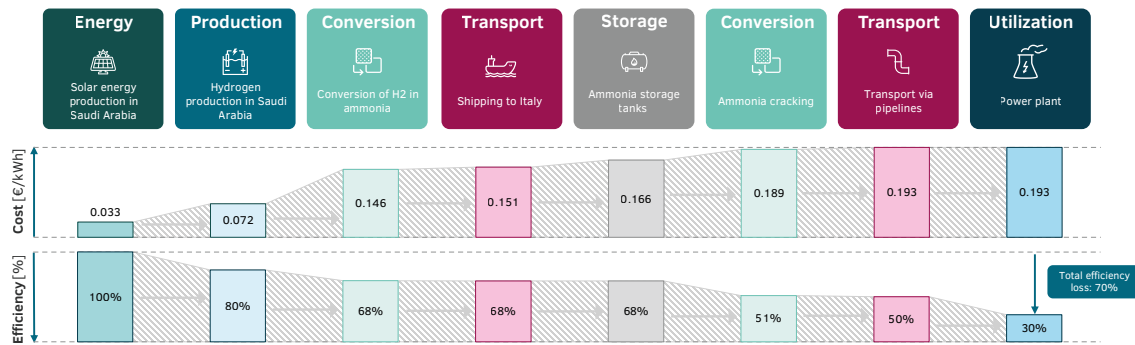


Figure 13: Value Chain A – Ammonia-based hydrogen transport from Saudi Arabia to Europe

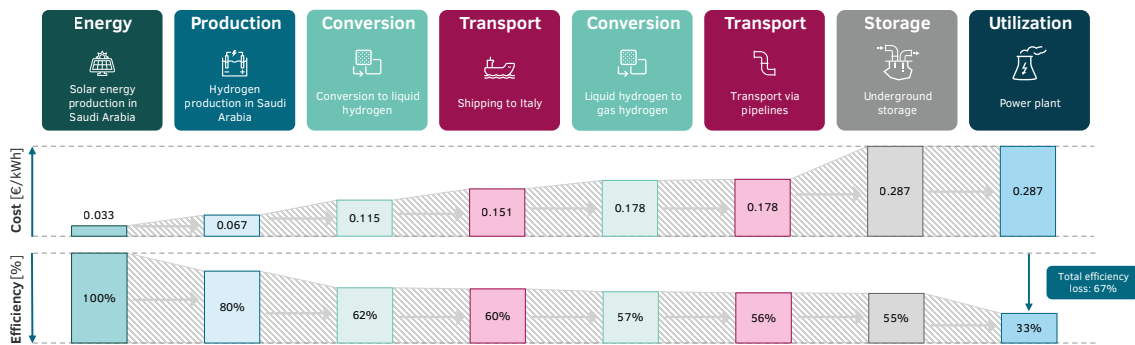


Figure 14: Value Chain B – Liquid hydrogen from Saudi Arabia to Europe

Conclusion

Analyzing the cost and efficiency trends of both value chains highlights their respective strengths and limitations. Value Chain A, which utilizes ammonia as a hydrogen carrier, achieves a delivered hydrogen cost of 0.193 €/kWh but suffers from significant efficiency losses of 70%, primarily due to energy-intensive processes like ammonia cracking and conversion. Despite these challenges, ammonia offers the advantage of leveraging existing infrastructure, making it a practical solution for long-distance hydrogen transport. For the annual hydrogen demand of 75,000 tons, Value Chain A would result in a total annual fuel cost of approximately 483 million € (calculated as $2.5 \text{ TWh} \times 0.193 \text{ €/kWh}$).

In contrast, Value Chain B, which relies on hydrogen liquefaction and direct transport, incurs higher costs of 0.287 €/kWh and efficiency losses of 67%. The liquefaction and regasification steps, while less complex than ammonia conversion

and cracking, contribute to substantial energy losses, making this option less competitive over long distances. For the same annual hydrogen demand, Value Chain B would lead to a total annual fuel cost of approximately 717.5 million € (calculated as $2.5 \text{ TWh} \times 0.287 \text{ €/kWh}$), resulting in a cost difference of 234.5 million € per year in favour of Value Chain A.

Overall, Value Chain A is better suited for global hydrogen transport, leveraging mature ammonia infrastructure despite its efficiency drawbacks. Value Chain B, while slightly more efficient, is hindered by higher costs and limited scalability for long-distance applications. This comparison highlights the importance of continued innovation in hydrogen transport technologies to reduce costs and improve efficiency, ensuring their economic and environmental viability.

3.4 End-to-End Value Chain for Heavy-Duty Mobility Solutions

Decarbonizing heavy mobility, especially long-haul trucking, is one of Europe's biggest challenges in the shift to sustainable energy. While BEVs lead the way for passenger cars, green hydrogen and e-fuels are emerging as alternative solutions for heavy-duty vehicles, offering ways to reduce emissions without compromising performance.

Currently, the heavy mobility sector in Germany remains largely dominated by diesel. According to the European Automobile Manufacturers' Association only 1.9% of trucks were powered by alternative fuels like hydrogen and e-fuels in 2022, while 1.1% were BEVs. These numbers highlight the need for cleaner technologies to play a larger role in the future.⁹

Green hydrogen, produced using renewable energy, is versatile. It can power fuel cells or serve as the basis for hydrogen-based e-fuels. Its ability to leverage parts of the existing gas pipeline infrastructure gives it an edge in distribution.

E-fuels, on the other hand, provide a transitional path by working with existing internal combustion engine (ICE) vehicles. They minimize emissions while avoiding the need for costly electrification of the current truck fleet, making them particularly appealing for the existing heavy-duty vehicle market.

Assumptions: Figures 15 and 16 illustrate two potential value chains for the supply of hydrogen to decarbonize 2% of the total demand for heavy mobility in Germany. Based on a consumption rate of 8 kg of hydrogen per 100 km, the total demand of hydrogen is 109 thousand tons for the first value chain.

While for the second value chain e-fuels is considered as the energy carrier for the heavy duty transport, with a consumption rate of 28 kg per 100 km, which in return rises the demand of e-fuels to approximately 383,000 tons to meet the same 2% share.

For both use cases, green hydrogen is assumed to be produced in Argentina using solar energy as the primary source. However, due to the different stages, with different efficiency losses, in each value chain, a Proton Exchange Membrane (PEM) of 2,000 MW was used in the calculations for the first value chain and a PEM of 1,700 MW was used in the calculations for the second value chain, which in return justifies the different production costs in the two use cases.

Value Chain A (Figure 15)

In this value chain, green hydrogen is produced in Argentina using solar energy and subsequently liquefied for transportation. The liquefied hydrogen is shipped to Germany, where it undergoes a regasification process via direct expansion and is stored in an underground cavern.

From the storage site, the hydrogen is transported via pipelines to distribution points located approximately 300 km away. At these locations, the hydrogen is compressed to 700 bar to fuel fuel cell electric trucks (FCET) for heavy mobility applications.

The total efficiency of this value chain is 17%, with 83% efficiency losses occurring across multiple steps, including liquefaction, shipping, regasification, and compression. These losses result in a total delivered hydrogen cost of 0.441 €/kWh, highlighting the energy-intensive nature of this pathway.

Value Chain B (Figure 16)

E-fuel (specifically e-diesel) is produced in Argentina after hydrogen production via the Fischer-Tropsch process. The e-fuel is then shipped to Germany and stored at the port in e-fuel tanks. To account for continuous supply throughout the year, it is assumed that 10% of the yearly demand is stored at any given time.

From the port, e-fuels are transported using trucks to fuelling stations across the country. At the fuelling stations, the e-fuels are pumped directly into the tanks of ICE trucks, enabling heavy-duty transport.

The total efficiency of this value chain is 17%, with 83% efficiency losses occurring primarily during hydrogen-to-e-fuel conversion, transport and distribution. Despite these losses, the delivered cost of e-fuel is 0.271 €/kWh, reflecting the simplicity of storage and compatibility with existing infrastructure for ICE vehicles.

⁹ European Automobile Manufacturers Association. Reliable Data & Statistics. ACEA

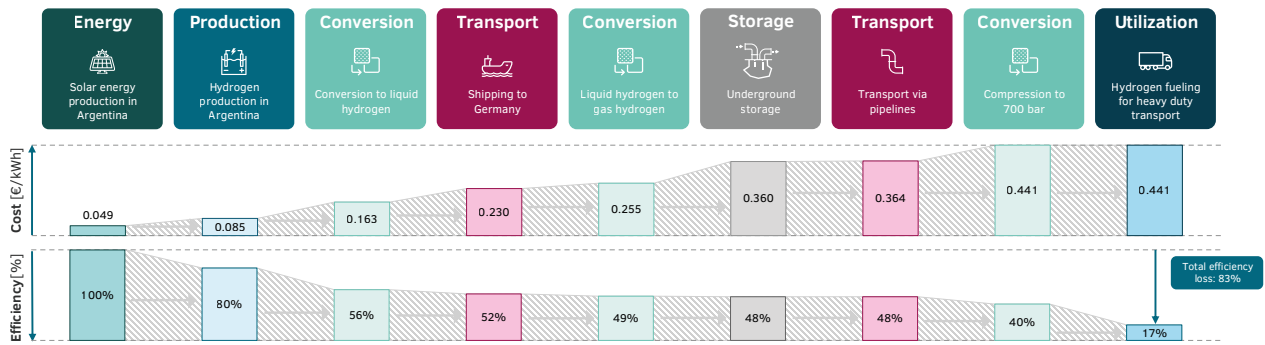


Figure 15: Value chain A – Hydrogen for FC heavy mobility

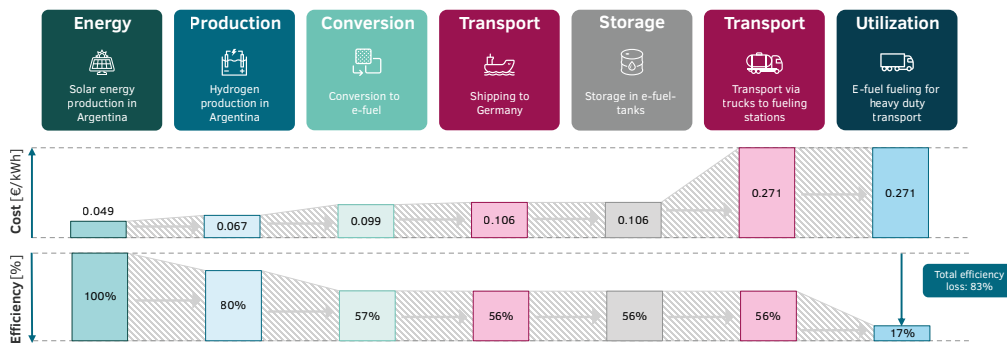


Figure 16: Value chain B – E-fuel for heavy mobility

Conclusion

The comparison between the two value chains highlights distinct trade-offs in cost, efficiency, and infrastructure readiness. Value Chain A, which relies on liquefied hydrogen, incurs higher costs of 0.441 €/kWh due to energy-intensive processes such as liquefaction, shipping, regasification, and compression. Despite these costs and efficiency losses of 83%, hydrogen offers a cleaner and more energy-efficient solution when used in fuel cell electric trucks (FCETs). For example, a heavy-duty truck using hydrogen (8 kg H₂ per 100 km) can travel 12,500 km with just 1 ton of hydrogen, showcasing the superior energy efficiency of hydrogen compared to e-fuels.

In contrast, Value Chain B, which converts hydrogen into e-fuels (e-diesel), achieves lower costs of 0.27 €/kWh due to simpler storage, transport, and compatibility with existing internal combustion engine (ICE) infrastructure. While e-fuels require more fuel to achieve the same result, they benefit from

a higher volumetric energy density compared to hydrogen. This makes them easier to store and transport over long distances, particularly in sectors with established infrastructure. For example, an ICE truck consumes 28 kg of e-fuel per 100 km, meaning it would travel only 3,571 km with 1 ton of e-fuel. While this demonstrates the lower efficiency of the e-fuel pathway in terms of mass (kg/km), the higher volumetric energy density of e-fuels means they take up significantly less space, offering advantages for certain transport applications where volume constraints are a consideration.

While e-fuels can act as a transitional solution leveraging existing systems, hydrogen provides a more efficient, long-term pathway for decarbonizing heavy-duty mobility, particularly as hydrogen infrastructure develops. Balancing cost, efficiency, and infrastructure readiness will be critical in shaping sustainable transport solutions.

3.5 Qualitative Assessment of the Value Chains

When evaluating hydrogen value chains from a broader perspective, it is essential to consider qualitative factors beyond efficiency and costs. These aspects influence scalability, reliability and long-term viability. Below is a detailed analysis of these key factors:

Technical Maturity

The technological readiness and maturity of the components within the hydrogen value chain affect reliability, scalability, and investment risk.

- › **Technology Readiness Levels (TRL):** Assessing TRLs for hydrogen production (e.g. PEM and alkaline electrolysis, natural gas reforming with CCS), storage, transport (pipelines, liquefaction), and end-use technologies (fuel cells, hydrogen combustion engines) helps gauge commercial viability. For instance, PEM electrolysis has reached TRL 8–9, indicating high maturity, whereas ammonia cracking is still in pilot phases (TRL 6–7).
- › **Innovation and Development:** Ongoing R&D is crucial to advancing less mature technologies, such as hydrogen storage systems, and to reducing costs through material and process innovations.
- › **Integration with Existing Infrastructure:** Repurposing existing infrastructure (e.g. natural gas pipelines or electrical grids) facilitates smoother adoption and reduces initial costs. Projects like the European Hydrogen Backbone demonstrate the feasibility of hydrogen pipeline networks.

Investment Costs

Investment costs represent the initial capital expenditure (CAPEX) needed to establish hydrogen infrastructure and technologies.

- › **CAPEX:** These include costs for production facilities (e.g. electrolyzers), storage systems, transport infrastructure (e.g. pipelines) and end-use technologies like fuel cells.
- › **Financing and Economic Viability:** Access to funding, stable regulatory frameworks, and economies of scale are essential for large-scale projects. Policy mechanisms like the EU Green Deal and US Inflation Reduction Act (IRA) reduce investment risks and attract private capital.
- › **Cost Reduction Potential:** Advances in electrolyzer efficiency, scaling effects, and government incentives continue to drive down costs, with electrolyzer prices decreasing by over 60% in the last decade.

Geopolitical Risks

Political risks encompass the potential for governmental or geopolitical factors to impact the hydrogen value chain. These include:

- › **Regulatory Changes:** Sudden shifts in policies or regulations – such as carbon pricing or hydrogen certifications – can impact production, distribution, and investment confidence. Stable policies, like the EU Green Deal or US Inflation Reduction Act (IRA), are crucial for attracting long-term investment.
- › **Geopolitical Stability:** Cross-border hydrogen supply chains are vulnerable to geopolitical risks, such as trade conflicts or sanctions. The Ukraine conflict, for example, has emphasized the importance of diversifying energy sources to reduce reliance on unstable regions.
- › **Subsidies and Incentives:** Consistent government support, such as subsidies under the EU Green Deal or tax credits from the US IRA, is critical to maintaining economic viability and ensuring global competitiveness for hydrogen projects.

CO₂ Footprint & Sustainability

Sustainability assesses the environmental and social impacts of the hydrogen value chain, ensuring its alignment with broader societal and climate goals.

- › **Environmental Impact:** Evaluating the lifecycle greenhouse gas emissions of hydrogen production is essential. Green hydrogen (produced from renewable energy) has the lowest emissions, while blue hydrogen (natural gas with CCS) and grey hydrogen (natural gas without CCS) have higher and more variable carbon footprints. For instance, blue hydrogen's emissions depend on the efficiency of carbon capture systems.
- › **Resource Utilization:** Hydrogen production requires significant natural resources, particularly water and land for renewable energy generation. In arid regions, such as the Middle East, the water demand for electrolysis poses sustainability challenges.
- › **Circular Economy:** Recycling and reusing materials, such as electrolyzer components or storage tanks, can improve resource efficiency and reduce waste in the hydrogen value chain. Advancing recyclable electrolyzers is a key focus area.
- › **Social Acceptance:** The success of hydrogen projects depends on public perception, community engagement, and social equity. Ensuring that projects create local benefits, such as jobs and infrastructure, can enhance acceptance and long-term viability.

Supply Chain Resilience

Resilience refers to the capacity of the hydrogen value chain to withstand and quickly recover from disruptions caused by technical failures, natural disasters, or market volatility.

- › **Supply Chain Robustness:** Decentralized and geographically diverse hydrogen production reduces dependence on single points of failure, ensuring greater supply stability. For instance, producing hydrogen across multiple regions (e.g. Europe, Middle East, and Latin America) enhances resilience.
- › **Flexibility:** The capacity to transition between hydrogen production methods (green, blue, grey) and adapt storage or transport solutions allows for better responses to changing supply-demand dynamics or infrastructure challenges.
- › **Risk Management Strategies:** Comprehensive contingency planning and redundant systems enable faster recovery from unexpected disruptions, such as extreme weather or geopolitical crises. The diversification of hydrogen supply chains is critical in mitigating such risks.

Conclusion











Taking these qualitative factors into account enables a comprehensive assessment of hydrogen value chains and helps stakeholders to reconcile economic feasibility with long-term adaptability and societal goals. This integrated perspective ensures that hydrogen technologies address current energy demands while supporting the transition to a sustainable and resilient energy future.

The figures below provide a qualitative assessment of the three use cases and six value chains introduced earlier, highlighting trade-offs between costs, risks, and long-term potentials. The color-coding in the table is used to provide a quick visual representation of each factor's impact on the value chains:











- › **Green** indicates favorable conditions or minimal challenges, such as low costs, high maturity, or minimal risks.
- › **Orange** represents neutral or moderate conditions, where trade-offs or uncertainties exist that require careful consideration.
- › **Red** highlights critical challenges or significant barriers, such as high costs, elevated risks, or low maturity levels, which may hinder feasibility or scalability.

This qualitative approach helps stakeholders identify opportunities and obstacles within each value chain, enabling informed decisions for optimizing hydrogen deployment across sectors.










End-to-End Value Chain for Green Steel Production

Value Chain	Technical Maturity	Investment Costs	Geopolitical Risk	CO ₂ Footprint	Supply Chain Resilience
Green steel production with self-produced hydrogen in Austria	 Technical maturity of H ₂ underground storage to be evaluated	 High investment costs for electrolysis plant, pipelines and storage	 Low or minimal geopolitical risk	 Low or minimal CO ₂ produced in this value chain	 Short and stable supply chain due to self-produced hydrogen
Green steel production in Austria with imported hydrogen from Morocco	 Technical maturity of H ₂ underground storage to be evaluated	 Low investment costs due to hydrogen importation	 Hydrogen transported through several countries	 High CO ₂ footprint due to hydrogen shipping to EU	 Supply chain could change in future due to new pipelines or political situation in involved countries

End-to-End Value Chain for Power Generation

Value Chain	Technical Maturity	Investment Costs	Geopolitical Risk	CO ₂ Footprint	Supply Chain Resilience
Producing ammonia in Saudi Arabia and transport it to Europe as energy carrier for H₂-fired gas power plants after ammonia-cracking	 High maturity of the technologies (Ammonia production through Haber-Bosch process and ammonia-cracking well-established) used except for purely H ₂ -fired power plants	 Investment costs encompass building ammonia production facilities and ammonia-cracking units, storage, and adapting gas power plants	 Political instability, changing regulations, or trade disputes can impact the reliability considering the cooperation between Saudi Arabia and Europe	 CO ₂ footprint depends on the energy source for ammonia production method and ammonia-cracking process; Relatively high CO ₂ -emissions during ammonia shipping	 Multiple value-chain-steps necessary for final utilization; Geopolitical situation between Saudi Arabia and Europe must be observed
Producing hydrogen in Saudi Arabia and export it to Europe as energy carrier for H₂-fired gas power plants	 High maturity of the technologies used except for purely H ₂ -fired power plants and maturity of underground storage	 Relatively high investment costs in adapting gas power plants and H ₂ storage infrastructure	 Political instability, changing regulations, or trade disputes can impact the reliability considering the cooperation between Saudi Arabia and Europe	 Relatively high CO ₂ -emissions during shipping of hydrogen	 Supply chain could change in future due to new pipelines and geopolitical situation between Saudi Arabia and Europe

End-to-End Value Chain for Heavy-Duty Mobility Solutions

Value Chain	Technical Maturity	Investment Costs	Geopolitical Risk	CO ₂ Footprint	Supply Chain Resilience
Producing hydrogen in Argentina and export it to Europe as fuel for heavy-duty	 High maturity of producing green hydrogen; Technical maturity of hydrogen trucks and infrastructure to be evaluated	 Relatively high investment costs considering transport; New hydrogen-powered fleets and infrastructure needed	 No significant political risk as EU has strong relations and energy trading history with Argentina	 Relatively high CO ₂ footprint due to hydrogen shipping to EU	 Relatively resilient supply chain; Infrastructure and fleets to be evaluated ("chicken-and-egg problem")
Producing e-fuels with hydrogen in Argentina and export it to Europe as fuel for heavy duty	 Medium maturity of used technologies	 Relatively high investment costs considering transport and conversion; E-Fuels can be used in existing combustion engines	 No significant political risk as EU has strong relations and energy trading history with Argentina	 High CO ₂ footprint due to hydrogen shipping to EU and CO ₂ emissions from combustion engines (even though just as much CO ₂ is bound during production)	 Relatively resilient supply chain



Favorable conditions with low costs, high maturity, or minimal risks.



Neutral conditions with trade-offs or uncertainties.



Major challenges like high costs, risks, or low maturity.

Figure 17: Qualitative assessment of the six E2E hydrogen value chains



4 Conclusion and Outlook

The global energy transition relies on hydrogen as a key driver of decarbonization across industries, transportation, and energy systems. However, meeting the growing demand sustainably presents a major challenge. In 2021, hydrogen consumption worldwide totaled 94 million tons, with refining, ammonia, and methanol production being the primary drivers. By 2050, demand is projected to surge to 450 million tons annually, spurred by growth in heavy industry, long-distance transportation, and renewable energy storage. However, current production levels, especially for green hydrogen, fall short. To meet future needs, electrolyzer capacity must undergo a massive expansion from the existing 1 GW to between 3,000 and 4,000 GW.¹⁰

Hydrogen's versatility is both its greatest asset and its biggest hurdle. Strategic deployment is critical to maximize its impact and avoid inefficiencies. High-impact sectors such as heavy industry, aviation, and hydrogenation offer irreplaceable decarbonization potential, while areas like domestic heating or passenger transport are better suited to alternatives like electrification or biomass. Ensuring hydrogen directed towards sectors where it delivers the greatest value is essential to its transformative potential.

This study revealed key opportunities and constraints within different hydrogen value chains. The analysis highlighted critical factors such as technological maturity, investment costs, CO₂ footprints, and supply chain resilience, providing a structured approach to evaluating their viability. Identifying bottlenecks like high infrastructure costs and energy losses allows targeted strategies for improvement, while opportunities like leveraging existing ammonia infrastructure underline near-term scalability potential.

The findings underscore that hydrogen is not a silver bullet but a crucial component of the future energy mix. Its transformative potential hinges on aligning infrastructure and production with high-value applications. For green steel production, locally produced hydrogen offers significant emissions reductions and energy security but faces hurdles with high initial investments and infrastructure requirements. Imported hydrogen, while presenting a lower upfront cost, carries geopolitical risks and

increased emissions from transport. Similarly, ammonia stands out as a hydrogen carrier for global transport due to its established infrastructure, although energy losses during conversion and cracking present challenges to overall efficiency.

In heavy-duty mobility, hydrogen and e-fuels emerge as key alternatives. E-fuels benefit from compatibility with current internal combustion engine technologies, offering a cost-effective transition option. However, their higher lifecycle emissions and inefficiencies in hydrogen-to-e-fuel conversion limit their long-term competitiveness. Hydrogen, with its greater energy efficiency in fuel cell electric trucks, represents a promising solution for sustainable heavy transport, albeit with higher costs and infrastructure needs.

Looking forward, international collaboration will be vital. Agreements between regions like the EU and Argentina highlight the potential for global hydrogen trade, but these efforts must address geopolitical risks and supply chain resilience. Additionally, technological innovation remains critical to reducing efficiency losses in hydrogen production, transport, and utilization.

In conclusion, hydrogen's role in the global energy transition will be shaped by how strategically it is deployed. Prioritizing sectors with the highest impact, scaling production responsibly, and fostering international cooperation will determine whether hydrogen can drive meaningful global emissions reductions. Without these measures, the hydrogen economy risks inefficiency and underperformance, missing the opportunity to transform the energy landscape.

To support this transition, our analytical model's modularity and flexibility allow for the simulation of diverse hydrogen value chains tailored to specific industries, regions, and applications. This tool empowers stakeholders to evaluate scenarios, optimize costs, and align strategies with evolving market dynamics and technological advancements. It enables industries and policymakers to design resilient, scalable, and impactful hydrogen ecosystems, ensuring a sustainable and adaptable energy transition.

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