Clean Hydrogen Partnership

Sustainable supply chain and industrialisation of hydrogen technologies

Summary Report

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SUSTAINABLE SUPPLY CHAIN AND INDUSTRIALISATION OF HYDROGEN TECHNOLOGIES

SUMMARY REPORT

CONTENTS

LIST OF ABBREVIATIONS

AEM	Anion Exchange Membrane
AFIR	Alternative Fuels Infrastructure Regulation
BoP	Balance of the Plant
CABM	Carbon Adjustment Border Mechanism
CAPEX	Capital expenditure
CCS	Carbon Capture Storage
CCUS	Carbon Capture, Usage and Storage
CHP	Combined Heat and Power
CRM	Critical Raw Material
DRI	Direct Reduction of Iron
ETS	Emission Trading System
EU	European Union
FRP	Fibre Reinforced Polymer
GHG	Greenhouse Gases
HDVs	Heavy-Duty Vehicles
HER	Hydrogen Evolution Reaction
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
LCA	Life-Cycle Analysis
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MEA	Membrane Electrode Assembly
NG	Natural Gas
OPEX	Operating expense
PCU	Pre-cooling Unit
PEM	Proton Exchange Membrane
PEMEL	Proton Exchange Membrane Electrolyser
PEMFC	Proton Exchange Membrane Fuel Cell
PFAS	Perfluoroalkyl substances
PFSA	Perfluorosulfonate/Perfluorosulphonic acid
PGM	Platinum Group Metals
PV	Photovoltaic
R&D	Research and Development
R&I	Research and Innovation

RED	Renewable Energy Directive
RFNBO	Renewable Fuel of Non-Biological Origin
RoW	Rest of the World
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
SO	Solid Oxide
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell
SWOT	Strengths Weaknesses Opportunities Threats
TFE	Tetrafluoroethylene
TRL	Technology Readiness Level

0. EXECUTIVE SUMMARY

This report delves into the European renewable hydrogen supply chain to offer recommendations for Europe to become a leader in the hydrogen economy.

0.1. Relevance of the hydrogen supply chain in the context of Europe and its competitors

The report examines the importance of the supply chain in achieving a net-zero economy and analyses EU hydrogen strategies and regulations, comparing them with those of other regions. It explores the significance of a robust, efficient, and independent hydrogen supply chain for the security and resilience of Europe's energy model and decarbonisation efforts. Developing the supply chain for hydrogen technologies is essential for Europe to address the transition from fossil fuel dependence, not only to avoid past mistakes (e.g., European dependence on Chinese solar PV components) but also to remain competitive compared with regions that are attracting and competing for these technologies.

The global expansion of trade and supply chains has enabled countries to enhance commercial ties. However, vulnerabilities have been exposed, particularly in technology supply chains, due to the COVID-19 pandemic and geopolitical tensions. Europe's energy transition plans, such as REPowerEU, aim to reduce fossil fuel dependency by leveraging domestic low-carbon energy sources and using renewable hydrogen as an energy carrier. Nevertheless, the reliance on imports for decarbonisation technologies remains a concern.

Initiatives such as the Net-Zero Industry Act and the updated Critical Raw Materials Act aim to address supply chain barriers. However, Europe faces challenges in transitioning from fossil fuels to renewable energy sources, which may require strategic materials that are not over-reliant on imports. Strengthening supply chains for emerging technologies such as renewable hydrogen is crucial to avoid repeating past mistakes, as seen with solar PV.

To evaluate the relevance of supply chain cost competitiveness in hydrogen production, an analysis comparing CAPEX and OPEX costs reveals that while initial CAPEX is a concern, factors such as technology efficiency and reliability are equally important. CAPEX is the key factor for individual energy installations, but is less significant in dual energy setups, where OPEX becomes the primary cost determinant. This underscores the multifaceted considerations – beyond simply CAPEX – used in evaluating hydrogen technology investments.

The development of European hydrogen technologies faces challenges due to insufficient financial and regulatory support compared with major competitors such as the US, China, and Japan. To remain competitive, European financing and regulatory capabilities may require improvements to support hydrogen technology development effectively.

- **US.** The recently introduced IRA offers significant financial aid with lower thresholds for qualification and no technology categorisation, thus promoting carbon reduction.
- **China.** Prioritises hydrogen production with strong financial and regulatory backing, outpacing European funding in the support provided for less mature technologies.
- **Japan.** Leads in R&D but still lacks specific regulations for renewable hydrogen.

0.2. Conclusions of the supply chain assessment for selected renewable hydrogen technologies

Additionally, the report evaluates the current and future competitiveness and circularity of the European Union’s supply chain across key technologies, providing detailed descriptions and SWOT analyses for critical components. Moreover, the report considers the potential future evolution of both supply chain competitiveness and sustainability and circularity levels.

The analysis of the European supply chain for hydrogen technologies reveals distinct focal points for leveraging strengths and areas for improvement which must be considered in the development of those technologies to maintain global leadership.

- **Main key points** in the current European hydrogen ecosystem providing **leverage for the future:**
  - Main **electrolyser manufacturers are based in Europe**
  - **World-leading Research and Development capacity** in several technologies (e.g., 5 out of top 10 global electrolyser patents are European)

  - **European customers prioritise local supply chains** as they demand quality and reliability
  - Leading **industry initiatives to reduce the use of CRMs** or develop alternatives
  - High-level knowledge based on **expertise in traditional industries in Europe**
  - **Regulatory boost for the local market** with new regulations to support competitiveness (e.g., CABM)
- **Main key points** in the current European hydrogen ecosystem **that need to be improved for the future:**
  - **Dependency on third countries for critical equipment** (e.g., CRMs, electronics)
  - **More complex project development** than in other regions
  - **Insufficient resources for competitive production and transport of H_2** (higher cost of production compared with other regions like North Africa, US and Middle East)
  - **Lack of recycling pathways;** use of energy-intensive processes; environmental impact
  - **Complex or underdeveloped regulations** to ensure safe H_2 transport and handling
- In particular, a number of **challenges were identified regarding the technologies selected** for this study. Several of the most critical are identified below:
  - **PEM electrolysers:** Presence of **only one European plant in the TFE chemical industry**
  - **Alkaline electrolysers: Chinese cost-competitive products** (i.e., CAPEX that can reach ~370 USD/kW vs. € 600 /kW for European products). Concerns about quality, customer support deficiencies, and lack of O&M services.
  - **Waste to Hydrogen: existence of barriers to the development of scaled-up plants** (e.g., regulation, social concern, current manufacturing capacities).
  - **Grid infrastructure: uncertainties regarding the future evolution of blending H_2** with current natural gas transport and distribution infrastructure.
  - **HRS and PEMFC: lack of commitment** from the European automotive sector to **promoting the development of hydrogen mobility**.
  - **New H_2 end-use technologies (H_2-DRI, H_2-gas turbines, synthetic methanol)** need competitive hydrogen production costs **to achieve scalability.**
- Furthermore, the **analysis of the circularity and sustainability** of these technologies has helped identify several challenges that need to be addressed to strengthen the hydrogen technologies supply chain in Europe:
  - **Environment.** There are concerns due to a lack of recycling pathways, the presence of harmful substances (PFAS), energy-intensive processes, water overconsumption, and the environmental impacts of extraction and usage.
  - **Society.** The safety concerns regarding the transport/handling of H_2 and NH_3 by public entities, coupled with low public awareness and knowledge of hydrogen, are significant societal issues.
  - **Economy.** Economic obstacles are posed by the challenges in energy efficiency and operating costs, the high investment costs involved in rare materials and technologies, the scale-up issues due to small production capacities, and the uncertainties arising from the low development level of technologies.

0.3. Recommendations to strengthen the European Hydrogen Supply Chain

Lastly, the report offers **recommendations and measures to address vulnerabilities and minimise the impact of disruptions in the supply of key components.** Throughout the study, insights from an Advisory Board comprising European industrial companies and leading research institutions ensured a comprehensive overview from European hydrogen experts. The **European hydrogen supply chain still faces immaturity in various general aspects, which poses challenges to maintaining competitiveness with other regions.**

0.3.1. Strengthening the hydrogen supply chain (general recommendations)

1. Intensify European **R&D projects focusing on the discovery of new technologies and materials to minimise the reliance on CRMs** (e.g., Ni, PGMs, Al, Ti) and other critical materials.
2. Prioritise R&D projects focusing on **manufacturing scale-up and automatisation of plants.**
3. Create specific programmes focusing on the **development of complementary, and currently immature, solutions for the hydrogen technologies** currently on the market.
4. **Introduce, review, or clarify hydrogen certification and standards** (e.g., PFAS ban, ammonia safety procedures, H_2 blending rate).
5. Promote specific supporting mechanisms for projects that target the **development of the most underrepresented technologies in the European hydrogen landscape** (AEM, Waste-to-H_2, NH_3 cracking, H_2-DRI, H_2-gas turbines, and synthetic methanol).
6. Ensure that funding programmes prioritise the **distribution of subsidies based on the impact on emission reduction or energy consumption.**
7. Ensure that funding programmes incentivise the **diversification of Made in Europe technologies** based on potential synergies to add robustness and independence.

0.3.2. Improvement of sustainability and circularity

1. Ensure that the industry as a whole adheres to **new requirements when applying for European funding:**
    a. **Advanced environmental reporting** is crucial to fostering industry collaboration, enhancing transparency, and promoting sustainability.
    b. **New and clear sustainability guidelines** must be implemented to oblige all companies to pursue the circular design of hydrogen products.
2. Develop a programme to **collect waste products and components, especially for small companies.**
3. In scenarios where alternatives such as direct electrification are feasible, **assess whether it would be more adequate to use hydrogen technologies** thorough an evaluation of the potential alternatives.

0.3.3. Necessary efforts to develop hydrogen projects in Europe

1. Projects should be granted both **CAPEX and OPEX funding, enabling transparent, long-term planning** by announcing grants for extended periods.
2. Demand-side subsidy schemes **should be tailored to specific industries.**
3. **Facilitate and promote demand** from off-takers by implementing a new framework that favours **long-term HPA contracts.**
4. **Foster collaboration between the projects awarded and encourage knowledge-sharing to expedite progress,** thereby enhancing the impact of the programme.

1. STUDY GOALS AND SCOPE

The purpose of this report is to analyse the current and future strengths and weaknesses of the European renewable hydrogen supply chain and provide recommendations to enable Europe to become a leader in the hydrogen economy and support long-term economic growth through a sustainable and reliable hydrogen supply chain. To achieve this objective, this document analyses:

- The significance of the supply chain in the hydrogen economy, including:
  - The importance of renewable hydrogen as a key element in achieving a net-zero economy in Europe.
  - The EU's main hydrogen strategies and regulations and a comparison against other regions.
  - Hydrogen supply and demand scenarios in Europe by 2025 and 2030, and the respective associated logistics infrastructures and asset investments.
  - The significance of a robust, efficient, independent hydrogen supply chain as a strategic element in the security and resilience of the European energy model and its decarbonisation process.
  - The importance of the circularity of materials and the inception of recycling techniques in hydrogen technologies.
  - The job opportunities created with the development of the hydrogen supply chain and the skillset needed to cover those positions.
- The current and future competitiveness and circularity of the European Union’s supply chain with respect to several key technologies, including:
  - Detailed description of the technology and the supply chain.
  - Identification of the most critical (sub)components for each technology.
  - Evaluation of the strengths and weaknesses of the most critical components of the supply chain using a SWOT framework.
  - Potential evolution of supply chain competitiveness in the future.
  - Levels of sustainability and circularity of these supply chains.
- Proposed recommendations and measures aimed at covering the vulnerabilities detected to minimise the potential impact of disruptions in the supply of the main (sub)components.

In preparing this study, we have received the input of an Advisory Board consisting of European industrial companies (i.e., manufacturers and assemblers) and leading research institutions. All the production, logistics and end-use technologies covered in the supply chain assessment are represented on the Advisory Board to obtain a comprehensive overview from European hydrogen experts.

The methodology for the development of this study was structured around three main tasks: State-of-the-art of hydrogen technologies, Supply chain assessment and Recommendations. Data collection was carried out across all areas in the various stages of the project using desk research, interviews with leading players, experts and researchers and a questionnaire sent to manufacturers along the various supply chains of the selected technologies.

The supply chain assessment methodology was developed carefully to cover all the critical aspects and issues that may arise in a comprehensive analysis of the renewable hydrogen technology supply chain. A framework involving four stages was designed to carry out the studies for all the prioritised technologies:

- Assessment of the supply chain itself, from its raw materials to its final products, and identification of the critical parts.
- Analysis of supply chain manufacturing competitiveness within Europe for all the critical elements. Complete and robust analyses required a complementary data collection strategy to overcome potential information gaps, based mainly on desk research and interviews with field experts.
- Analysis of the strengths and weaknesses of the European hydrogen supply chain. Within this task, a deep dive into the weaknesses was carried out, and the evolution of the detected vulnerabilities was evaluated.
- Analysis of the sustainability and circularity of all technologies.

2. RELEVANCE OF THE RENEWABLE HYDROGEN SUPPLY CHAIN

2.1. Renewable hydrogen as a key element to reach the net-zero goal

The global energy system consumed approximately 410 EJ in 2023, mainly from fossil molecules, across the industrial (e.g., chemicals, steel), transport and mobility (e.g., cars, shipping, aviation), and building sectors. Although electrification solutions will play an important part in decarbonisation, molecule-based energy carriers are likely to deliver approximately 30–35% of total energy consumption by 2050, according to the IEA [1]. Renewable hydrogen has the potential to meet approximately 10% of total energy consumption, equivalent to 35 EJ, especially in high-temperature processes, as feedstock or a reduction agent in industrial processes, in heavy-duty vehicles and for renewable electricity storage.

The specific potential and timing of the use of clean hydrogen varies by sector. In the chemicals sector, grey hydrogen is already in use and, therefore, few asset changes and limited investments are needed to produce ammonia and methanol using clean hydrogen. Similarly, refining also uses grey hydrogen, meaning that relatively few process changes will be required to make the switch. In addition, emerging regulations are promoting take-up by 2030 in these sectors, as well as in aviation and road freight.

Demand driven by pressure from customers for sustainable products can also play a role in early take-up in sectors such as steel (H_2-DRI) or shipping (synthetic methanol), although large-scale adoption will likely come after 2030. There is great potential for economic sectors and applications to use hydrogen as a key element to achieve their complete decarbonisation and make a net-zero emissions scenario possible.

2.2. European strategy and regulatory context for hydrogen

2.2.1. European Union regulatory framework

The EU made a commitment in 2018 to become a net-zero greenhouse emission economy by 2050, setting a global example on decarbonisation and sustainability policies. The energy transition and decarbonisation commitments are at the core of EU legislation and are the driving force behind the modernisation of the economy and society. In compliance with the Paris Agreement signed in 2016, the *European Green Deal* [2]was launched in July 2019, establishing the 2050 climate-neutral binding target for the EU. Under the *European Green Deal* umbrella, a series of strategies were initiated to establish specific targets and actions to implement this decarbonisation commitment. The EU's hydrogen strategy, *A Hydrogen Strategy for a Climate-Neutral Europe* [3], was adopted in 2020. This strategic framework envisions the establishment of a robust European hydrogen ecosystem, emphasising research and innovation, and sets the target for renewable hydrogen electrolyser deployment at over 40 GW and domestic production at 10 Mt by 2030. The ultimate goal is to extend these endeavours to a global scale to contribute to a climate-neutral economy.

In July 2021, the European Commission released the *Fit for 55* package [4], a set of proposals to revise and update EU legislation and to put in place new initiatives to ensure that the EU's policies are in line with its climate goals, including the target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990. While the *Fit for 55* package legislation was under discussion, Russia's invasion of Ukraine in February 2022 seriously disrupted the EU's energy landscape. This situation triggered an unprecedented energy crisis, highlighting Europe's dependency and the potential for disruption of the EU member states' energy security due to geopolitical tensions. In response, the European Commission presented the *REPowerEU* plan in May 2022 [5], which focused on increasing the EU's energy independence. The development of renewable hydrogen is one of the key elements of the plan. The *REPowerEU* plan updated the target for renewable hydrogen electrolyser deployment to over 60 GW by 2030, as well as the target for hydrogen domestic production to 10 Mt, with an additional 10 Mt of imports, and 4 Mt in derivatives such as ammonia. A total estimated investment of € 27 bn will be needed to meet the updated target. This plan prioritises not only energy independence through renewable hydrogen, but also the development of domestic electrolyser manufacturing capacity, setting a yearly target of 17.5 GW [6] by 2025.

The European energy transition and independence plans under the *Fit for 55* package, accelerated by the *REPowerEU* strategy, includes several legislative measures [4]. Among the most relevant are the *Revised Emission trading system* (ETS), *Carbon Border Adjustment Mechanism*, *ReFuelEU Aviation Regulation*, *FuelEU Maritime Regulation*, *Alternative Fuels Infrastructure Regulation* (AFIR) or the *Revised Renewable*

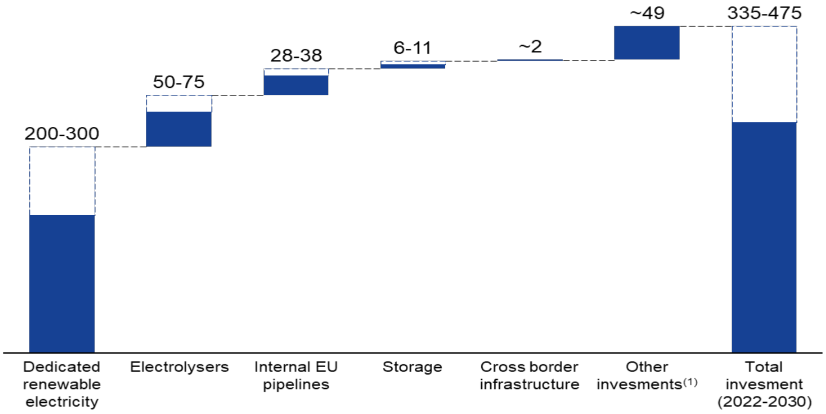
Energy Directive (i.e., RED III). RED III sets a RFNBO demand objective of 42% of the total hydrogen used in industry by 2030, and of 60% by 2035[1].

Of particular note under RED III are the Delegated Acts on renewable hydrogen and RNFBOs recently adopted by the European Commission. These two Acts clarify and set the rules on the criteria to be met by hydrogen producers to be considered renewable. The rules established in the Delegated Acts apply to both domestic hydrogen and hydrogen imported through voluntary schemes. The Delegated Acts establish additionality and correlation as key principles to be met in order to consider the hydrogen produced to be renewable.

2.2.2. European Union funding lines

The deployment of the renewable hydrogen economy will require the collaboration of legislators, public institutions, and private companies. The alliance between players along the whole renewable hydrogen value chain will be essential to scale up solutions, to build new transport and logistics infrastructures and to develop a liquid and reliable market. The European Commission has estimated the investments needed for the deployment of renewable hydrogen by 2030 [5] at € 335-475 bn, including € 200-300 bn for renewable electricity production (see Figure 1).

Figure 1 Hydrogen production and logistics investment needs (€ bn, accumulated 2030) [5]



(1) Other logistics investments (i.e., distribution, hydrogen refuelling stations)
Source: *REPowerEU* plan

The implementation of technological alternatives based on hydrogen are becoming cost-competitive, although they still require additional funding to replace current fossil fuel-based solutions. The most significant funding initiatives for the development of the renewable hydrogen economy are: Important Projects of Common European Interest (IPCEI) [7], Horizon Europe [8], European Regional Development Fund and the Cohesion Fund [9], Just Transition Fund [10], InvestEU Fund [11], Innovation Fund [12], Connecting Europe Facility – Energy (CEF-E) [13], Connecting Europe Facility – Transport (CEF-T [14]), LIFE Programme [15], Modernisation Fund [16], Recovery and Resilience Facility [17] and the European Hydrogen Bank [18]. This mechanism will support the objectives stated in the *Green Deal Industrial Act* targeting the unlocking of private investment in renewable hydrogen technology supply chains in the EU.

2.2.3. European supply chain strategies

The unprecedented crisis caused by the COVID-19 pandemic, the disruption of supply chains and geopolitical instability require a firm response from the EU. The potential offered by renewable hydrogen for overcoming the energy crisis and achieving long-term decarbonisation targets needs a clear regulatory framework to provide legislative and investment security for member states and private agents.

It is worth highlighting the efforts made by the EU, not only towards developing new legislative packages for energy transition and independence, but also towards implementing new strategies relating to EU industrial capacity and resilient supply chain schemes for clean technologies in which renewable hydrogen plays a key role. The new paradox in the EU energy transition and independence roadmap is the expected switch from dependency on fossil fuel imports to reliance on raw materials, manufactured components and equipment produced and imported from third countries. In response to these concerns, in February 2023 the Commission presented the *EU Green Deal Industrial Plan* [19]. This roadmap aims to improve the competitiveness of the

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[1] The EU Commission originally proposed 50% by 2030, which was increased to 78% by the *REPowerEU* plan

EU's net-zero industry through the development of a more supportive and responsive environment for scaling up its manufacturing capacity for clean technologies. The *Green Deal Industrial Plan* complements the *EU Green Deal* (energy transition) and the *REPowerEU* plan (energy independence). The *Green Deal Industrial Plan* is built around four pillars that aim to ensure a competitive and reliable domestic clean tech industry:

- **Predictable and simplified regulatory environment** through the development of two acts, the *European Net Zero Industry Act* [20] and the *European Critical Raw Materials (CRMs) Act* [21].
- **Faster access to funding:** simplification of IPCEI project approval, EU funds aimed at manufacturing investments for net-zero technologies, amendments to the *Temporary Crisis and Transition Framework* [22], revision of the General Block Exemption Regulation [23], and the creation of the *European Sovereignty Fund* [24].
- **Enhancing skills** to develop the competencies needed to create a qualified European workforce.
- **Open trade for resilient supply chains.**

Two main measures among the different initiatives covered under the *EU Green Deal Industrial Plan* are noteworthy: the *European Net Zero Industry Act* and *the European Critical Raw Materials Act.*

- The *European Net-Zero Industry Act* [20] aims to boost European manufacturing capacity for net-zero technologies in line with EU decarbonisation goals. Targets include reaching 40% of EU annual deployment needs by 2030 and ensuring free movement of these technologies within the Single Market.
- The *European Critical Raw Materials Act* [21] aims to provide the EU with resources and strategies to secure access to reliable and sustainable CRM supplies. This recently announced Act provides an updated EU list defining CRMs and a shorter list of strategic materials for renewable hydrogen technologies. The Act details strategies for the development of a resilient and robust CRM supply chain, such as reducing bureaucracy barriers and authorisation processes for CRM projects. It also proposes the creation of strategic projects relating to CRMs to facilitate access to financing tools.

One of the main concerns of the EU is not only the development of a competitive local net-zero industry but also the protection of the EU Single Market from unfair trade through foreign subsidies that disrupt the EU's clean technology industry and its supply chains, leading to their relocation. Through the *Green Deal Industrial Plan*, the EU will endeavour to enforce policies to mitigate the uncertainties surrounding global competition for clean technologies.

2.3. Global renewable hydrogen strategies

The increasing popularity of renewable hydrogen has encouraged countries all over the world to establish knowledge and policy hubs aimed at the development of a global renewable hydrogen economy. Among the many collaborative initiatives, the *International Partnership for Hydrogen and Fuel Cells in the Economy* (20 countries) and the *Mission Innovation – Clean Hydrogen Mission* (co-led by Australia, Chile, the EU, the UK, and the US) should be highlighted.

2.3.1. Technological development strategies

To assess Europe's stance on hydrogen technologies, it is essential to compare the EU's targets and strategies with those of other prominent regions and economies:

- **United States of America.** The US stands out due to the *Inflation Reduction Act* (IRA) [25], which provides direct financial support in the form of tax credits for domestic production and investments in renewable hydrogen. Although the US official definition for clean hydrogen sets a similar GHG emission threshold to RED III (i.e., ~3kgCO_2/kgH_2), the IRA supports projects with up to 4kgCO_2/kgH_2. The US aims to decrease the production cost of renewable hydrogen by 80%, bringing it down to \$1/kgH_2 in a decade, in the expectation that this cost reduction will naturally lead to massive hydrogen adoption.
- **Asia.** The taxonomy for renewable hydrogen contains ambiguities and there are sometimes higher thresholds for GHG emissions that double those of the EU. China's strategy aims to increase its production to become a leading manufacturing economy given its industrial advantages such as cost competitiveness and large supplier availability (e.g., materials, technology, components, electronics). Japan and Korea have attractive programmes relating to R&D and hydrogen penetration in adopted final applications.

  South Korea's target is to become the global leader in hydrogen-powered-cars and fuel-cell manufacturing by 2030 and it has established a strategy to manufacture the required components for hydrogen-fuelled road vehicles domestically by 2040 [26]. Japan has worked on developing strategies for domestic hydrogen manufacturing capabilities through R&D programmes that will enable it to achieve widespread adoption of renewable hydrogen and increase its leadership in fuel-cell manufacturing and exports [27]. China has expressed concerns about the global trend of the local relocation of industries, as it fears its manufacturing capacity may be affected by the redesign of clean technology supply chains [28].

- **Australia.** Australia has a very wide definition of renewable hydrogen, although the government is aiming to reduce the barriers for investing in the hydrogen industry and one of the ways of accomplishing this is by offering regulatory guidance. Additionally, several Australian regions (Tasmania, New South Wales, Western Australia, etc.) have released their own Renewable Hydrogen action plans and strategies, with the aim of scaling up renewable hydrogen production and provide funding.

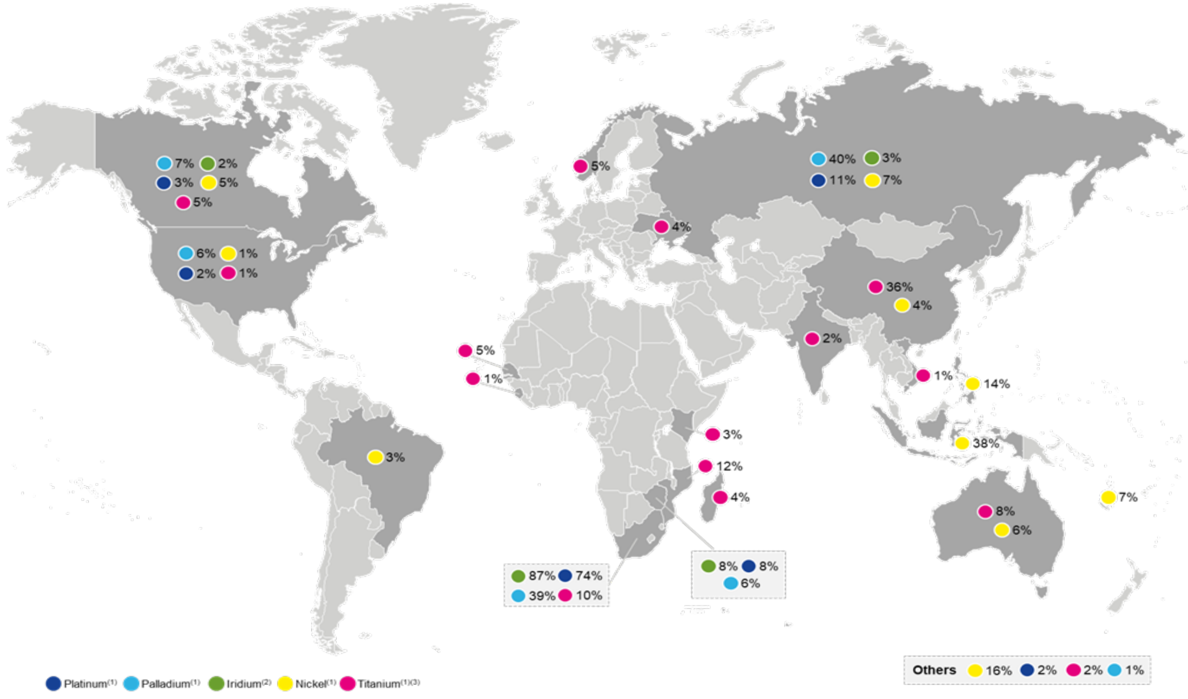
Whereas the EU strategy is built around highly ambitious targets, minimum shares and robust definitions for renewable hydrogen, these other leading regions have reframed their efforts towards creating a favourable investing environment. The strategies followed by the US, Asia and Australia are focused on delivering direct economic support for renewable hydrogen production, R&D activities and industry for supply chain attraction. Nevertheless, some of these regions have developed regulatory frameworks with more lax or ambiguous definitions of renewable hydrogen taxonomy which introduce potential sustainability risks. Others like the US, which have similar definitions for renewable hydrogen, have designed a laxer structure for investment in the sector.

2.4. The relevance of supply chains

Governments and industries fearing unexpected severe disruptions have been rethinking supply chains and investments in domestic technology manufacturing. Resilient supply chains will act as a lever to drive the energy transition in Europe. However, the dependence of most decarbonisation technologies on imports of materials, components, and equipment is an issue of great concern to European industries.

The coming years will pose a challenge to the EU, not only in terms of how to secure a reliable domestic industry, but also how to procure sufficient strategic raw materials to satisfy EU domestic needs so that a bottleneck is not created in the implementation of EU industrial plans on net-zero technologies. The availability of CRMs is a competitive advantage afforded to only certain regions in the world (see Figure 2), with Europe expected to be a significant importer. To address this concern, the recently updated *Critical Raw Materials Act* [21] has proposed strategic partnerships, cooperation agreements and R&D programmes to reduce the dependence on strategic materials through the development of alternatives and the use of recycling.

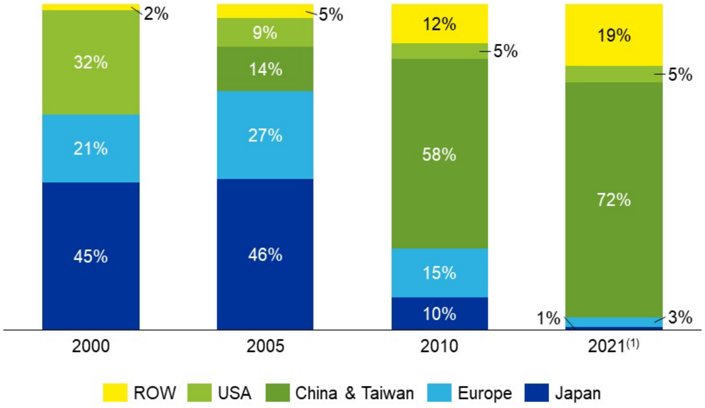
Figure 2 Global mining production of strategic raw materials for hydrogen [29] [30]



(1) Mining production in 2021; (2) Production in 2018; (3) Ilmenite and rutile
Source: US Department of Interior; US Geological Survey; Wood Mackenzie; International Platinum Group Metals Association; European Commission; Britannica; Monitor Deloitte

The experience of developing other mature renewable energy supply chains, such as solar PV, may be used as a guide to the development of a stable, secure, and local renewable hydrogen supply. Taking this technology as an example, Europe’s leading position in global solar PV installed capacity, representing ~20% [31], is of particular note. Nevertheless, it is highly dependent on Chinese manufacturers which make up ~70% of global manufacturing capacity for solar PV components [32]. Although Chinese players are now undeniably the leaders in the field, back in 2005 Japan led global production with 46% of the market share, followed by Europe with 27%, whereas Chinese production was negligible. This shows it is essential to strengthen the supply chain for key emerging technologies at an early stage of maturity to avoid a similar outcome to solar PV manufacturing in which China dominates (see Figure 3).

Figure 3 Share of solar PV cell manufacturing capacity by region



Notes: (1) PV module production; Source: Jäger-Waldau, Arnulf. (2018). PV Status Report 2018; PV Status Report 2007; IEA (2022), Solar PV Global Supply Chains, IEA, Paris; Monitor Deloitte

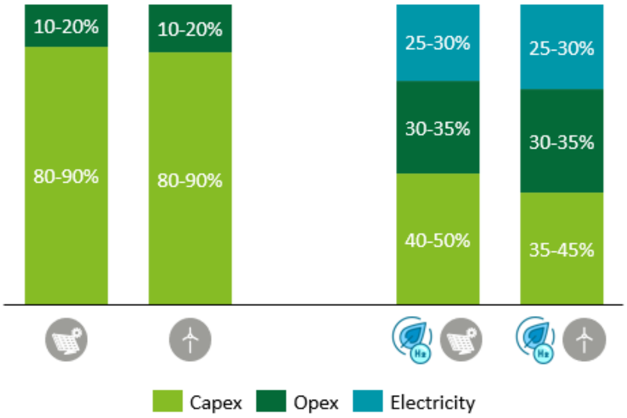
The REPowerEU initiative aims to increase the European Union's electrolyser installed capacity to over 60 GW by 2030, necessitating collaboration among European manufacturers. The success of introducing renewable hydrogen technologies relies on establishing resilient supply chain frameworks, addressing inefficiencies through sustainable design schemes, and managing dependency on critical raw materials and components. The *European Clean Hydrogen Alliance*, formed under the EU's efforts, includes commitments from electrolyser manufacturers to scale up domestic production to 17.5 GW/year. The EU is prioritising risk mitigation in large-scale hydrogen deployment, focusing on supply-chain vulnerabilities and import dependencies. Initiatives such as the *European Hydrogen Strategy* and the *EU Green Deal Industrial Plan* emphasise the importance of resilient and circular supply chains to prevent barriers to hydrogen adoption and avoid potential industry loss. As renewable hydrogen production expands, the complexity of supply chain management will intensify, underscoring the urgency of building robust schemes to maintain Europe's technological leadership in the energy transition.

2.4.1. The relevance of supply chain cost competitiveness in H_2 production

There is a lack of fully developed commercial applications for some key hydrogen technologies, which results in higher initial CAPEX investments. However, this is not the main factor of concern when analysing these technologies, as their competitiveness is not driven solely by their investment cost, but also by the efficiency, reliability, and availability of the technology, customer support or O&M services. For example, it is important to differentiate hydrogen technologies from others such as renewable energy; solar PV technologies are differentiated mainly by cost as their efficiency is similar between global manufacturers. On the other hand, hydrogen production technologies are still being developed, making them immature in terms of efficiency. When investing in hydrogen production technologies, economic efficiency is an important factor to be considered, but is not as significant in other technologies due to factors such as the technological complexity inherent to hydrogen production.

The relative significance of CAPEX and OPEX per type of technology installed has been analysed on single power generation installations (solar or onshore wind) and on dual energy installations (electrolyser and solar or onshore wind). The analysis challenges the hypothesis that when considering the installation of hydrogen production technologies with a renewable source, the relative significance of CAPEX in the final product cost is reduced significantly vs. a situation involving renewable generation. The results (see Figure 4) demonstrate that the CAPEX of individual renewable generation installations represents 80-90% of the total costs. Whereas, when combined with an electrolyser to produce hydrogen (dual energy installations), electrolyser CAPEX accounts for only 35-50% of the total costs depending on the type of combined energy source, which is a significant reduction compared with single power generation installation. This means that OPEX (considering the renewable electricity sourcing as an OPEX) for dual energy installations is the most important determining factor for the cost of hydrogen production, accounting for over half of the total costs (50-65%).

Figure 4 Type of costs per project technology (%)



Source: Monitor Deloitte

The CAPEX factor in hydrogen production is therefore not as significant as in other energy transition technologies such as renewable power generation. This could mean that the most economically efficient player, the one with lowest CAPEX, will not be the winner in the race for market dominance as there are other factors that must be taken into consideration for project developers, such as the aforementioned efficiency, reliability and availability of the technology, customer support or O&M services, which play an important part in total investment costs.

2.5. Circularity of materials and recycling techniques for hydrogen technologies

2.5.1. Circularity in design

Hydrogen technologies present a novel array of opportunities for sustainability. However, their integration and design play a crucial role in achieving circularity. To achieve a circular economy, materials must follow a circular lifecycle, in which the value of products is preserved for as long as possible, and materials are preferably reduced, reused, or recycled. Implementing sound manufacturing practices, starting from the product design phase, is vital to accomplishing this. Design trends that promote sustainability include **modular design** and **design for disassembly/recyclability,** which minimise the need for complete equipment unit replacements.

These techniques enable the disassembly and recycling of products, but it is important to note that there is a lack of information on the environmental repercussions. Such information is crucial for making appropriate design choices. Therefore, to complement the design techniques and assist in material selection, as well as to monitor the carbon footprint and environmental impact of the product, it is advisable to employ both of the following methods: **material passports** and **Life Cycle Analysis (LCA).**

2.5.2. Recycling of materials

When a product reaches the end of its life and its components and materials are no longer reusable, recycling becomes necessary. To ensure proper disposal, the technology must be dismantled carefully and the materials categorised so they can be sent to their respective recycling processes.

Recycling entails a list of benefits for industry: substituting primary raw materials, reducing dependency on imported materials, reducing environmental impacts by lowering energy use and CO_2 emissions, improving waste management, avoiding landfill and incineration of metals, and supporting economic activities in Europe through the recycling value chain for the materials.

2.5.3. Challenging materials

Despite the implementation of smart design principles such as modularity and design for recyclability, which aim to minimise material usage and facilitate recycling, there are certain types of materials that present inherent challenges. In the case of hydrogen technologies, these challenges primarily revolve around two main groups:

- **CRMs:** critical due to supply risks and strategic importance. Recyclability and circular use of CRMs is vital for economic and geopolitical independence. However, the current recycling rates for most of these remain low and require improvement. Smart designs that facilitate the dismantling of technologies and enable efficient recovery are as essential as research on recycling techniques themselves [33].
- **PFAS materials:** this category encompasses per- and polyfluoroalkyl substances, which constitute a wide range of synthetic chemicals known for their fluorine content. These substances are water and soil contaminants which have negative health effects and are present in everyday products. Unfortunately, hydrogen technologies are dependent on these materials, without viable alternatives in some cases (e.g., fluoropolymer used in PEM membranes). The existing regulations on these substances remain uncertain and under development [34].

2.6. Skills and workforce in the hydrogen supply chain

2.6.1. The opportunities for job creation represented by hydrogen technologies

Opportunities within Europe's hydrogen industry are unparalleled. Estimates suggest that for every €1 million in revenues in the industry, the following direct and indirect jobs will be created: [35]:

- Advanced industries (machinery and equipment, automotive, etc.): 10 direct and indirect jobs.
- Manufacturing of equipment and end-use applications: 13 direct and indirect jobs.
- Aftermarket services and new business models: 15 direct and indirect jobs.

Considering these ratios and an ambitious market size of ~€150 billion [35], the EU H_2 industry is projected to employ over 1 million people by 2030. Around 500,000 jobs would be created in the manufacturing of hydrogen production and distribution equipment, and in the establishment of infrastructure for end-use applications. ~350,000 more jobs would be linked to value-added through fuel cells, specialised components, and end-use applications. If this trend continued, by 2050, the EU H_2 industry would employ up to 5.4 million people.

Roles in the EU hydrogen supply chain require highly qualified individuals with engineering capabilities and technical expertise. Among the workforce requirements, the core occupations can be divided into two categories:

- **Engineers,** such as chemical, electrical, mechanical or production engineers, amongst others.
- **Plant and maintenance operators,** ranging from lab technicians to plant managers.

This list does not cover all the range of possible job opportunities in the hydrogen supply chain, but it does represent a fair picture of the current opportunities available in the EU hydrogen sector.

2.6.2. Common skills among hydrogen technologies

Key skills for the available job positions in hydrogen technologies include knowledge of the properties, behaviour and potential risks associated with hydrogen, as well as being able to employ the necessary safety measures. Other skills that apply to several positions are understanding electrochemical reactions and processes and hydrogen production using electrolysers. More specific skills, depending on the job position, range from knowledge of automated process systems to appropriate selection of certain electrolyser components [36]. This list does not cover the entire range of the most sought-after skills in the hydrogen supply chain but it does represent a fair picture of the skills that the EU hydrogen sector is currently looking for.

There is an opportunity for these skills to be transferred to and from other industries (e.g., Oil&Gas, chemicals), although the most potentially transferrable are in natural gas processing. This is mainly due to the decades of expertise accumulated by EU companies in the chemical sector.

Despite this, certain core occupations have relatively small talent pools, such as renewable power interconnection specialists, instrumentation and control maintenance, or safety engineers, for which skill development incentives to reduce the shortages are required since there is expected to be a rise in demand for these positions and interest in working in the hydrogen industry is now increasing, but not at a sufficient rate to meet the demand for new hires.

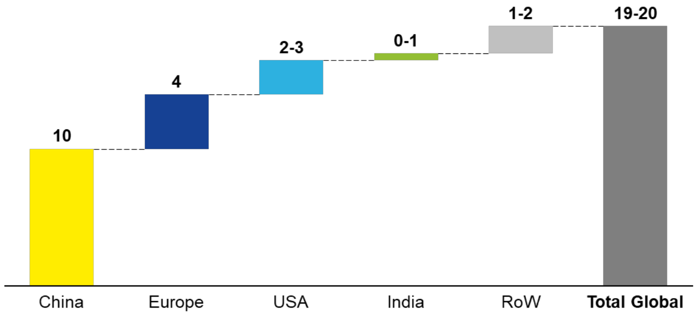
3. SUPPLY CHAIN ASSESSMENT FOR SELECTED RENEWABLE HYDROGEN TECHNOLOGIES

3.1. Production technologies' supply chains

3.1.1. Electrolysers

In 2023, Europe represented nearly 25% of total global electrolyser manufacturing capacity, ahead of the US and India, but behind China's manufacturing capacity (over 55% of total global capacity, see Figure 5).

Figure 5 Current global manufacturing capacity per region (GW/yr; 2023) [37]

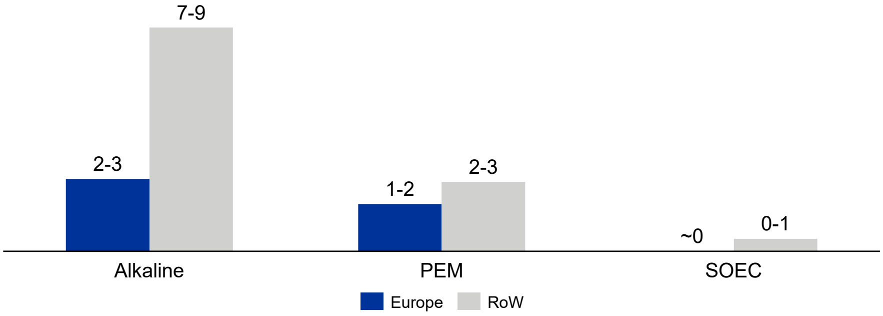


Source: Monitor Deloitte; Global Hydrogen Review 2023, IEA

Alkaline (ALK) electrolysers have the largest manufacturing capacity due to technological maturity and lower manufacturing costs. In Europe, ALK accounts for ~1.5 times the current PEM manufacturing capacity (~55% vs. ~35%). SOEC and AEM production are almost negligible, although these technologies are expected to play a key role in the long-term strategy as they are not dependent on noble metals.

PEM is the technology where Europe is the strongest with over 40% of total global manufacturing capacity (see Figure 6). In ALK, Europe lags behind the leading players in this market as, in 2022, Europe accounted for 25% of total global manufacturing capacity.

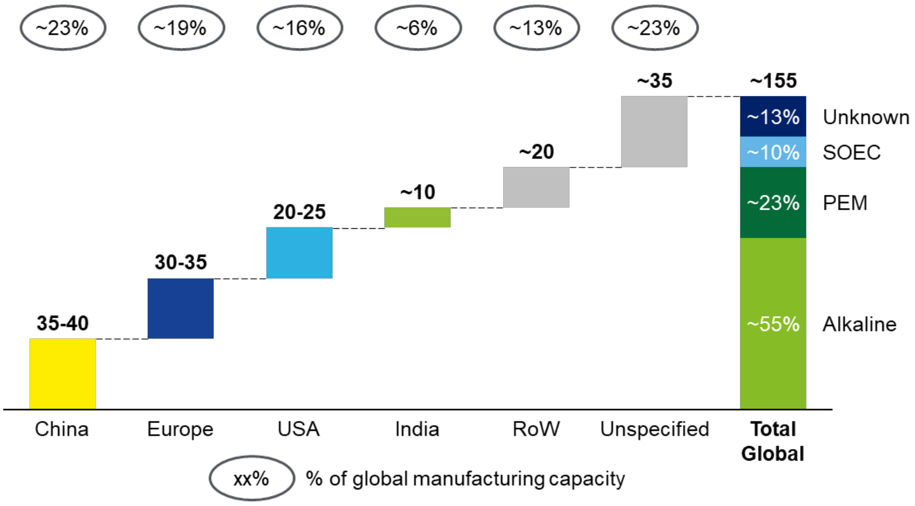
Figure 6 European electrolyser manufacturing capacity vs. other regions (2022; GW/year)



Source: Monitor Deloitte; Global Hydrogen Review 2022, IEA; European Commission; Hydrogen Europe; S&P Global

In the future, the manufacturing capacity will evolve as new players enter the market and compete with China for market dominance (see Figure 7). Europe will maintain its market share close to ~20% (vs. ~25% in 2023), but China's market share will be reduced to ~25% (vs. ~55% in 2023) as India and the Rest of the World (RoW) gain ground in the global landscape (~20% in 2030 vs. ~13% in 2023) [37].

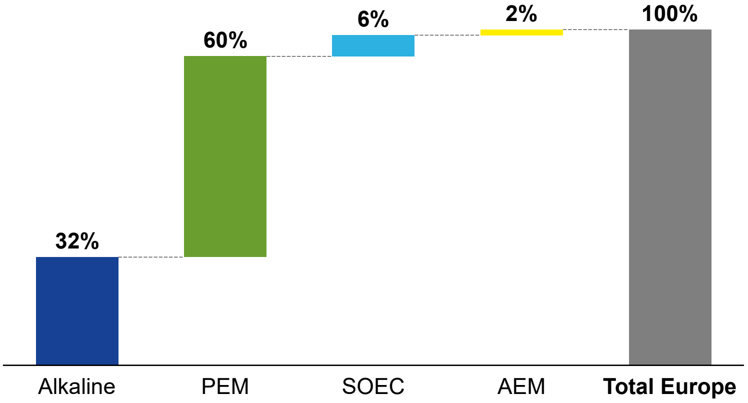
Figure 7 Expected global electrolyser manufacturing capacity per region (GW/yr; 2030) [37]



Source: Monitor Deloitte; Global Hydrogen Review 2023, IEA

The same analyses for electrolyser manufacturing capacity compared to other regions' deployment of production capacity show Europe's leadership in PEM electrolysers. This technology will be the most significant for European manufacturers, representing 60% of the EU's total manufacturing capacity (see Figure 8).

Figure 8 Expected EU electrolyser manufacturing capacity by type (GW/yr; 2030) [38]



Source: Monitor Deloitte; Clean Hydrogen Monitor 2023 – Hydrogen Europe

The role played by China is remarkable as by 2030 its capacity to manufacture ALK electrolysers is expected to be over 95% of its production capacity deployment. However, PEM will play a secondary role in the increase in Chinese manufacturing capacity, representing only 5% of total Chinese electrolyser capacity. The increase in PEM manufacturing capacity, led by Europe, demonstrates the EU's R&D leadership in this technology. Although PEM electrolysers are not as mature and cost-effective as ALK (only considering CAPEX), they represent a well-established commercial technology that aims to overcome issues affecting ALK electrolysers (e.g., limited operating range). Whereas Europe's focus will be on manufacturing advanced, more complex electrolysers (i.e., PEM) and, consequently, on marketing high value-added electrolysers with a strong background in innovation, Chinese manufacturing strength will lie in producing cost-effective mature ALK electrolysers.

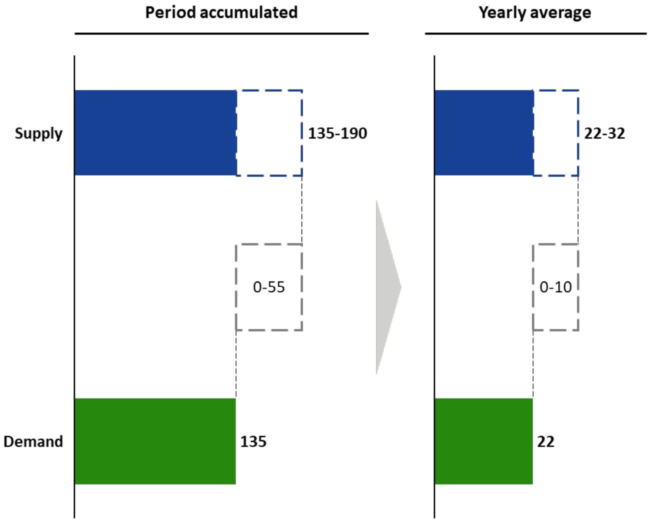
Europe will also increase its efforts to develop its capacity to manufacture other electrolysers currently under development, such as SOEC and AEM electrolysers. European companies are currently the leading AEM electrolyser manufacturers and are paving the way to scaling up production. Asian economies are lagging behind in this technology, but interest is expected to increase in this region as AEM reaches technological maturity and scale-up develops. The manufacturing capacity of these new types of electrolysers will foreseeably take off in the next 2-3 years and, therefore, they will have a larger potential share than currently projected.

The future electrolyser manufacturing capacity, based on announced expansions, is expected to multiply ~8 times, to reach a global production capacity of ~150 GW/year in 2030 (see Figure 7). As mentioned, the EU's share of electrolyser manufacturing capacity will be reduced slightly to ~20% which, depending on the source considered, would translate to 30-35 GW of annual European manufacturing capacity in 2030. It is worth mentioning the consolidation of the manufacturing of new technologies, such as SOEC and AEM electrolysers, even though they are expected to account for a small fraction of manufacturers' plans by 2030.

Production capacity is expected to increase with new expansion plans. There are two main companies (Siemens and Thyssenkrupp) pushing for the expansion of projects and scalability in Europe to account for ~8 GW/year of production capacity in 2030.

The demand for electrolysers noted by off-takers is expected to increase with new announcements and projects in the industry. In comparison to production capacity, the increase in this demand is not uniform. However, it is worth mentioning that in 2025 and 2030 there will be an important spike in demand as most projects are expected to start operating then (see Figure 9).

Figure 9 Accumulated and average yearly European electrolyser capacity supply/demand gap (GW/year; 2025-30)



Source: Industry experts; Specialised websites; Monitor Deloitte

As can be seen in Figure 9, the **expected average production capacity per year** for the period from 2025-2030 **is estimated to be 22-32 GW**, depending on the materialisation of possible manufacturing ramp-ups. It should be considered that this average has been estimated assuming a 100% capacity utilisation of manufacturing plants, which in real life is closer to 85% of utilisation, or 19-27 GW. **The demand is expected to average 22 GW/year** for the same period. It should also be considered that it has been assumed that the electrolysers used in the announced projects will be supplied by European manufacturers. In reality, the demand for European electrolysers will be 22 GW/year, plus the capacity of exported electrolysers, minus the capacity of electrolysers imported from third countries. Therefore, assuming perfect conditions, it can be concluded that the current development of stated plans and the anticipated demand for electrolysers for **2025-2030 will result in a significant overcapacity of 0-10 GW per year in Europe**.

All this implies that forthcoming plans to expand manufacturing capacity in Europe might face risks concerning the anticipated high production supply in the following years until 2030, unless Europe can achieve global competitiveness and transition into becoming an exporter of electrolysers to bridge the projected overcapacity. Achieving this hinges on attaining lower production costs compared to other regions, which depends to a large extent on the type of electrolyser developed. The cost and availability of CRMs has a significant influence on the electrolyser's price, alongside other factors such as market support and economic initiatives.

3.1.1.1. Proton Exchange Membrane (PEM) electrolyser

3.1.1.1.1. Supply chain description

PEM electrolysers stand at TRL 9 since the technology is well-developed with a significant market share. However, they still require extensive development to meet future hydrogen demand. Renewable hydrogen production through PEM electrolysis depends on more components than the electrolyser itself, including separators, dryers, and an electricity source.

The criticality assessment has been applied to every component (see Table 1). The result of the analysis, combined with information provided by industrial experts, indicates that the MEA subcomponents are essential.

Table 1 Criticality assessment of (sub)components of a PEM electrolyser

		PEM Electrolyser						
		Membrane Electrode Assembly (MEA)						
	(Sub) components	Electrolyte membrane	Cathode	Anode	Gas Diffusion Layer	Bipolar plates	End plates	Seal
Criteria	Cost	5	5	5	2	3	1	1
	Performance	5	5	5	3	2	2	3
	Technical development	5	5	5	3	3	1	1
	Results	Critical	Critical	Critical	Semi-critical	Semi-critical	Not critical	Not critical

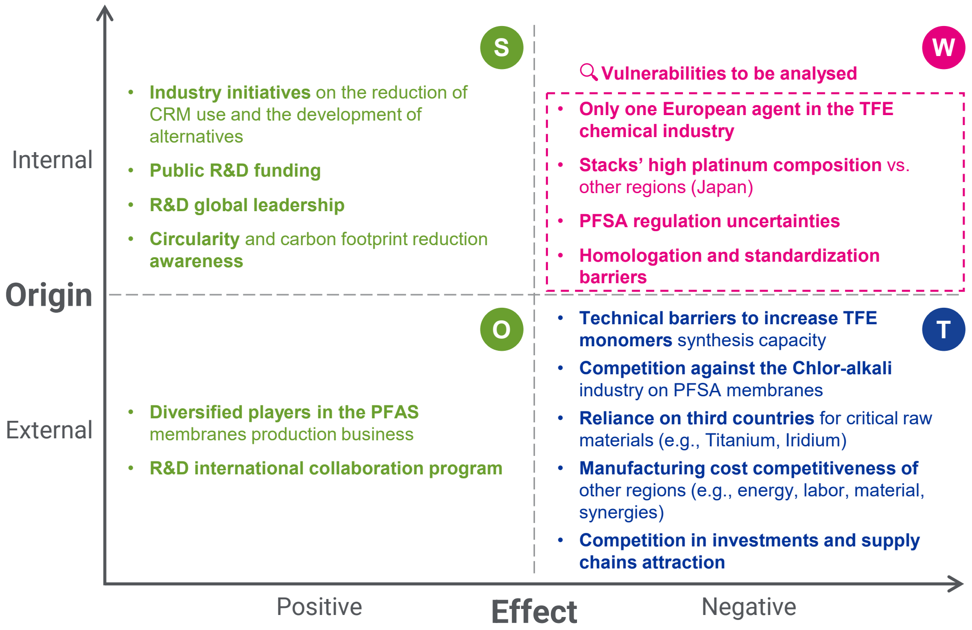
Source: SWECO; Industrial experts

3.1.1.1.2. SWOT analyses

The principal European opportunity relating to this technology lies in the diverse players in the PFAS membranes production business and the international R&D collaboration programmes. The players in the PFAS industry represent a chance to develop cost-efficient solutions due to the competitiveness of the market and avoid any possible supply chain issues regarding a critical component for the assembly of the final product.

There are also certain threats that could have a negative impact on the evolution of European PEM electrolysers, namely the reliance on materials from third countries or the competition vs. other sectors for obtaining investment and procuring subcomponents.

Figure 10 SWOT matrix of European capability factors for PEMEL



Source: Monitor Deloitte; Interviews with experts

The EU has the following strengths in R&D, innovation and sustainability awareness:

- **Industry initiatives on reducing the use of CRMs or developing alternatives.** The EU is aware of the barriers and dependencies that materials can create in the local industry. However, in line with the *EU Net-Zero Industry Act*, a proactive approach seems to have been taken in this respect, with investments being made to develop solutions to overcome any potential issues arising in the scale-up process.
- **Public R&D funding.** The EU is a leading research economy in clean technology development and implementation. It has many attractive programmes for the development of energy transition technologies, which represent one of the main levers for creating fair and sustainable growth. R&D schemes seem to have proven successful since the EU has been established as the global leader in patents.

- **Global R&D leadership.** Most of the net-zero technologies still require intensive research before they are commercially available and competitive but investing in their development is the first step toward independence regarding know-how and expected further export of proprietary technology. Historically, the EU has shown its strength in technological research and innovation, creating a hub of highly qualified domestic researchers. The challenge for the EU remains to turn this knowledge into industrial capabilities.
- **Awareness of circularity and carbon footprint reduction.** The scale-up of the manufacturing of net-zero technologies gives rise to environmental concerns. However, PEM industrial companies are working to implement environmentally sustainable processes. Sustainability and circularity policies are at the core of the EU's energy transition plans and regulatory packages. The awareness created and robust policies adopted are clearly an EU strength, making local industries develop sustainable solutions, and setting a global example by increasing the sustainability criteria to be met for imports.

Based on the SWOT analysis (see Figure 10), the vulnerabilities identified are due to regulatory barriers or uncertainties:

- **Only one European plant in the TFE chemical industry.** The high technical and economic barriers make it risky to relocate the TFE chemical industry to Europe and enable the success of the capacity expansion initiatives needed to satisfy current and expected needs for PEM electrolysers. The regulatory uncertainties regarding TFE use in PEM electrolyser manufacturing make the redirection of the chemical industry's investments or capacity expansion plans uncertain.
- **PFSA regulatory uncertainties.** There is concern among some European chemical industries regarding the uncertainties surrounding the use of PFAS, which include PFSA. A decision is being awaited from the EU on the essential uses of fluorinated components and whether they will be allowed in PEM manufacturing. There is also the risk that other regions will get ahead in capacity expansion or industry attraction measures by creating a favourable regulatory and economic environment, thereby establishing a dependency on third-country imports of PFSA membranes if their use for PEM electrolysers is still allowed. If fluorinated components used in PEM manufacturing were eventually banned, European industries would need to start working on a transitional scale-up phase for other feasible non-fluorinated based membranes, progressing from the research stage to mass manufacturing.
- **Homologation and standardisation barriers.** Some manufacturers complain that the time to market and approval of new products or (sub)components for their commercialisation is considerably higher in Europe than in other regions due strict regulations. This weakness will need to be analysed since Europe risks discouraging research by the industry players as well as the fact that they may redirect the commercialisation of their new products to other regions with fewer bureaucracy barriers.
- **Stacks' high platinum composition.** Asian manufacturers have achieved reduced platinum-based stacks which European manufacturers have not yet been able to achieve.

The evolution of these vulnerabilities has been assessed on the basis of two variables: importance of the sectors with shared supply chains and technical evolution.

- **Only one European plant in the TFE chemical industry.** The increasing importance of hydrogen technologies has disrupted this supply chain which will be stressed in the upcoming years. The regulatory restrictions on fluorinated components is a barrier to the development of new plants or capacity expansion plans. Additionally, many operational barriers are not expected to be solved either in the short or medium term and, therefore, the relocation of the industry to Europe or capacity increases do not seem to be feasible options. All in all, this weakness is expected to increase in the short term given that alternative non fluorinated membranes still remain under research and are not widely commercialised.
- **PFSA regulatory uncertainties.** The competition with other industries is expected to stabilise or even increase in the coming years given the importance of Chlor-alkali products for the chemical industry **[39]**. Indeed, other technically viable alternatives also compete with other critical sectors. Technical development of other types of chemical-based membranes to substitute the currently used PFSA are now under research, but there are still technical barriers to overcome. Therefore, this vulnerability will likely increase in the coming years as PEM electrolysers relying on PFAS membranes are being installed.
- **Homologation and standardisation barriers.** Competition for industry and knowledge attraction is expected to increase in the coming years given the trend towards protectionism in the strategic supply chains. Countries capable of developing and commercialising new improvements in short lead times will naturally attract industry developers and researchers. PEM technology and its associated (sub)components are expected to undergo considerable technical development. Europe can leverage on

being one of the global leaders in electrolysis R&D to commercialise these innovations. The evolution of this weakness is unknown and depends on Europe's future capacity to retain talent and commercialise new discoveries.

- **Stacks' high platinum composition.** Europe's high dependency on platinum-based components such as stacks is exerting stress on the technology supply chain. Currently, with the difference in expertise between Europe and Asian countries, this dependency has become even more evident due to less developed PEM technology compared to these other countries. This dependency is expected to decrease due to new discoveries regarding the technology. However, it should also be considered that if the development of the technology is not sufficient, the supply chain will become more stressed as Europe will become more and more dependent on imports from third countries for other PEM components as well.

3.1.1.1.3. Sustainability and circularity

Based on the sustainability assessment (see Table 2) the PEM electrolysis technology demonstrates the highest scores in the categories of "Biodiversity and environment" and "Material use and recyclability". These findings suggest a greater likelihood of negative impacts associated with these factors. The impacts are mostly associated with the use of materials classified as PFAS and the dependency of renewable energy and PGM, since hydrogen will be as "renewable" as the energy employed to produce it (see Section 2.5).

Table 2 Sustainability assessment of PEM electrolysers

Biodiversity and Environment	• High water consumption, potentially detrimental to biodiversity and environment if deployed in water-scarce regions. • Dependency on PFAS-based membranes. • Production process contributes to air pollution if electricity is not from renewable sources.
Health and safety	• Use of PFAS. While not a threat to health or safety once configured into the electrolyser membrane, the production stage of the fluorinated polymer can be complex and hazardous. • The production, storage, and handling of hydrogen poses potential explosion and fire risks.
Material use and recyclability	• Use of materials classified as PFAS. • Use and dependency on materials classified as CRMs (e.g., PGM catalysts). • Underdeveloped recyclability procedures, particularly for key parts like membrane or CRMs.
Robustness and flexibility	• Requires deionised water, which consequently needs water purification technology. • High maintenance requirements to maintain system performance and longevity.
Energy intensity and efficiency	• Operation of the stack generates a hydrogen output at approximately 50 bars, this requires a lot of energy to compress for storage and some end uses (250-700 bars). • Potential energy losses during the conversion process of electricity to hydrogen.

3.1.1.1.4. Conclusions on PEM electrolysers

PEM electrolysers are expected to cover a high percentage of future European hydrogen production. Although a bit less efficient than alkaline, PEM offers several advantages: lower operation temperatures, higher current densities and output hydrogen pressure, the use of a solid electrolyte, a more compact design, and the possibility of intermittent operation. The latter makes it a perfect option for hydrogen production from renewable sources such as solar and wind power, which generate energy intermittently. The compactness also makes PEM more suitable for transport applications.

MEA is considered to be critical, particularly due to the use of precious metals (PGM catalyst). Iridium, platinum and titanium are used as benchmarks due to their catalytic activity and chemical, thermal, and mechanical stability. All of which are key characteristics due to the harsh conditions and acidic environment within the cell, causing material corrosion. The choice of material has a severe impact on performance and lifetime.

The main strategic challenges within the PEM electrolyser supply chain continue to be the regulatory uncertainties concerning fluorinated chemicals needed in membrane manufacturing and the equipment homologation requirements with significantly higher time to market than in other regions.

Finally, the sustainability assessment reveals the categories of "Biodiversity and environment" and "Material use and recyclability" (e.g., dependency on CRMs such as PGM catalysts) to have a greater likelihood of negative impacts.

3.1.1.2. Alkaline (ALK) electrolyser

3.1.1.2.1. Supply chain description

Alkaline electrolysers and the other types of electrolysers depend on supporting technology known as Balance of Plant (BoP), such as compressors, storage tanks, heat exchangers, separation systems, and others.

According to the (sub)components identified and the criticality assessment based on information provided by industrial experts, the MEA components are considered the most critical when compared to the other parts. In comparison to other technologies, they are all categorised as "semi-critical" (see Table 3):

Table 3 Criticality assessment of (sub)component of an alkaline electrolyser

	Alkaline Electrolyser								
		Membrane Electrode Assembly (MEA)							
	(Sub) components	Membrane (Diaphragm)	Cathode	Anode	Electro -lytes	Gas diffusion layers	Bipolar plates	Seal	End plates
Criteria	**Cost**	3	3	3	2	2	2	2	2
	Performance	4	4	4	3	3	2	1	1
	Technical development	3	3	3	2	2	1	1	1
	Results	**Semi-critical**	**Semi-critical**	**Semi-critical**	**Not critical**	**Not critical**	**Not critical**	**Not critical**	**Not critical**

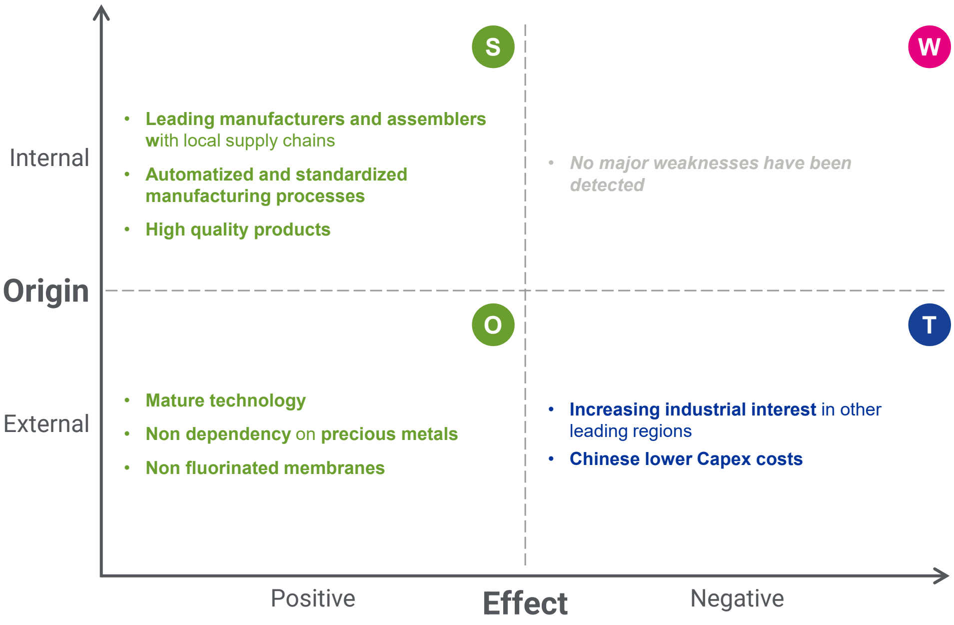
Source: SWECO; Industrial experts

3.1.1.2.2. SWOT analyses

The main European opportunity relating to this technology consists of its high degree of maturity, its lack of dependence on precious metals and the use of non-fluorinated membranes.

Structuring capability factors in a SWOT framework shows the main threats posed by the competition in other economies on the attraction of investment and the reduction of manufacturing costs. Whereas Europe has traditionally focused on technological development and R&D activities, China has leveraged its competitive advantages (e.g., manufacturing capabilities, availability of suppliers, labour) to deliver commercial cost-competitive products. Even though the global market penetration of Chinese alkaline electrolysers is currently low, they could eventually replace European local demand for electrolysers.

Figure 11 SWOT matrix on European ALKEL capability factors



- **Leading manufacturers and assemblers** with local supply chains
- **Automatized and standardized manufacturing processes**
- **High quality products**

- *No major weaknesses have been detected*

- **Mature technology**
- **Non dependency** on **precious metals**
- **Non fluorinated membranes**

- **Increasing industrial interest** in other leading regions
- **Chinese lower Capex costs**

Source: Monitor Deloitte; Interviews with experts

European strengths can be classified into two areas: knowledge leadership and manufacturing reliability:

- **Leading manufacturers and assemblers with local supply chains.** Key players have been identified within the ALK electrolyser EU market that have well-established local supply chains but also export their electrolysers and subcomponents to foreign customers. Within the alkaline electrolyser supply chain, no critical dependence on third countries has been detected, other than certain concerns regarding nickel supply due to its strategic role in the production of many clean technologies.
- **Automated and standardised manufacturing processes.** EU manufacturers have professionalised mass manufacturing capacity, with a trend toward automation and standardisation of assembly lines, enabling them to expand their production capacities. This strength demonstrates that European industry is capable of effectively scaling up knowledge of mature alkaline technology into commercial electrolysers.
- **High-quality products.** European alkaline electrolyser manufacturers are known for their reliability, customer service and convenient O&M. European manufacturers could leverage this strength to establish a value proposition based on high-quality products.

The European alkaline technologies supply chain does not present major bottlenecks apart from the complex regulatory environment and bureaucracy. Even though it is not a “weakness”, it is important to **stress the threat that China poses to the European manufacturing supply chain.** China has several competitive advantages (e.g., strong subsidies programmes, low manufacturing costs, etc.) that result in a **final product with very low CAPEX in comparison to European products** [40]. China is expected to become the market leader in alkaline technologies; however, it still needs to address certain concerns (e.g., reduced safety, the need for improved post-selling services or an increase in R&D) to become the undisputed global leader.

No remarkable European supply chain vulnerabilities regarding alkaline electrolysers have been detected. It is a mature technology, with defined local manufacturing and supply chain processes. The only threat is Chinese cost competitiveness, which will remain strong in the coming years. Europe will have to reduce its production costs to be able to face this threat and not risk losing market dominance.

3.1.1.2.3. Sustainability and circularity

The sustainability assessment shows that ALK electrolysis technology has the highest score in "Biodiversity and Environment" (see Table 4), meaning negative impacts associated with these factors are more likely to occur.

Table 4 Sustainability assessment of alkaline electrolysers

Biodiversity and Environment	• High water consumption, potentially detrimental to biodiversity and environment if deployed in water-scarce regions. • Use of KOH and other caustic compounds that could change pH of local bodies of water. • Production process contributes to air pollution if electricity is not from renewable sources. • Use of PFAS in the membranes for KOH production in the chloralkaline industry as well as in the material used for sealings and gaskets (e.g., Teflon).
Health and safety	• The KOH required in the electrolyte solution is classified as harmful and corrosive in safety data sheets, housing it on site will require additional safety measures. • The production, storage, and handling of hydrogen poses potential explosion and fire risks. • Use of PFAS in the membranes for KOH production in the chloralkaline industry and also potentially in the material of the gaskets.
Material use and recyclability	• Though components seem recyclable to a certain extent, the companies have not shown any established pathways for component recycling. • Use of materials classified as CRMs, e.g., nickel and iridium (for production of KOH). • Use of materials classified as PFAS in the supply chain of the electrolyte.
Robustness and flexibility	• Requires deionised water, which requires water purification technology. • While dynamic, it is recommended for applications in industrial sites with a stable load. • The BoP must be adapted to handle an alkaline solution, due to corrosion concerns.
Energy intensity and efficiency	• Operation of the stack generates hydrogen output at approximately 30 bars, this requires a lot of energy (250-700 bars) to compress for storage and some end uses. • Potential energy losses during the conversion of electricity to hydrogen.

3.1.1.2.4. Conclusions on alkaline electrolysers

Alkaline electrolysers are expected to cover a significant percentage of future hydrogen production in the coming years, as they are slightly more efficient and, therefore, have a larger global presence than PEM electrolysers (65% of market in 2030 [41]) due to the level of maturity of the technology and the use of cheaper components.

The alkaline electrolyser's MEA is considered to be a semi-critical component due to the use of cheaper metals but is the most critical component for this technology. The maturity of the technology seems to have peaked, with no major advances in the last few years, resulting in a low criticality score.

However, even though technical barriers are not a major issue for alkaline electrolysers, there are still some concerns over the technology as the number of R&D programmes launched with a focus on alkaline improvements has declined over the years. Additionally, China poses a great threat in the market due to its cost competitiveness which, based on several publications by confirmed sources (IEA), threatens to push Europe out of the market, leaving China in a monopoly-like position with over 50% of the global share due to its faster lead times and greater cost competitiveness, with prices that may reach ~370 €/kW (vs. 600 €/kW for Europe). [37] [40]

Finally, the sustainability assessment shows that "Biodiversity and environment" is the category with the greatest likelihood of producing negative impacts.

3.1.1.3. Solid Oxide (SOEC) electrolyser

3.1.1.3.1. Supply chain description

SOEC electrolysers differ from other electrolysis technologies since they operate at a much higher temperature range of between 700-850°C. Most of the energy required to produce the hydrogen is obtained in the form of heat, reducing the electric input that the electrolysis needs. Their working principle makes them less dynamic than PEM or alkaline electrolysers, and they also have a relatively larger carbon footprint. On the other hand, they are an ideal option for continuous stationary applications and in combination with processes that can act as the heat source. The integration of a SOEC within a process requires additional equipment for the balance of plant. The scope of the study limits the analysis to the cell stack that composes the SOEC, regardless of application, and filters out any complementary technology necessary for implementation.

According to the criticality criteria and the information provided by industrial experts, the assessment classified the electrolyte, electrodes, and interconnectors as being critical. The sealings are also important (see Table 5).

Table 5 Criticality assessment of SOEC components

Solid Oxide Electrolyser Cell (SOEC)							
	(Sub) components	**Electrolyte**	**Cathode**	**Anode**	**Interconnectors**	**Sealing & frames**	**End-plates**
Criteria	**Cost**	3	4	3	3	3	1
	Performance	5	5	5	5	3	1
	Technical development	5	5	5	5	4	1
Results		Critical	Critical	Critical	Critical	Semi-critical	Not critical

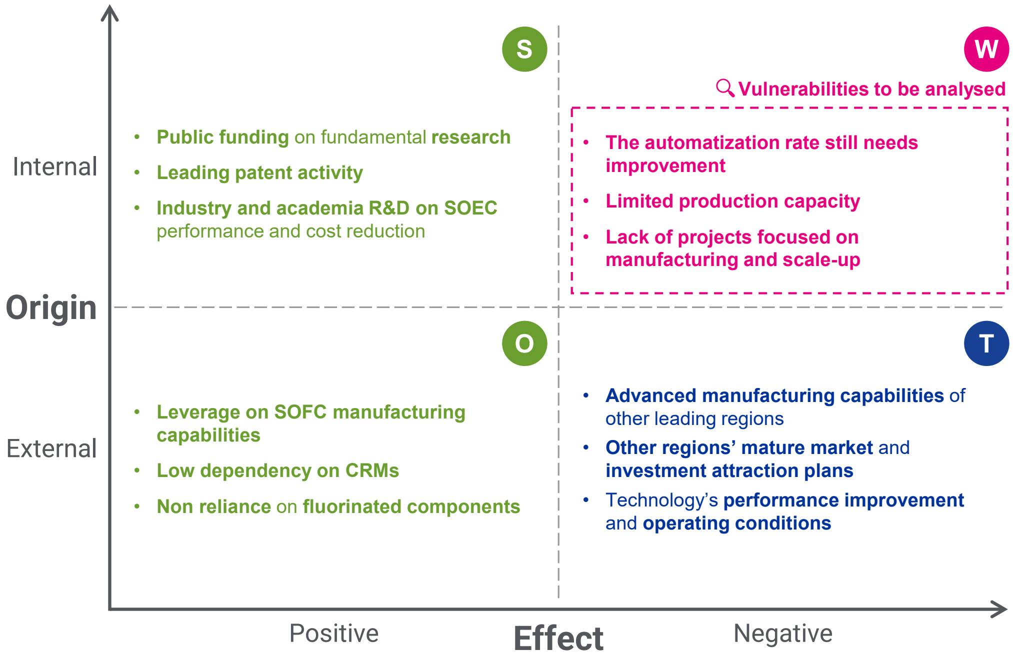
Source: SWECO; Industrial experts

3.1.1.3.2. SWOT analyses

European competitiveness was analysed using a SWOT matrix framework (Figure 12) showing that the main opportunities relating to this technology lie in its non-reliance on fluorinated components. The SOEC technology is not reliable on CRMs in general either, but the cathode catalyst in particular does rely on CRMs (e.g., yttrium, nickel) and it currently has the highest cost share, at ~20%, in SOEC manufacturing. Additionally, the manufacturing capacity and industrial knowledge relating to solid oxide fuel cells could be an opportunity to boost domestic production and reverse application as electrolysers.

On the one hand, the threats lie in the technology itself, such as its integration in real industrial environments, and in degradation concerns related to high operating temperatures. On the other hand, the maturity of other markets (e.g.,, the US), with higher manufacturing capacity and capabilities to attract investment, is a concerning threat that could potentially displace European leadership in SOEC technology.

Figure 12 SWOT matrix on SOEC European capability factors



Source: Monitor Deloitte; Interviews with experts

European competitiveness is still based on R&D initiatives, high patent activity and public economic support:

- **Public funding for fundamental research.** There have been many public initiatives with special focus on fundamental research into SOEC technology. Experts raised the importance that these public aid facilities have played in the positioning of Europe as a global leader in high temperature electrolyser knowledge. Manufacturers also acknowledged the need to extend this funding, especially in relation to the scale-up of industrial manufacturing, to prevent production bottlenecks once demand increases as more commercial and cost competitive products are developed.
- **Leading patent activity.** Research entities and industrial players are allocating resources to SOEC technological and commercial product development. The challenge is still to turn knowledge into mass cost competitive products and maintain leadership in the face of the growing US presence.
- **Industrial and academic R&D on SOEC performance and cost reduction.** SOEC technology still faces many technical challenges related to real industry process integration and cost competitiveness. Research entities have been acknowledged to be collaborating with industry in technical performance improvements. EU manufacturers are working towards the development of electrolysers in terms of the scale of MW to be installed in real industrial environments, leveraging on Europe's leading knowledge capabilities.

The weaknesses detected in European SOEC technology relate to the scale-up of the European industry's manufacturing capacity. Some industrial experts project a potential bottleneck in manufacturing, and the possibility of relocation to other regions, once the technology reaches full technological maturity and demand increases, especially from industrial players looking to decarbonise their activities (see Figure 12):

- **The automatisation rate still needs improvement.** As there are very few commercial products and demand volumes are low, European manufacturers have not yet faced any serious manufacturing bottlenecks. Nonetheless, manufacturers highlight the long training periods and manual manufacturing processes of the domestic suppliers on which they rely. Manufacturing training and quality assurance are challenges now faced by SOEC manufacturers. The SOEC industry should continue making strides to improve its automatisation and certain companies are already making efforts in this direction [42].
- **Limited production capacity.** This vulnerability represents a potential bottleneck in the future when demand scales up and manufacturing capabilities have not been adapted correspondingly. Currently, there are few EU manufacturers and increasing competition to attract investment, especially in the US market, where industrial and manufacturing capabilities are more mature, resulting in scale differences of SOEC products.

- **Lack of projects focused on manufacturing and scale-up.** Apart from potential future bottlenecks, a current issue is that SOEC projects are not focused on manufacturing but rather on the research into and performance optimisation of materials and components. This results in a lack of competition with major global manufacturing suppliers. Some EU companies are making sustained efforts to expand their manufacturing capacity [43], but the industry in general lacks more focus on projects aimed at scaling up.

The evolution of vulnerabilities based on technological changes and the importance of other industries shows that the low automation rate vulnerability will increase, whereas limited production capacity evolution is unknown:

- **The automatisation rate still needs improvement.** The mass production and assembly of SOEC subcomponents will require European industrial players to have higher automatisation rates. Not only will automatisation be needed to satisfy domestic SOEC demand but also to reduce manufacturing costs and achieve high-quality products. This vulnerability is expected to increase due to the high barriers found in the automatisation of the industry in the short term due to the learning curve required by European suppliers, and competition with other industries for the knowledge and resources required for the automatisation of industrial processes.
- **Limited production capacity.** A high level of technological evolution is expected in SOEC technology which will result in the standardisation of SOEC manufacturing processes and operational characteristics. Nonetheless, competition for the attraction or retention of manufacturing and industrial processes will play a major role in the coming years. The development of this vulnerability is unknown and depends on EU players' abilities to support the scale-up of industrial capabilities and on the development of a well-established domestic demand through the definition of SOEC applications.
- **Lack of projects focused on manufacturing and scale-up.** As SOEC technology increases its market size in Europe, new initiatives towards the scale-up of facilities should be incentivised. However, this vulnerability is unknown as it is highly dependent on the development of a well-established domestic demand through the definition of SOEC applications.

3.1.1.3.3. Sustainability and circularity

The SOEC technology faces challenges primarily in terms of "Robustness and Flexibility" (see Table 6). These challenges stem from the robustness of the concept design of these types of cells and the lack of equipment flexibility. Regarding the latter, interviews confirm that its size and start-up times make it perfect for continuous operation in industrial sites. However, this is also limiting it, since it cannot be turned on/off according to renewable energy dynamic behaviour and it requires a large input of thermal energy.

Table 6 Sustainability assessment of solid oxide electrolysers

Biodiversity and Environment	• High water consumption, potentially detrimental to biodiversity and environment if deployed in water-scarce regions. • Production process contributes to air pollution if electricity is not from renewable sources.
Health and safety	• High operating temperatures may pose safety risks during operation and maintenance. Risk of thermal burns during direct interaction with the system. • The production, storage, and handling of hydrogen poses potential explosion and fire risks.
Material use and recyclability	• Use of materials classified as CRMs, e.g., Nickel, Lanthanum. • Though components seem recyclable to a degree (at small scale), no established pathways for component recycling have been demonstrated by companies at industrial levels. • Interviews state that the available techniques for recycling do not present a viable business case against sourcing new materials due to the complexity and high cost of the process.
Robustness and flexibility	• Requires deionised water, which implies the necessity of water purification technology. • The technology can adapt to varying loads, aligning with dynamic patterns of renewable energy sources to a significant extent, and can swiftly transition between fuel cell/electrolyser operational modes if equipment is maintained hot, and BoP is appropriately configured. • High operating temperatures reduce lifespan of components, increasing maintenance requirements. At current TRL the durability of interconnectors to sustain heating cycles is low. • The technology is underdeveloped, although close to commercialisation in short-mid term, and still unreliable for industrial applications. Durability of the interconnectors is main issue.
Energy intensity and efficiency	• Operation of the stack generates a hydrogen output at approximately atmospheric pressure, requiring a lot of energy to compress for storage and end uses (250-700 bars). • Potential energy losses during the conversion process of electricity to hydrogen.

3.1.1.3.4. Conclusions on Solid Oxide electrolysers

SOEC electrolysers differ from the other types of electrolysers in that in the coming years they will not have a large presence since ALK and PEM electrolysers will dominate the global picture (3% vs. 97%) due to the early stage of deployment of SOEC (TRL 7-8).

There are still several major strategic challenges in the Solid Oxide electrolyser supply chain that need to be solved before the regular use of the technology. SOEC is still a costly technology due to the current level of automation rate of the supply chain process, an issue that is being tackled. Besides, manufacturers still have limited production capacity, limiting the potential scale-up of demand and potentially causing bottlenecks.

Finally, SOEC faces challenges in "Robustness and flexibility" due to the robustness of the cell concept design and the equipment’s lack of flexibility.

3.1.1.4. Anion Exchange Membrane (AEM) electrolysers

3.1.1.4.1. Supply chain description

AEM is one of the newest technologies in the field of electrolysers which blends the concepts of the PEM and alkaline electrolysers. As with any electrolyser, it cannot act on its own and therefore the balance of the plant is adapted to the choice of technology. As can be seen in the summarised information, other hydrogen technologies come into play in the plant design. However, the scope of this case study is limited to the AEM electrolyser stack.

The criticality assessment of the identified components based on information by industrial experts leads to the same result as for PEM electrolysers, which makes sense considering that all the components have similar functions. The results point to the membrane and both electrodes as the critical components (see Table 7). The gas diffusion layers and bipolar plates are semi-critical, but still important, especially in terms of technical developments since they can be integrated and used to support and boost the catalyst.

Table 7 Criticality assessment of (sub)components of an AEM electrolyser

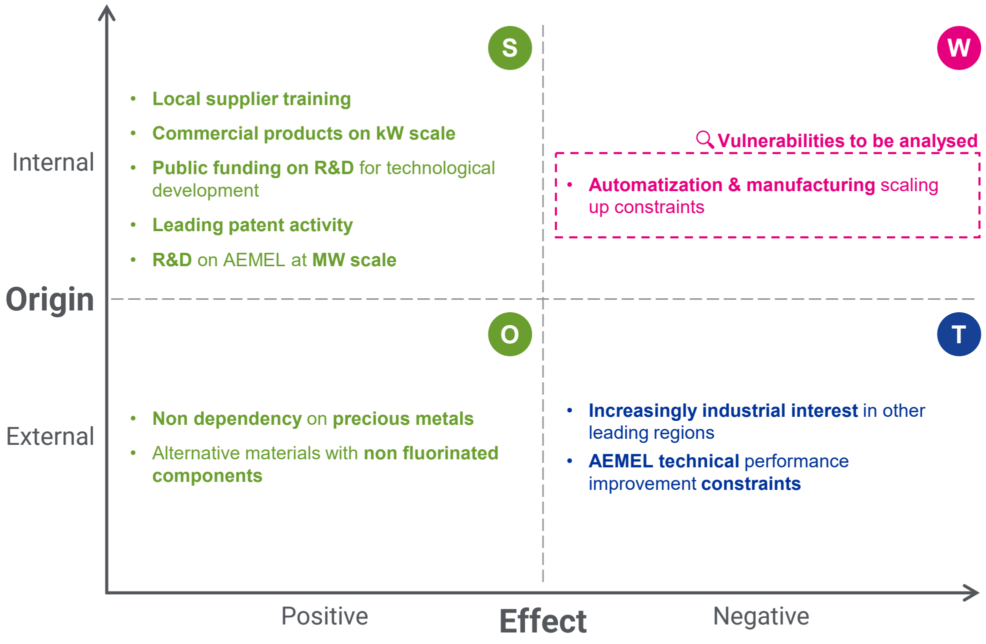
		AEM Electrolyser						
	(Sub) components	Membrane Electrode Assembly (MEA)				Bipolar plates	End plates	Seal
		Electrolyte membrane	Cathode	Anode	Gas Diffusion Layer			
Criteria	**Cost**	3	3	2	2	3	1	1
	Performance	5	5	5	3	2	2	3
	Technical development	5	5	5	4	4	1	1
	Results	**Critical**	**Critical**	**Critical**	**Semi-critical**	**Semi-critical**	**Not critical**	**Not critical**

Source: SWECO; Industrial experts

3.1.1.4.2. SWOT analyses

The opportunities relating to AEM electrolysers lie in their non-reliance on precious metals and fluorinated components. The threats relate to the uncertainty concerning the technical performance of AEM technology and the increasing interest from other leading economies, which could potentially attract investment and concentrate the manufacturing capacity by leveraging their industrial competitiveness (e.g., automation, local suppliers, lower labour and energy costs, etc.).

Figure 13 SWOT matrix on AEMEL European capability factors



Source: Monitor Deloitte; Interviews with experts

Europe's strengths lie in its R&D activity and capacity to turn knowledge into an operational commercial product:

- **Training of local suppliers.** European manufacturers recognise the availability of local manufacturers and suppliers that are capable of learning to produce the required (sub)components with the features demanded. The *EU Net-Zero Industry Act* highlighted the importance of developing domestic supply chains and training local suppliers, raising the issue of the need to reduce dependencies on third economies that could lead to bottlenecks in the manufacturing of new technologies.
- **Commercial products on kW scale.** Europe has leading players that can deliver commercial electrolysers with low capacity on the kW scale that are suitable for distributed generation to end consumers (e.g., housing applications, refuelling stations). For example, Enapter offers 2.4kW electrolysers and a 1MW modular system made up of 420 AEM stack cores. Sunfire (DE) is currently researching the development of an industrial scale electrolyser. European manufacturers can leverage their current knowledge and manufacturing capabilities to increase electrolyser size for large-scale applications (i.e. in industry).
- **Public funding for R&D on AEM electrolyser technological development.** The Horizon 2020 and Horizon Europe research programmes, the EU-funded projects with a specific focus on AEM electrolyser development, included participation from research institutions and academia, as well as industry and manufacturers. There were requests and interest from funded projects in electrolyser installations using mature technologies, such as PEM and alkaline, to include a pilot AEM electrolyser (with kW capacity) to test its performance in a real-world environment.

Europe can leverage the synergies between academia and industry to continue developing solutions and testing to overcome durability and technical constraints (see Figure 13):

- **Leading patent activity.** Europe has leading players in AEM manufacturing (e.g., Enapter), with industrial R&D activity and product development being the European industry's main strengths.
- **R&D on AEMEL at MW scale.** European electrolyser manufacturers have recently shown increasing interest in entering the AEM business. A great deal of the industry's efforts are aimed at developing AEM electrolysers at MW scale, suitable for large-scale applications, such as in industry or grid balancing. The R&D initiatives' focus on extrapolating knowledge and manufacturing capabilities of mature electrolyser technologies to AEM development has shaped the roadmap of the leading European electrolyser manufacturers seeking to achieve a commercial product based on their expertise in PEM and ALK.

Interest in hydrogen has increased steadily in recent years and so have AEM electrolysers that are aimed at improving technological performance and reducing manufacturing costs given their potential lack of dependency on PGM metals. Europe could take the lead in the manufacturing of this electrolyser, with no dependency on third country materials or imports [44], by leveraging its capacity to turn knowledge into viable commercial products. Nevertheless, Europe has weaknesses or vulnerabilities concerning manufacturing scale-up capabilities:

- **Automatisation and manufacturing scale-up constraints.** Although there is capacity to train local European suppliers on building domestic supply chains, there is an industry concern regarding manufacturing scale-up capabilities given that most of the processes are still rather manual.

The evolution of the vulnerability described has been assessed based on a two-pronged framework considering the importance of other regions/sectors and the forecast development of the technology.

- **Automatisation and manufacturing scale-up constraints.** This vulnerability is expected to increase in the coming years due to the low automation rate and steep learning curve for local EU suppliers regarding the manufacturing of novel AEM electrolysers. There are many mature industries and processes demanding automation equipment which could detract from the attention required by the AEM industry.

3.1.1.4.3. Sustainability and circularity

The sustainability assessment of the AEM electrolyser yields the same scores as the ALK technology (see Section 3.1.1.2.3) due to shared building materials and electrolytes resulting in similar issues (see Table 8). Therefore, AEM technology also shows the largest potential for negative impacts in the “Biodiversity and Environment” category. This is influenced by using PFAS in the production of the electrolyte, which usually consists of a KOH solution. The production of PFAS involves the use of non-recyclable membranes that contain PGM catalysts, similar to those used in PEM.

Nevertheless, the main difference between AEM and ALK technologies lies in their flexibility. AEM electrolysers are projected to be more compact and dynamic, like PEM. Consequently, AEM technology is expected to score better than ALK in the "Robustness and flexibility" category. However, AEM electrolysers are still at a low TRL and face durability challenges, which ultimately makes their scores equal.

Table 8 Sustainability assessment of AEM electrolysers

Biodiversity and Environment	• High water consumption, potentially detrimental to biodiversity and environment if deployed in water-scarce regions. • Use of KOH and similar compounds can modify pH of local water bodies if leaked. • Production process contributes to air pollution if electricity is not from renewable sources. • Use of PFAS in the membranes for KOH production in the chloralkaline industry and in the material of the sealings and gaskets (e.g., Teflon).
Health and safety	• KOH needed in the electrolyte solution is classified as harmful and corrosive in safety data sheets, housing it on site will require added safety measures. • The production, storage, and handling of hydrogen poses potential explosion and fire risks. • Use of PFAS in the membranes for KOH production in the chloralkaline industry and in the material of the sealings and gaskets (e.g., Teflon).
Material use and recyclability	• Material recycling at end of life must be confirmed and requires attention at high TRLs. • Use of materials classified as CRMs such as Nickel and iridium to produce KOH. • Use of materials classified as PFAS in the supply chain of the electrolyte.
Robustness and flexibility	• Requires deionised water, which implies the necessity of water purification technology. • The BoP needs to be adapted to be able to handle an alkaline solution, due to corrosion. • Technology is underdeveloped, with a low TRL, and still unreliable for industrial applications. Durability of the membrane has been highlighted as one of the main issues.
Energy intensity and efficiency	• Operation of the stack generates a hydrogen output up to approximately 30 bars, this requires a lot of energy to compress for storage and some end uses (250-700 bars). • Potential energy losses during the conversion process of electricity to hydrogen.

3.1.1.4.4. Conclusions on AEM electrolysers

AEM electrolysers are one of the newest technologies in the hydrogen production industry with almost no presence in the electrolyser market.

This new technology offers several advantages when compared to its peers: it is relatively cheap, it produces a highly pure hydrogen, its production cycle is fully scalable, and the response time is very competitive. However, it still has a low degree of maturity, making it less efficient (technically and economically) than the other electrolysers in the market (ALK, PEM, SOEC). Besides, the AEM electrolyser supply chain has weaknesses regarding certain other capabilities such as the lack of automation of some processes in the industry (many are still manual).

Moreover, the sustainability assessment reveals that "Biodiversity and environment" is the category with greatest likelihood of producing negative impacts influenced by using PFAS.

In conclusion, AEM electrolysers offer a series of advantages, but the technology still lacks sufficient maturity to compete with the leading and more mature competitors in the market.

3.1.2. Waste to hydrogen

3.1.2.1. Gasification

3.1.2.1.1. Supply chain description

This section aims to cover the production of hydrogen using waste materials as feedstock. Different types of waste fractions can be reprocessed into energy carriers through a wide variety of techniques. The primary focus lies on biomass gasification with organic waste - comprising biomass (forest residues), food waste (municipal waste), animal by-products (oils), etc. - given the abundance and carbon footprint of organic materials among waste resources.

The pathways to generate hydrogen from an organic waste source are three: electrochemical, biological, and thermochemical. Amongst these solutions, the latter has gained more relevance as it is more cost-effective, offers different schemes to adapt to the organic waste feed and has the highest TRL [45] [46]. Within the thermochemical routes, two main processes exist: gasification (conversion of organic waste materials from a solid state to a gas product through thermal treatment in the presence of an oxidising agent) and pyrolysis (thermal decomposition of organic waste materials in the absence of oxygen).

Although both gasification and pyrolysis perform similarly [47], there is a global trend towards gasification [46]. Organic waste gasification is more relevant as the subprocesses in the conversion route are existing industrial processes with high maturity and efficiency, which makes this process closer to commercial readiness, and the actual production of the projects in development has reached larger scale levels.

The criticality assessment based on information by industrial experts (see Table 9) identifies the gasification stage as critical, including both the reactor and catalyst, as they are key to the overall performance of the process. Although to a lower degree, the hydrogen maximisation and purification sections are also of importance since they influence the hydrogen yield and purity, the latter being particularly important for certain applications.

Table 9 Criticality assessment of the organic waste gasification process

		Organic waste gasification						
	(Sub)Components	Pre-treatment	Gasification		Syngas purification	Hydrogen maximization	Hydrogen purification	BoP
			Reactor	Catalyst				
Criteria	Cost	1	4	2	2	3	3	1
	Performance	2	5	5	3	3	4	1
	Technical development	1	5	5	2	2	3	1
	Results	Not critical	Critical	Critical	Not critical	Semi-critical	Semi-critical	Not critical

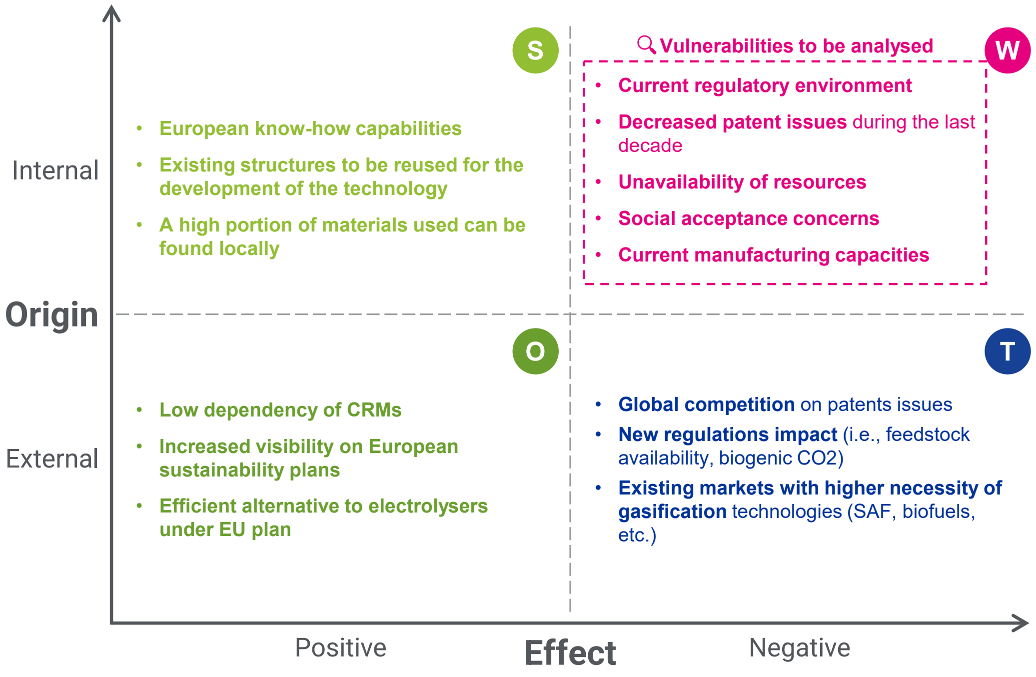
Source: SWECO; Industrial experts

3.1.2.1.2. SWOT analyses

European competitiveness was analysed using a SWOT matrix framework (Figure 14) which showed that the main opportunities relating to this technology in Europe lie in the fact that there is no reliance on CRMs for the equipment used in the production of hydrogen. There has also been a recent increase in the visibility of the technology as an alternative to decarbonisation in European sustainability plans. Depending on its evolution, the technology has the possibility of gaining a major presence and establishing itself as an alternative to other major renewable energy sources or other hydrogen production technologies such as electrolysers.

However, there are certain associated threats that could have a negative impact on the evolution of European Waste to Hydrogen technologies. There is significant global competition in patents issuance where the US leads the market with ~35% of total patents issued. Europe is not far behind, but with new funding schemes released in the US (IRA), the difference is set to become even larger. In addition, the uncertainty over the issuance of new regulations regarding the categorisation of biogenic CO_2 or renewable feedstocks are major threats to the development of this technology. There is also significant competition for the use of gasification technologies from other markets (e.g., SAF, biofuels) that have no alternative technologies for production.

Figure 14 SWOT matrix on Waste to Hydrogen European capability factors



Source: Monitor Deloitte; Interviews with experts

European competitiveness in the Waste to Hydrogen technologies supply chain depends on the strengths derived from the know-how achieved, the technology's existing structures, and the local supply of materials:

- **European know-how capabilities.** Europe has been using these technologies for decades, which has resulted in manufacturers and researchers obtaining unique advanced know-how on Waste to Hydrogen technologies in comparison to other regions.
- **Existing structures to be reused for the development of the technology.** Europe is a region with high expertise in the chemical/refinery industries. Waste to Hydrogen reuses much of the equipment used in these industries (i.e., gasification), providing a good base from which to continue evolving.
- **A high portion of materials used can be found locally.** The materials needed for this technology can generally be found in Europe with local suppliers available in the market.

Additionally, several weaknesses have been detected with respect to Waste to Hydrogen technologies (see Figure 14):

- **Decreased patent issues during the last decade.** There has been an alarming decrease in the issuance of new patents for Waste to Hydrogen technologies. If the trend is not reversed, innovation for these technologies will remain stagnant in comparison to others such as electrolysers, and the industry will not obtain the attention required to develop an optimal alternative for hydrogen production.
- **Unavailability of resources.** The development of this technology in Europe must also take into consideration the operating costs associated with the region. Although electricity consumption is significantly lower than in other technologies (i.e., electrolysers), there are other resources such as water and steam which are less available in the European region that may result in higher operating costs.
- **Barriers to develop plants:**
  - The current regulatory environment is not completely stable and clarified as the feedstocks used are difficult to categorise into organic/non-organic origins resulting in secondary concerns regarding financial capabilities and the criteria applicable to each technology.

  - The absence of manufacturing facilities presents a significant challenge in the research and development of the technology necessary to attain optimal equipment specifications.
  - There is a generalised societal concern in the agricultural sector regarding the obtention of the feedstock used in the process. If biomass collection is too intensive, the agricultural sector could be adversely affected as it would have insufficient biomass to use as fertilizer. Europe is not a region with extensive agricultural land in contrast to other regions such as China and, therefore, it is crucial to achieve optimal biomass collection to satisfy all the agricultural sector's needs.

The projected evolution of the vulnerabilities described was evaluated using a two-pronged framework considering the importance of other regions and sectors and the forecast development of the technology.

- **Decreased patent issues.** Latest trends suggest that there are no major advances being made in the issuance of new patents which means that this weakness is expected to increase in the short term. Continuing research on this technology and its translation into commercial products might help Europe achieve innovative products which overcome current technical limitations. This will mitigate the competition with other regions' product offerings and help maintain Europe's industrial significance and independence.
- **Unavailability of resources.** This vulnerability should not represent a major concern in the development of the technology; however, it is not expected to decrease in the long term due to the unavailability of certain resources in Europe in comparison to other regions.
- **Barriers to develop plants:**
  - **Current regulatory environment.** The evolution of this vulnerability is currently unknown as it will depend to a large degree on the development of the technology and the competitiveness and importance of other technologies in European sustainability plans. If other hydrogen production technologies acquire more significance and competitiveness in terms of costs, the role of Waste to Hydrogen and the development of favourable regulations and new funding lines may be jeopardised.
  - **Current manufacturing capacities.** Waste to Hydrogen technologies have not achieved full development as demonstrated by the fact that not many plants have been rolled out due to the complex regulatory environment which is not focused on the development of this technology. This vulnerability is expected to increase in the future as the focus moves toward other hydrogen production technologies such as electrolysers, relegating Waste to Hydrogen to a secondary role.
  - **Social acceptance concerns.** Once its use is normalised, and optimal biomass waste collection has been achieved, the vulnerability should be reduced and is therefore dependent on its future use.

3.1.2.1.3. Sustainability and circularity

The sustainability of the gasification process for organic waste depends on its use under specific conditions. The carbon intensity and costs of the produced hydrogen are strongly influenced by the type of feedstock (low carbon footprint like organic waste/biomass) and the compatibility/effectiveness of carbon capture methods. The main advantage of the process is its potential for carbon reduction rather than the production of energy.

For these reasons the gasification process scores equally in all categories in the sustainability assessment (see Table 10). The list of potential impacts to the environment becomes exponentially high the moment that resources are spent to produce feedstock for the process. If improperly managed gasification plant can contribute to environmental pollution and occupational health and safety hazards [48].

Table 10 Sustainability assessment of gasification of organic waste/biomass to H_2

Biodiversity and Environment	• Air pollution: Localised emissions of CO_2 and potentially other GHG emissions, NOx compounds and particulate matter. The technology relies on carbon capture methods for low emissions, which are still mostly in development and not 100% effective. • Water and soil pollution: tar, char and dust particles that can contain heavy metals or other contaminants that can affect soil and plant growth and pollute wastewater streams. • Use of land for biomass production that can disrupt ecosystems and affect biodiversity.
Health and safety	• High operating temperatures may pose safety risks during operation and maintenance. • The production, storage, and handling of hydrogen poses potential explosion and fire risks. • Generation of organic dust particles and gases that are toxic and detrimental for health.
Material use and recyclability	• Use of materials classified as CRMs (e.g., Nickel in the catalyst). • Need for catalyst regeneration. • Find ways to reuse, recycle or treat the waste products of char and tar, particularly tar.

Robustness and flexibility	• The process can be relatively flexible. However, to achieve higher yields, it must be tailored to a specific feedstock and process parameters. It is also a continuous process that needs a continuous feed, which is dependent on biomass/organic waste availability. • Operation at very high temperatures requires a large energy input, therefore it is an energy intensive process. It depends on received waste heat from other processes to lower costs. • Technology is underdeveloped, not at commercial TRL, and still unreliable for industry.
Energy intensity and efficiency	• It generates a hydrogen output generally under 10 bars, this requires a lot of energy to compress for storage and some end uses (250-700 bars). • Very energy intensive process due to the operation at high temperatures. • Low energy density of biomass/organic waste feedstocks.

3.1.2.1.4. Conclusions on waste to hydrogen

Waste to Hydrogen, or organic waste gasification, is a mid/high maturity technology with still a long road ahead in terms of manufacturing scale-up.

This technology offers several advantages when compared to its peers in the hydrogen production industry: high yield of hydrogen, which can be converted flexibly to other outputs, and consumption of almost no electricity in the process. However, the technology has not yet reached final maturity levels due to the complexity of the process and further research has yet to be carried out on the feedstocks and catalysts used.

Moreover, the Waste to Hydrogen European supply chain has no major dependencies on CRMs. It has a strong know-how and technological base for the development of this technology due to decades of expertise in similar industries, such as the chemical and refinery sectors. The supply chain also has vulnerabilities relating to certain capabilities such as the current regulatory environment, the decreased issuance of patents globally, the social acceptance concerns or the lack of current manufacturing capacities.

Finally, the sustainability assessment reveals that all categories analysed have similar degrees of likelihood to produce negative impacts. It is important to highlight that the main advantage of this process relies on its potential to reduce carbon emissions due to the feedstock used.

In conclusion, Waste to Hydrogen technologies offer several great advantages for hydrogen production but still lack the market backing to make progress in terms of research and manufacturing scale-up.

3.2. Logistics technologies' supply chains

Hydrogen logistics encompass the processes and infrastructure necessary to store, transport and distribute hydrogen from its production site to its destination in end-use devices. Hydrogen logistics are a key part of the supply chain since having robust and well-established storage systems for every application is crucial to tackling the current and potential demands of the hydrogen energy market and, therefore, they play an essential role in the development of the hydrogen economy. Moreover, transportation and distribution form a large part in the cost, energy consumption and emissions associated with hydrogen pathways.

There are several technical challenges involved in transporting hydrogen vs. natural gas due to its unique properties. Hydrogen has the lowest energy density of all gases, which means that a larger volume is needed to transport the same amount of energy, which leads to higher transportation costs as more infrastructure is required. Additional costs come from hydrogen liquefaction due to its boiling low point vs. natural gas. Hydrogen is also a highly flammable gas, meaning that high-pressure leakage makes it highly prone to spontaneous combustion. Consequently, handling hydrogen demands additional safety procedures and equipment when compared to traditional fuels. Besides, due to hydrogen being a smaller element, it can easily penetrate solid metals, causing hydrogen atoms to be absorbed and diffused within the infrastructure. An in-depth understanding and control of hydrogen logistics is needed to make the whole value chain as efficient as possible. Within logistics, there are three subphases: storage, transportation, and distribution.

- **Storage:** the rising global interest in utilising renewable energy sources rather than relying on fossil fuels has made hydrogen storage very attractive. Other renewable energy sources such as wind and solar power are hugely dependant on the weather which can cause mismatches between supply and demand. Hence hydrogen storage has great potential to bridge this gap. Renewable hydrogen can be stored in many ways, depending on the required volume and application. For large volumes and long-term storage, hydrogen can be kept in underground storage, such as in salt caverns, depleted natural gas and oil reservoirs, rock caverns or aquifers. For short-term storage and smaller volumes, hydrogen can be stored in high-pressure tanks in gaseous form, liquid form, in liquefied carriers (LOHC) or as NH_3.

- **Transportation:** feasible and expansive clean hydrogen transportation systems are required to connect distant areas which have cost-efficiency advantages with other parts of the supply chain. Depending on mode of transportation and distance, different technologies are used for transportation. For shorter distances, grid infrastructure is used, which can be pre-existing networks that are retrofitted to allow for hydrogen transportation. For mid-length distances, pipelines can again be used, as well as compressed gas trailer trucks. Trucks using ammonia or liquefied hydrogen can also be used for mid-length distances. For long-distance transportation, shipping vessels are mostly used, with hydrogen in the form of ammonia, LOHC or liquefied. Both onshore and offshore pipelines can also be used for long-distance transportation.
- **Distribution:** enabling hydrogen distribution is key to ensuring that it is utilised correctly at points of use and that it reaches the end users. If the final destinations are situated at a short distance, hydrogen can be distributed by road or pipeline. Hydrogen can also be delivered through Hydrogen Refuelling Stations.

Regarding regulations concerning hydrogen logistics technologies, the Commission included a hydrogen and decarbonised gas markets package in the Fit-for-55 package, involving two new legislative proposals:

- **Recast EU Gas Regulation** [49]: the principles governing the gas market in the EU will be applied and expanded to include hydrogen and renewable gases. To encourage their integration into the gas grid, tariffs for these gases have a discount of 100% in the first year following the recast of the regulation, and of 75% in following years. The European Network of Network Operators of Hydrogen (ENNOH) will be created to facilitate the development of a hydrogen infrastructure, enhance cross-border collaboration, and establish an interconnector network. The ENNOH will establish a ten-year network development plan, which includes commercially significant interconnections and feasible transportation networks.
- **Recast directive on EU gas and H_2 networks** [50]: the proposal would bring changes in the hydrogen logistics sector that would mean a new chapter dedicated directly to new rules for future hydrogen network, storage, and terminal operators, as well as hydrogen interconnections with third countries. Additionally, the integrated network planning for gas markets would be refined and extended to cover hydrogen markets.

3.2.1. Hydrogen based carriers

3.2.1.1. Ammonia as a hydrogen carrier

3.2.1.1.1. Supply chain description

Ammonia (NH_3) is the second most widely produced stock chemical after sulfuric acid, with a global annual production of over 200 Mt. Ammonia is mostly obtained in the Haber-Bosch process through the catalytic reaction of hydrogen and nitrogen. The primary consumer of ammonia is the fertilizer industry. However, with the evolution of the hydrogen economy, ammonia could emerge with a new role as an energy carrier [51] [52]. Part of the appeal of ammonia as a hydrogen carrier, alongside a mature production and logistics network, is that it can be transported as a liquid at ambient temperature and lower pressure ranges, which makes it more manageable for transport than hydrogen, either liquified or as a compressed gas.

Since the technologies for ammonia production and distribution mechanisms are very mature, the scope of the study is focused on the reconversion of the ammonia back to hydrogen, a process known as **ammonia cracking**. Europe will mostly play a role as one of the leading importers of ammonia in the new energy market, making the cracking a relatively important step if the imported ammonia is intended to act as a hydrogen carrier. Cracking ammonia to obtain hydrogen is not a novel technique. It has been used for decades in the fields of metallurgy for galvanising and annealing metals [51]. However, a short-term technological evolution is expected to optimise production towards hydrogen and lower the costs.

According to the criticality criteria and the information provided by industrial experts, the assessment classifies the reactor and catalyst as critical. The separation section has less importance (see Table 11).

Table 11 Criticality assessment of the ammonia cracking process

Ammonia cracking process					
	(Sub)Components	Reaction section		Separation section	Balance of the plant (BoP)
		Reactor	Catalyst		
Criteria	**Cost**	3	3	4	2
	Performance	5	5	3	1
	Technical development	4	4	3	1
	Results	**Critical**	**Critical**	**Semi-critical**	**Not critical**

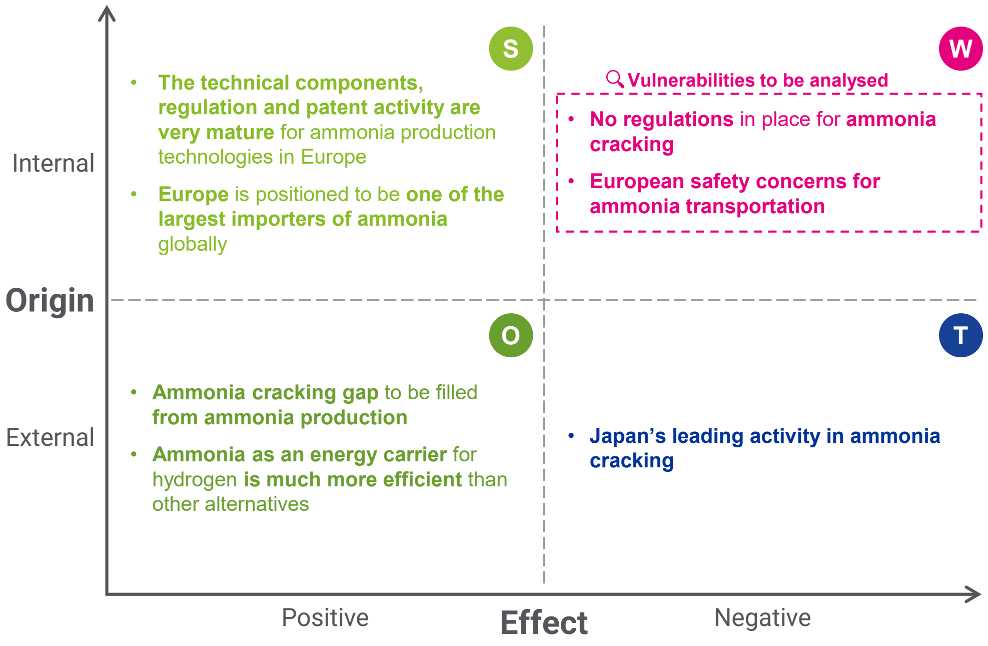
Source: SWECO; Industrial experts

3.2.1.1.2. SWOT analyses

European competitiveness was analysed using a SWOT matrix framework (Figure 15) which showed that the main opportunities of this technology lay in the use of ammonia as an energy carrier. It is currently emerging as an alternative in the role of an energy carrier for hydrogen due to the ease of transportation compared to hydrogen. Once the use of ammonia as an energy carrier is widespread throughout the industry, there will be a massive gap to be filled as the production of ammonia is much greater than the demand from the ammonia cracking industry. These technologies could benefit and scale up the industry.

Alternatively, there are certain associated threats that could have a negative impact on the evolution of European ammonia technologies. In the ammonia production industry, Europe leads with almost ~40% of total patents issued in the last decade, vs. just ~20% from Japan. However, when comparing ammonia cracking patents, Japan clearly dominates the market with 60% of total patents, three times more than European countries (20%) in the last 10 years. Besides, the historical and current use of ammonia globally has always been in the fertilizer industry. Companies from this sector will compete to obtain ammonia. The challenge remains to see if production will scale up as a result of this increased demand for ammonia and to determine whether or not the hydrogen and fertilizer industries will compete to obtain this product.

Figure 15 SWOT matrix on Ammonia cracking European capability factors



Source: Monitor Deloitte; Interviews with experts

European competitiveness in the ammonia technologies supply chain lies in the strengths derived from process efficiency in terms of production yield, low electricity consumption and output flexibility:

- **Ammonia production technologies are very mature.** The technology for producing ammonia has been used for decades. Therefore, all the variables that must be considered with regard to the technology (regulations, funding, TRLs, R&D, etc.) are already mature and there is no urgent need to improve current conditions. However, this technology is only the precursor of ammonia cracking technologies. It serves as a support for ammonia cracking but does not drive the technology globally.
- **Europe's leading net import position.** Europe currently has higher clean ammonia production costs than other regions due to its limited access to cheap renewable electricity. This positions Europe as one of the leading net importers of ammonia globally, which will have to be converted back into hydrogen for its use.

The weaknesses detected regarding ammonia technologies are rooted in the lack of regulations present in the sector and the safety concerns over ammonia transportation (see Figure 15):

- **No regulations in place for ammonia cracking.** Although there is already considerable support for ammonia production technologies, ammonia cracking technologies are not as globally developed. The technology is mature, but there is no sign of regulatory support (new laws reinforcing the use of ammonia cracking) or similar activities to drive the development of the technology.
- **European safety concerns for ammonia transportation.** Ammonia transportation and storage is being rigorously investigated because of several public accidents in recent years. Some ports supervisors have pointed out that the standards for storing ammonia are outdated, and transporting this substance can be dangerous, posing a risk of major incidents and accidents.

The evolution of the abovementioned vulnerabilities was evaluated based on a two-pronged framework considering the importance of other regions/sectors and the expected evolution of the technology.

- **No regulations in place for ammonia cracking.** As the use of the technology increases due to ammonia's new role as an energy carrier and its expected technological development, new regulations will be put in place, and this vulnerability will decrease. The challenge remains to see when this new role is going to be taken and when regulators will react to this new technology in the market.
- **European safety concerns for ammonia transportation.** As the regulations associated with ammonia evolve and ammonia becomes more developed as an energy carrier, safety concerns will be dissipated.

3.2.1.1.3. Sustainability and circularity

Currently, the production of ammonia is carried out through a combination of steam methane reforming (SMR), to obtain hydrogen, and a Haber-Bosch process. This manufacturing method consumes ~1.8% of the annual global energy. Therefore, the production of the hydrogen and nitrogen mixture is the biggest contributor to the costs. Since these processes are mainly powered through fossil fuels, this leads to a production of 400 million tons of CO_2 per year, equivalent to 1.2-1.6% of the global carbon dioxide emissions [51] [52] [53].

There are some Life Cycle Analyses for ammonia as a carrier which conclude that the impact of ammonia depends mostly on the method of hydrogen production. In the case of ammonia produced using hydrogen from electrolysis, the electrolysis step has the most influence over the indicators for the analysis.

Ammonia production involves significant energy consumption and, unless renewable sources are used, the reduction in carbon emissions would be minimal. Using ammonia as a carrier for hydrogen introduces additional impacts resulting from the reconversion process in addition to those associated with its production, which combined with the intrinsic properties of the ammonia itself, mean ammonia scores high in terms of the potential impacts in the categories of "Biodiversity and Environment", "Health and Safety" and "Energy intensity and efficiency" (see Table 12). Regarding the latter it should also be considered that the cracking itself is also energy intensive.

Interviewees highlight that the appeal of ammonia as a carrier lies in its ability to facilitate transportation compared to hydrogen, without carrying the carbon content associated with other carrier substances. However, it is crucial to acknowledge that the feasibility of this import pathway relies heavily on the development of regulations concerning the source, trade, and use of ammonia for hydrogen production. These regulations are currently under development and need to be carefully established to ensure safe and sustainable practices.

Table 12 Sustainability assessment of ammonia cracking

Biodiversity and Environment	• Manufacturing of ammonia uses 2% of annual global energy. Potential issues in supply of necessary energy through renewables and reliance on fossil fuels, generating emissions. • Risks of water pollution from release of ammonia, by-products and wastewater generated during the production process. At high concentrations it can be toxic to aquatic organisms. • Ammonia pollution impacts species composition through soil acidification, direct toxic damage to leaves and altering the susceptibility of plants to frost, drought, and pathogens. • References evaluating the process in terms of environment are low. Its effects on the carbon and nitrogen cycles needs to be assessed. There is uncertainty of environmental impact.
Health and safety	• The production, storage, and handling of hydrogen poses potential explosion and fire risks. • High operating pressure and temperatures pose safety risks by leaks and equipment failure. • NH_3 is corrosive to skin, eyes, lungs, presenting dangers if in contact, inhaled or swallowed. • NH_3 is flammable and presents fire and explosion hazards, on top of those of the hydrogen.
Material use and recyclability	• Materials of the installation must be carefully selected and often replaced due to corrosion. • Use of materials classified as CRMs (e.g., Nickel in the catalyst).

Robustness and flexibility	• Time-consuming start-up and shutdown process, reducing operational flexibility. • Dependence on production of large amounts of renewable hydrogen. • Challenge to optimize cracking process to achieve cost-effectiveness and flexibility.
Energy intensity and efficiency	• High efficiency losses in cracking stage, the reconversion loses of ammonia back to hydrogen can amount to 30-40% (vs. for Haber-Bosch which are 20-30%). • Energy intensive process due to electricity/heat requirements for production and cracking, leading to high energy consumption and carbon emissions if energy is not renewable. • Potential challenges in capturing and utilising waste heat or by-product gases to improve energy efficiency in the ammonia cracking process. • Potential increase of the production of ammonia for its intended use as an energy carrier. This will increase the demand of the ammonia market, aggravating the competition.

3.2.1.1.4. Conclusions on ammonia as a hydrogen carrier

Ammonia has been used historically for the fertilizer industry but has now emerged as an energy carrier for hydrogen as it is easier to transport than hydrogen itself. Its supply chain, from production to cracking (reconversion to hydrogen at ports), is considerably mature as this process has been used for decades.

However, technological improvements are yet to be made in order for Europe to hold its competitive position. Europe has to improve efficient cracking technologies to compete with other regions such as Japan where continuous efforts have been made to develop these technologies. This is a key challenge for the development of ammonia cracking as Europe is expected to become one of the global importers of ammonia, as production costs in other regions are forecasted to be much lower due to cheaper access to renewable energy generation.

In addition, other main strategic challenges within the ammonia cracking supply chain continue to be the lack of a favourable regulatory context preventing the development of this technology, and the safety concerns that surround the transportation of ammonia. Europe will have to solve the location to develop this technology cautiously and will have to develop a regulatory environment that will support it.

The sustainability assessment reveals that “Health and safety”, "Biodiversity and environment" and “Energy intensity and efficiency” are the categories with most likelihood of having a negative impact. This is due to the large energy consumption needed to produce ammonia and the safety concerns regarding its transportation.

3.2.2. Storage technologies

3.2.2.1. Hydrogen storage tanks

3.2.2.1.1. Supply chain description

Compressed hydrogen tanks are a mature technology that has been used for decades. However, in the emerging hydrogen economy, there is a strong need for them to be improved and adapted to serve new applications (e.g., mobility).

To be able to store hydrogen in tanks, additional elements such as compressors, valves and pipelines are needed. However, these elements are either mature technologies with no critical requirements for hydrogen additional to those imposed by the tanks themselves (e.g., material compatibility, leakage resistance) or they pose a whole new set of challenges that should be addressed in a separate case study (e.g., pipelines, valves).

To identify the most important elements for the supply chain analysis, the tank components undergo a criticality assessment which is combined with information provided by industrial experts (see Table 13).

Table 13 Criticality assessment of compressed hydrogen tank components

	Compressed hydrogen storage tank								
	Components & Sub-components	Structural components			Safety and control				Vessel support
		Wrap	Liner	Neck	Relief valve	Sensors	Tank valve	Dome protection	
Criteria	**Cost**	5	4	1	3	3	1	1	1
	Performance	5	5	3	2	2	2	1	1
	Technical development	5	5	1	2	1	2	1	1
	Results	Critical	Critical	Not critical	Not critical	Not critical	Not critical	Not critical	Not critical

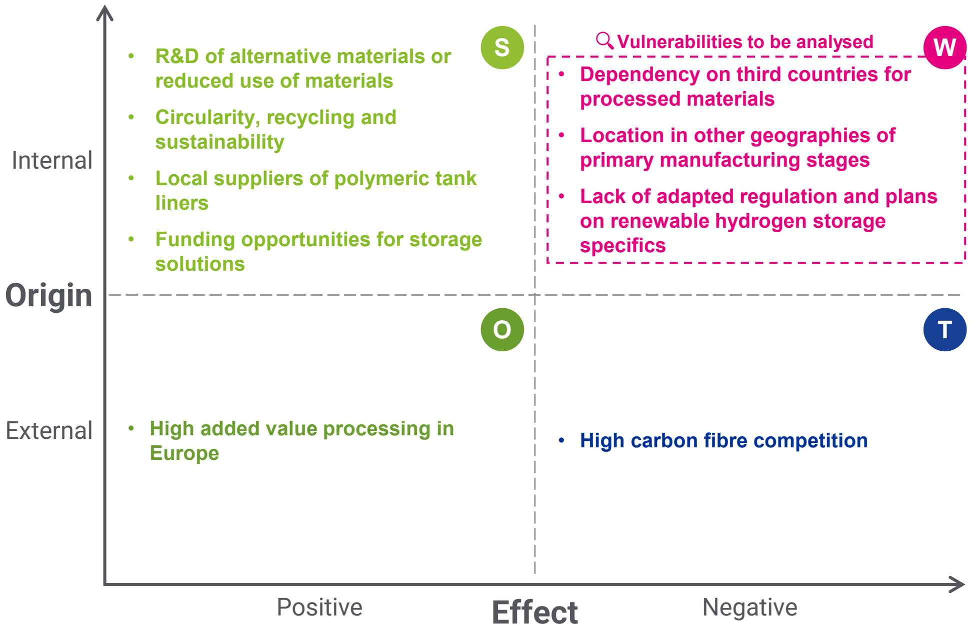
Source: SWECO; Industrial experts

3.2.2.1.2. SWOT analyses

The SWOT matrix developed (Figure 16) has categorised the main factors currently affecting the competitiveness of European storage tank manufacturing. Opportunities should be taken regarding the levers for reinforcing storage tank manufacturing, focusing mainly on the high added value of processing materials/components in Europe.

The main threat and negative factor beyond the direct control of European legislators is the increasing competition for the carbon fibre used in Type IV tank manufacturing. The wind energy and aviation sectors' increasing demand for carbon fibre is a consequence of the energy transition policies and the recovery of economic activity, respectively. The increase in demand of both sectors is therefore a good sign of the implementation of energy transition and recovery plans. However, this has stressed not only the EU carbon fibre market but also the global supply capacity.

Figure 16 SWOT matrix of European capability factors for hydrogen tanks



Source: Monitor Deloitte; Interviews with experts

The main EU manufacturer strengths lay on R&D activities, as well as in initiatives on circularity and recycling:

- **R&D of alternative materials or reduced use of materials.** European hydrogen tank manufacturing companies are proactively taking the lead in assessing environmental concerns and competition for processed materials for the coming years. One strength is the EU's awareness of these issues, and its investment in innovation is aimed at implementing solutions before mass manufacturing commences. The initiatives focus either on the inclusion of more sustainable alternative materials or on the design of new material configurations that allow a reduction in the quantity of processed materials while maintaining performance levels. The EU's R&D initiatives and its leading energy transition policies are the driving force behind companies' investments in sustainable process designs and supply chains.
- **Circularity, recycling and sustainability.** Although sustainable materials recovery techniques are currently being developed, they have not yet been commercially implemented; EU companies are conducting research and are interested in implementing these techniques as part of their offering and their differentiated value.
- **Local suppliers of polymeric tank liners.** The manufacturing of this critical component used in tanks for mobility applications (e.g., type IV) can leverage the mature domestic polymer industry. This strength can be taken as an example of how to restructure an established local industry and incorporate it in the hydrogen economy.
- **Funding opportunities for storage solutions.** EU factories have the capability to attract final-processing or high added value industrial activities, which, added to the far-reaching R&D funding programmes, places Europe in the position of a global leader in innovation and continuous improvement. Europe can leverage this capability to deliver highly valued new products not only to domestic customers but to foreign countries as well.

Several weaknesses have been detected regarding the reliance on third countries and suppliers for components and materials, as well as the lack of an adapted regulation for the industry (see Figure 16):

- **Dependency on third suppliers:** this is a concern in terms of carbon fibre supply, given the manufacturing capacity domination of Asian companies and the technical and cost barriers to local development in Europe.
- **Location of part of the early-stage manufacturing processes in third countries** as a consequence of the strategy for imports of pre-processed goods that can be categorised as commodities. Economy-of-scale schemes implemented in the last few decades have made it possible to optimise costs and mass production effectively. However, they are a weakness given the dependency created on third economies.
- **The lack of adapted regulation and of plans regarding renewable hydrogen storage specifics,** with similar issues to the ones stated for the PEM electrolyser, is a recurrent concern expressed by European manufacturers.

The evolution of the detected vulnerabilities in tank manufacturing is assessed based on the importance of the sectors with shared supply chains and technical development.

- **Dependency on third countries for processed materials.** Carbon-fibre manufacturing activity is expected to remain located in Asian countries due to their advantages in terms of know-how and cost competitiveness. Additionally, the development of alternative storage tanks for mobility applications that does not depend on carbon fibre is not expected to take place, as from a technical perspective the use of carbon fibre is already an optimal solution. It is worth mentioning the R&D initiatives of European manufacturers to decrease the dependency on composite materials; however, this will foreseeably not have a major effect on the distressed carbon fibre supply chain. All in all, this vulnerability is expected to increase in the coming years.
- **Location of primary production stages in other geographical regions.** Due to recent geopolitical instability, the domestic relocation of strategic industries is a trend expected to become increasingly significant in the coming years. Nonetheless, industry relocation will depend on companies' investments, customer-base location and economies of scale. It should also be noted that the EU's ambitious hydrogen economy plan will encourage storage tank manufacturers to increase their current production capacity. All efforts should focus on these expansion plans, helping to build a favourable environment in which the new manufacturing capacity is kept in Europe. Lastly, the EU's R&D activities and its capacity to attract added value production will likely contribute to retaining industrial knowledge of new processing and manufacturing techniques. This vulnerability is expected to decrease due to local production retention plans.
- **The lack of adapted regulation and of plans regarding renewable hydrogen storage specifics.** This weakness is similar to the one for PEM technology. Europe lags behind other regions in terms of the approval of regulations and the time to market for new solutions. Although certain steps towards strategic and regulatory frameworks for hydrogen specifics are being taken, other countries could surpass Europe in the commercialisation of new solutions and the deployment of market innovations. The evolution of this vulnerability is unknown as it will depend on whether Europe is capable of releasing a regulatory and strategic framework adapted to new R&D product deployment.

3.2.2.1.3. Sustainability and circularity

The potential impacts associated with tanks are generally limited and arise primarily from the materials used, the absence of recycling techniques for certain materials, and the inherent hazards associated with hydrogen storage. Consequently, the sustainability assessment predominantly highlights potential impacts in the categories of "Material use and recyclability" and "Health and safety" (see Table 14).

Table 14 Sustainability assessment of compressed hydrogen tanks

Biodiversity and Environment	• Storage at low pressures is safer than at high pressures but requires a larger space for containment due to the low density of hydrogen. This might prompt the construction of large tank parks, which could entail the use of a larger proportion of the available land for industrial activities.
Health and safety	• The production, storage, and handling of hydrogen pose potential explosion and fire risks. • Containment at high pressure poses safety risks in terms of possible leaks and mechanical failure of the equipment.

Material use and recyclability	• Use of materials classified as CRMs (e.g., carbon fibres, aluminium). • Recycling techniques for carbon fibres involve shredding, and the use of the shredded fibres is limited to other purposes. The recycling process cannot maintain the quality of the fibres, so they cannot be reused for pressure vessel construction. • Resins and coatings of the carbon fibres are not recyclable.
Robustness and flexibility	• The liner in type III/IV tanks can perform in industrial applications but is still sensitive in terms of fatigue resistance and temperature changes after refilling cycles, making it prone to collapse.
Energy intensity and efficiency	• Production methods generate hydrogen at <50 bars; thus, a lot of energy is required to compress the hydrogen for storage and some end uses (250-700 bars).

3.2.2.1.4. Storage tanks - conclusion

Hydrogen storage tanks are classified into four types according to the materials used in the structure. Each of them present different weight and pressure ranges for storage, making them fit for stationary or mobile storage.

Analysing the subsystems, the vessel structure is found to be the critical element in the supply chain, due to a correlation between material limitations and the density of hydrogen. Therefore, the main challenge is to develop materials that can store hydrogen at high pressure, and thus in lower volumes, at a low cost. Additional boundaries are added in terms of the design of the materials, depending on their end-use, since weight is a limiting factor for transport applications.

Tank supply chains are relatively mature, with most of the knowledge being obtained from the Oil&Gas industry. The main vulnerability that has been identified is the increasing competition for the carbon fibre, which is managed mainly by highly-experienced and highly-cost competitive Asian players.

The sustainability assessment shows that "Material use and recyclability" is the category with greatest likelihood of producing negative impacts.

3.2.2.2. Hydrogen refuelling stations

3.2.2.2.1. Supply chain description

Hydrogen refuelling stations (HRSs) play a key role in facilitating the deployment of hydrogen mobility throughout the EU. Due to the specific properties of hydrogen gas, a specialised and complex infrastructure (vs. conventional refuelling) is required to refuel vehicles with hydrogen safely and efficiently. Operational hydrogen pressures in vehicles are currently at 350 bar for heavy-duty vehicles (HDV) and 700 bar for light-duty vehicles.

Currently, there are approximately 250 HRSs in Europe [54], but this number is expected to increase under the Alternative Fuels Infrastructure Regulation (AFIR) to comply with EU targets. This means that enough HRSs would be deployed in all urban nodes to serve light and heavy vehicles and there would be an HRS every 200 kms in the TEN-T core network by 2030.

HRS technology can be divided into three types based on the state of the supplied hydrogen: gaseous, cryogenic and solid hydrogen carriers. HRSs for cryogenic and solid hydrogen carrier-based hydrogen are still under development and commercial vehicles for these types of hydrogen are not yet available. Boil-off losses, robustness of components, safety, regulation, and standards are still major issues and require research. At present, gaseous HRSs are the most common due to the higher maturity and availability of gaseous hydrogen vs. cryogenic hydrogen and solid hydrogen carriers. Cryogenic and solid hydrogen carrier-based refuelling stations are excluded from this scope due to their early stage of development, lack of commercial viability, and high infrastructure costs.

The two technically critical components (PCUs and hydrogen dispensers) are analysed at subcomponent level to identify the critical elements making up the HRS infrastructure (see Table 15 and Table 16).

The technology of refilling vehicles with gaseous fuel is well developed. Today there are already many CNG and LNG filling stations. Hydrogen, natural gas and other fuels are used in industry in all kinds of conditions. The various steps used in a hydrogen filling station are therefore not new technologies, although they have not yet been integrated on a large scale for use by the public. Companies are now exploring the best system integrations for obtaining the most efficient, safest, and fastest filling in the most economical way. When components come into contact with hydrogen this causes hydrogen-induced cracking and, therefore, any parts in contact with hydrogen must be adapted to minimise this phenomenon.

Table 15 Criticality assessment of hydrogen refuelling stations – PCU

	Pre-Cooling Unit (PCU)						
	(Sub) Components	**Refrigerant**	**(Two-stage) Compressor**	**Condenser**	**Thermostatic expansion valve**	**Evaporator**	**System control**
Criteria	**Cost**	2	4	1	1	3	2
	Performance	3	3	1	1	4	4
	Technical development	3	2	1	1	4	4
	Results	Semi-critical	Not critical	Not critical	Not critical	Critical	Critical

Source: SWECO; Industrial experts

All the PCU components are well-developed technologies that do not have specific design aspects relating to hydrogen, except for the evaporator. This is the only component that interacts with hydrogen. The other components are all mature technologies of no specific relevance to this study. Therefore, the analysis will focus on the evaporator. Besides the physical components, control is also a critical aspect of the current refrigeration system. Extreme temperature fluctuations and system dynamics make it hard to achieve an optimal control over the cooling/dispensing operations.

Table 16 Criticality assessment of hydrogen refuelling stations – Dispenser

	Dispensers								
	(Sub) Components	**Filters**	**Valves and Meters**					**Hose**	**Nozzle**
			Mixing valves	**Flow meter**	**Valves**	**Breakaway**	**Sensors**		
Criteria	**Cost**	1	3	4	3	4	4	1	1
	Performance	2	3	4	4	4	3	2	3
	Technical development	2	3	4	4	4	2	3	3
	Results	Not critical	Semi-critical	Critical	Critical	Critical	Semi-critical	Semi-critical	Semi-critical

Source: SWECO; Industrial experts

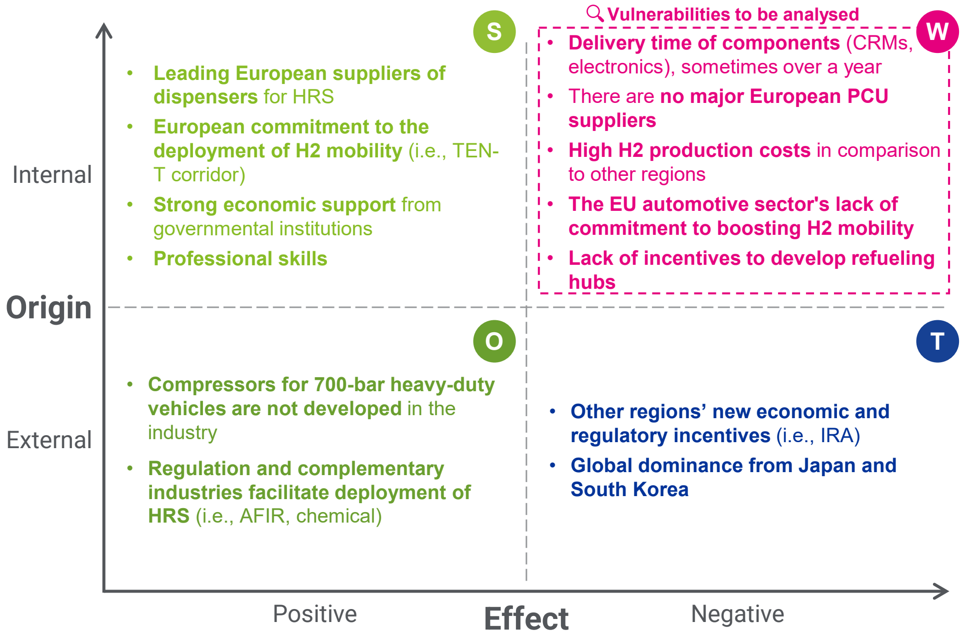
For the roll-out of HRSs with high filling speeds, the reliability of the breakaways and valves is of critical importance. Valves and metering equipment are responsible for 60% of the total costs of a dispenser. This is because of the complex sensors required for hydrogen leakage detection and flame protection [55].

3.2.2.2.2. SWOT analyses

The main opportunities of this technology consist basically of the support provided by updated regulations and complementary industries, and the development of new compressors for HDVs. In Europe there is committed support for the deployment of HRSs which is backed by new regulations targeting this issue (e.g., AFIR) and new initiatives like the TEN-T corridor. As the future of hydrogen mobility is focused on long distance, there is an opportunity for HDVs to become a cost-effective solution for transport. HRSs capable of meeting these vehicles' needs will be required, but the market for 700-bar compressors to resolve this potential concern has not yet been developed. Europe has an opportunity to establish itself as a leading supplier of these compressors and boost hydrogen HDVs on a global level. The chemical industry in Europe is highly mature and has synergies with the hydrogen industry that would facilitate the development and deployment of the necessary equipment.

There are certain associated threats that could negatively impact the evolution of the European HRS supply chain. Even though global patent trends have been changing in recent years and Europe is the current leader in patent issues, Asian countries, led by Japan and South Korea, have already made considerable strides and, at present, they are still the global manufacturing leaders in this sector. The maturity and capabilities of these competitive markets or others such as the US, with higher manufacturing capacities and a greater ability to attract investment (e.g., IRA), also pose a significant and concerning threat that could relegate Europe from being a potential technology exporter to essentially becoming an importer of HRS components.

Figure 17 SWOT matrix of European capability factors for HRS



Source: Monitor Deloitte; Interviews with experts

European competitiveness in the HRS supply chain depends on the support provided by the existing commitment to develop the technology, the local supply of specific components, and the professional skills and capabilities:

- **European commitment to the deployment of H_2 mobility.** In the last few years Europe has shown a strong commitment to supporting hydrogen technologies for mobility infrastructure by providing considerable economic support and regional initiatives in the form of corridors (e.g., the TEN-T corridor).
- **Leading local suppliers of dispensers.** European suppliers have particular expertise in the dispenser component of HRSs. Some local suppliers are global leading exporters of this component.
- **European professional skills.** Europe has developed significant expertise in HRS due to the efforts made in research and in the issuance of patents, which have resulted in the EU HRS industry obtaining unique know-how.

In addition, several weaknesses have been detected with respect to the HRS technology supply chain (see Figure 17):

- **Delivery time of components.** For several reasons (geopolitics, the pandemic, and others), some HRS technology components (e.g., CRMs, electronics) have been experiencing delivery time issues in the last few years. According to experts there are no major issues regarding particular materials or components, but this is a weakness that needs to be addressed so that the sector can develop.
- **No major European PCU suppliers.** Of the various HRS components, PCUs have been identified as vulnerable as there are no major EU PCU suppliers available right now. Manufacturers have mentioned that there are no major delivery issues, but this is another vulnerability to be addressed in the HRS industry.
- **High H_2 production costs.** One of the main vulnerabilities preventing the hydrogen mobility sector from developing faster is the high cost of production of renewable hydrogen. Europe does not have the capacity to produce large quantities of renewable hydrogen due to the scarcity of renewable resources in comparison with other regions which could become more cost competitive than Europe, which, together with the demand for green electricity from other end-users, leads to higher production costs.
- **The EU automotive sector's lack of commitment to boosting H_2 mobility.** While in Europe the mobility sector and its OEMs are focusing on the use of battery electric vehicles, the leading OEMs in Asian countries (Japan and South Korea) have been making continuous efforts to develop hydrogen mobility.

- **Lack of incentives to develop refuelling hubs.** One of the solutions to make HRSs more economically competitive is to develop refuelling hubs to reduce costs by achieving economies of scale. However, as some of the technologies that would be used in this solution are not developed on a large scale (e.g., electrolysers, 700-bar compressors), industry players are reluctant to devote efforts to develop these solutions.

The evolution of the weaknesses is assessed using two variables: the importance of the sectors with shared supply chains, and technical development.

- **Delivery time of components.** The European HRS industry is still at the development stage in comparison with other regions. Therefore, many of the materials and components used in the industry are yet to be optimised and new solutions may become available in the market. Although time could resolve some of the existing geopolitical issues, Europe has a chance to become a leading player for some of these alternative components and thus avoid delivery time issues in its supply chain. However, it is uncertain whether European players will find the solution and, therefore, it is not known how this vulnerability will evolve.
- **No major European PCU suppliers.** Europe is still developing its HRS industry in comparison with other regions. The availability of certain components, such as PCUs, might become a vulnerability as there are no major EU suppliers yet. The aim is to resolve this vulnerability in the short term with new support for hydrogen mobility technologies, but this issue will have to be monitored due to other regions' leadership regarding this specific component.
- **High H_2 production costs.** With the increase in renewable energy capacity in Europe, cheaper renewable electricity should be more accessible and, as a result, the production of renewable hydrogen should be cheaper. This vulnerability should decrease in line with the development of the European electricity system.
- **The EU automotive sector's lack of commitment to boosting H_2 mobility.** The technological development of fuel cells and access to cheaper renewable hydrogen should result in a decrease in this vulnerability since OEMs would then drive the deployment of hydrogen mobility technologies.
- **Lack of incentives to develop refuelling hubs.** The reluctance to develop refuelling hubs will be resolved once the complementary solutions such as electrolysers are manufactured on a greater scale and become cheaper. This vulnerability should decrease in line with the development of EU's hydrogen infrastructure system.

3.2.2.2.3. Sustainability and circularity

The impact of HRSs relates to the use of materials, hydrogen handling and storage safety, and the robustness of the technology considering the lack of experience of these installations. For that reason the impacts detected are quite straightforward and, in consequence, the highest scoring categories in the sustainability assessment are "Health and safety", "Material use and recyclability" and "Robustness and flexibility" (see Table 17).

Table 17 HRS sustainability assessment

Biodiversity and Environment	• Potential use of PFASs in sealing materials. • Air and water pollution from leaks of coolants. In response to the significant environmental impact of previously prevalent cooling fluids, which are now being banned, efforts are underway to develop new generations of cooling fluids.
Health and safety	• The production, storage, and handling of hydrogen pose potential explosion and fire risks. • Potential use of PFASs in sealing materials. • Due to possible high-volume, fast hydrogen flows in refuelling operations, along with the presence of weak points for leaks in the system (e.g., valves), the safety risks in populated areas are high. For safety reasons, manufacturers require nozzles and hoses to be replaced every six months. Material requirements to ensure safe operation are also higher.
Material use and recyclability	• Use of materials classified as Strategic Raw Materials (e.g., nickel). • Need for new materials and coatings to counter hydrogen embrittlement. • For safety reasons, manufacturers require nozzles and hoses to be replaced every six months. Material requirements to ensure safe operation are also higher.

Robustness and flexibility	• HRSs are dependent on the transport of hydrogen and underdeveloped logistics. • The hydrogen must be of very high purity before it can be used in an HRS system. This places restrictions on hydrogen source and compressor capabilities. • The robustness and capabilities of the compressors and pipelines still need investigation. Hydrogen embrittlement has an impact on materials that is not yet fully understood.
Energy intensity and efficiency	• The high compression needs for refuelling results in relatively high energy consumption. • Cooling needs (up to -40°C) also imply a relatively large energy expense in the process.

3.2.2.2.4. Hydrogen refuelling stations - conclusion

HRSs represent a mature technology under development across Europe. However, Japan and South Korea, due to their robust support for hydrogen mobility technologies, currently lead the global advances in this field.

The current reliance on BEVs for mobility in Europe poses a significant challenge for the hydrogen mobility sector as it competes for market share. European OEMs concentrate primarily on BEV development, in contrast to Asian regions, which prioritise the advancement of hydrogen mobility solutions, including HRSs and PEMFCs.

Despite this challenge, Europe's HRS supply chain exhibits a high level of maturity, boasting a developed local component supplier industry. However, some long-term issues persist, such as a shortage of PCU suppliers and delays in component delivery, attributable primarily to the current geopolitical situation.

The widespread adoption of HRSs hinges on the ability of technological solutions to achieve competitive prices. The production cost of renewable hydrogen remains high in Europe due to limited renewable resources. The potential solution of deploying refuelling hubs for cost reduction and scalability is not incentivised in the market. The emphasis remains on R&I, rather than on manufacturing and scale-up, leaving Europe lagging behind internationally. Nevertheless, recent years have seen increased efforts, showcasing a strong commitment to hydrogen mobility solutions, exemplified by initiatives such as the TEN-T corridor and regulatory measures such as the AFIR. Europe stands poised to emerge as a global leader by reducing renewable hydrogen costs and introducing innovative solutions like refuelling hubs or 700-bar compressors for HDVs.

Lastly, the sustainability assessments highlight potential negative impacts in categories such as "Health and safety," "Material use and recyclability," and "Robustness and flexibility." These concerns arise primarily from the storage and handling of hydrogen, which pose explosion risks, as well as from the technology's reliance on complementary and underdeveloped transportation methods, such as hydrogen pipelines.

3.2.3. Distribution technologies

3.2.3.1. Grid infrastructure

3.2.3.1.1. Supply chain description

To use hydrogen in any type of application, it must be transported from the production to the consumption site. To do this in a cost-effective manner, hydrogen must be in the right physical condition (temperature, pressure) and chemical condition (bonding to a carrier molecule) for transportation, due to the low volumetric energy density of hydrogen gas. The scope of this study covers the transportation of hydrogen through pipelines, which is expected to form the bulk of hydrogen transportation and distribution in Europe. The European Hydrogen Backbone is planned for 2040 and will span 53,000 kms. An essential aspect of this network will be the need to achieve and maintain the correct pressure of hydrogen (up to 100 bar depending on transmission or distribution), for which compressors are an essential component.

This chapter discusses the different technologies relating to hydrogen pipelines and compressors, along with their current issues and technical barriers. The important role of hydrogen compressors throughout the entire hydrogen value chain will also be examined.

The criticality analysis of the pipelines (see Table 18) focuses on new hydrogen pipelines, and not on the retrofitting of existing pipelines. These new pipelines are primarily capital-intensive. Not only the cost of placing and installing pipelines underground, but also the expenses relating to the necessary booster compressors, contribute significantly to the overall costs. In addition to the investment costs, the pipelines' performance with regard to hydrogen embrittlement and further developments in the performance of hydrogen compressors should also be considered. FRP (Fibre Reinforced Polymer) pipelines are still undergoing further development. In particular, the hydrogen permeability and aging caused by hydrogen gas need to be improved.

Table 18 Criticality assessment of pipelines

Pipeline system					
	(Sub) Components	Pipeline	Compressor	Valves	Gas meters
Criteria	Cost	5	4	2	1
	Performance	4	4	3	2
	Technical development	4	4	4	2
Results		Critical	Critical	Semi-critical	Semi-critical

Source: SWECO; Industrial experts

For compressors (see Table 19), the focus is mainly on centrifugal compressors as they are widely used in the natural gas industry but are not commercially available for pure hydrogen applications. Other compressors, such as diaphragm or ionic liquid compressors, are interesting for hydrogen applications and are currently commercially available, although they require further research for better optimisation. Further innovation and evolution of hydrogen compressors will determine which types of compressors are most suitable for specific hydrogen applications.

Due to the presence of hydrogen, all materials in contact with it in the compressor must be resistant to embrittlement or corrosion. Additionally, all valves, seals, and gaskets must be adapted to minimise leaks.

Table 19 Criticality assessment of centrifugal hydrogen compressors

Centrifugal Compressor												
	(Sub) Components	Control system	Pressure reducers	Valves and Meters			Inlet	Outlet	Impeller	Diffuser	Vanes	Volute Casing
				Flowmeter	Valves	Sensors						
Criteria	Cost	3	1	2	2	4	3	3	4	3	3	4
	Performance	1	1	3	3	3	4	4	5	4	4	4
	Technical development	2	1	3	4	2	4	4	5	4	4	4
Results		Not critical	Not critical	Semi-critical	Semi-critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical

Source: SWECO; Industrial experts

3.2.3.1.2. SWOT analyses

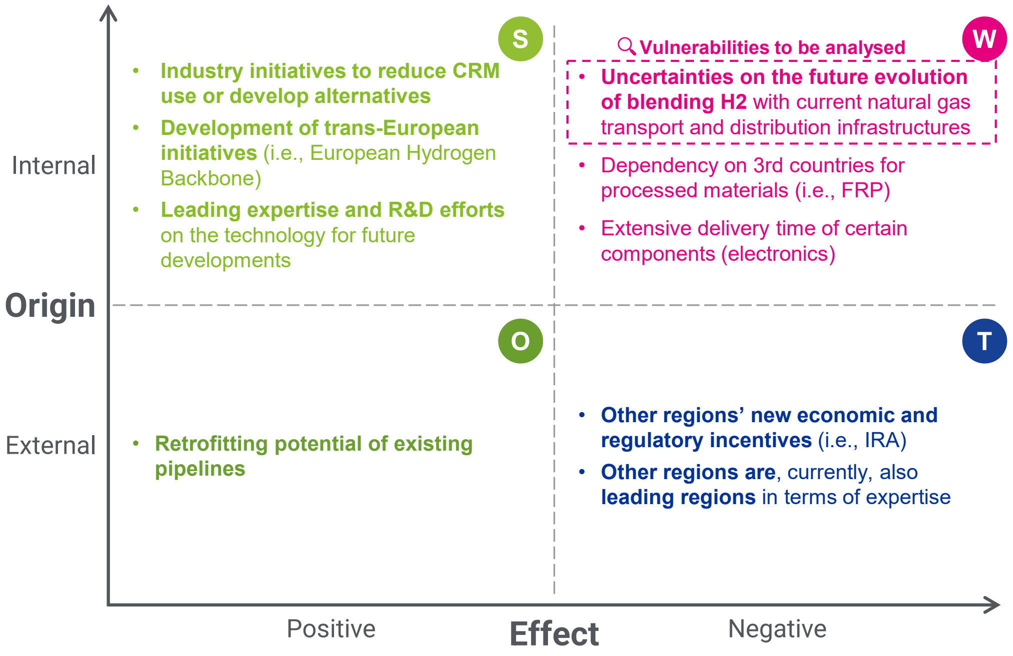
European competitiveness was analysed using a SWOT matrix framework (Figure 18) which showed that the main opportunity provided by this technology consists basically of the considerable potential to retrofit current natural gas pipelines in Europe. Although China and the US control the largest pipelines for natural gas globally [56], the maturity of the chemical industry in Europe means that there is a unique opportunity to reuse existing pipelines for the transportation of hydrogen all over the region.

There are also some associated threats that could have a negative impact on the evolution of the European grid infrastructure for hydrogen. The construction of new hydrogen pipelines and the retrofitting of existing natural gas pipelines have a common factor, which is the use of alternative materials to prevent hydrogen embrittlement in the pipelines. These usually include materials, such as nickel, which have been designated as critical (CRMs) or strategic, for which most of the mines are located outside Europe. These materials and others, such as fibre-reinforced polymers, present a threat to the European hydrogen supply chain. Carbon fibre-reinforced polymers, for example, have over 80% of their total world production and processing outside Europe (~60% in Asia-Pacific and ~20% in the US), creating a dependency for Europe on third countries for this material.

In addition, due to the possibility of decarbonisation solutions in Europe, alternatives exist that may be used instead of hydrogen, such as biogas. These solutions would compete directly with hydrogen to the potential detriment of the final demand in the industry. Europe as a region must optimise the use and applications of both alternatives to prevent misuses of technologies and foster promising projects in the long term.

It is important to highlight that, even though Europe is a clear leader in global patent trends in terms of the patents issued over the last few years, other regions, but mainly the US, are currently also expert regions in the research and operation of these technologies. Lastly, the maturity and capabilities of these competitor markets with a greater manufacturing capacity and better possibilities for attracting investment (e.g., the US and its IRA) represent major threats that could potentially make Europe an importer of this technology.

Figure 18 SWOT matrix of European capability factors for hydrogen grid infrastructure



Source: Monitor Deloitte; Interviews with experts

European competitiveness in the hydrogen grid infrastructure technology supply chain depends basically on the strengths arising from industry initiatives to reduce the use of CRMs, the implementation of European initiatives to develop the technology, and the leading expertise and R&D efforts of the industry today:

- **Industry initiatives to reduce CRM use or develop alternatives.** The EU is aware of the barriers and dependencies that materials can create in the domestic industry. Nevertheless, European industries, in alignment with the EU Net-Zero Industry Act, have taken a proactive approach in this matter by investing in the development of solutions to overcome potential issues that may arise in industrial upscaling.
- **European initiatives to develop the European hydrogen grid infrastructure.** In the last few years Europe has shown a strong commitment to supporting hydrogen technologies for the improvement of the hydrogen grid infrastructure, providing considerable economic support and implementing regional initiatives such as the European Hydrogen Backbone. The aim of this particular initiative is to foster market competition, security of supply, security of demand, and cross-border collaboration between European countries, which will result in a strong boost for the industry and European players' overall commitment on hydrogen.
- **Leading expertise and R&D efforts.** Although this technology is already mature, intensive research is still required before the industry can become competitively optimised. Due to its experience in similar industries such as the chemical industry, the EU has historically been strong in the research and innovation of pipelines and compressors, which has created a highly qualified domestic hub of researchers, as shown by Europe's leadership in the global issuance of patents in the last decade. The remaining challenge for the EU is to find the way to turn this knowledge into industrial capabilities.

There is one major weakness with respect to grid infrastructure technologies (see Figure 18):

- **Uncertainties regarding the future evolution of blending H_2 with current natural gas transport and distribution infrastructure.** There is uncertainty over the optimal blending rate of hydrogen with natural gas. Some countries are conservative, accepting levels of up to 2-5% hydrogen, and others already accept a 10% blending rate. There are already cases where pipelines and compressors have performed at high levels of efficiency with 20% blending rates. The discrepancies between these different blending rates are a major weakness that may have an impact on national and European industries moving forward.

The evolution of the weaknesses is assessed using two variables: the importance of the sectors with shared supply chains, and technical development.

- **Uncertainties on the future evolution of blending H_2 in current natural gas transport and distribution infrastructure.** As materials and components become optimised in the industry, and the use of hydrogen is normalised, the reluctance to accept higher blending rates will be reduced and countries will reach common ground. As a result, this vulnerability is expected to decrease in the medium term.

3.2.3.1.3. Sustainability and circularity

The sustainability assessment yields high scores for potential impacts in the categories of “Biodiversity and environment”, “Material use and recyclability” and “Robustness and flexibility” (see Table 20).

The impacts on the environment are derived mostly from the construction phase, in which biodiversity, soil and water can be severely affected. The intensity of the impact will depend on the route of the hydrogen backbone, the territory it passes through and the ecosystems encountered on the way. Air pollution can also be caused by the traffic generated by the construction activity, although this is considered a temporary impact and not a long-term effect of the installation.

In terms of materials, the development of coatings or new structures resistant to hydrogen embrittlement is key for both pipelines and compressors. This will also help to reduce hydrogen losses throughout the network and create a more robust system. The quality and purity of the hydrogen in the pipeline is still unknown, but it is likely to be too low for the requirements imposed by the main applications (e.g., electrolysers require purity >99% H_2). This leads to additional expenses in equipment for the end uses to purify hydrogen on site.

Table 20 Sustainability assessment of grid infrastructure

Biodiversity and environment	• The pipeline installation can have a major impact on soil and water systems during the installation and recovery phase. • The impact of the pipeline installation can cause biodiversity loss/ecosystem disruption during the installation and recovery phase. • Potential impacts related to the toxicity of ionic liquids for aquatic and terrestrial ecosystems.
Health and safety	• Hydrogen pipeline safety must be guaranteed at all times. Therefore, materials resistant to hydrogen embrittlement are important. • Presence of PFAS materials within the system (e.g., PTFE).
Material use and recyclability	• Use of materials classified as CRMs (e.g., carbon fibres, titanium alloys, nickel alloys). • Recycling techniques for carbon/glass fibres involve shredding and is thus limited to use for other purposes. Current recycling cannot maintain sufficient quality to reuse fibres for FRP pipelines. • Need for new materials and coatings to counter hydrogen embrittlement.
Robustness and flexibility	• Limited conservation of hydrogen purity in the lines could interfere with certain applications, requiring purification equipment on site. • Uncertainty regarding the robustness and flexibility of the system due to the lack of experience in large hydrogen pipeline backbones. • The pressure ranges within the grid infrastructure might not match most pressures required by storage and end-use options, requiring installations that adapt the pressure of the H_2 before its use on site.
Energy intensity and efficiency	• Energy losses during transit through the pipelines. • High energy consumption of compression systems.

3.2.3.1.4. Grid infrastructure - conclusion

The primary mode of hydrogen transportation anticipated to dominate Europe in the coming decades is that using pipelines. While hydrogen grid infrastructure technology is currently under development across Europe, notable initiatives such as the European Hydrogen Backbone (53,000 kms for 2040) already exist. Two paths for developing the technology are being considered: that of building new infrastructure exclusive for hydrogen transportation or that of retrofitting existing gas infrastructure. Neither of these solutions presents CRM-related supply chain issues.

However, improvements are needed to optimise hydrogen transport solutions, for which hydrogen embrittlement is a particularly relevant issue. Efforts are ongoing to identify optimal materials for components (e.g., fibre reinforcement layers), but there are concerns about reliance on third countries (Asia) where the markets for these materials are concentrated. The main challenge lies in the uncertainties regarding the optimal blending rate for hydrogen with natural gas. Varying levels, from 2% to 10%, could pose challenges for national and European regulations.

Despite these concerns, Europe has the opportunity to establish itself as a leading player. Ongoing initiatives, such as the European Hydrogen Backbone, showcase the region's commitment to pipeline hydrogen transportation. Retrofitting existing gas pipelines for hydrogen transportation or blending hydrogen with natural gas is another promising avenue, with studies demonstrating efficient performance under 20% blending rates.

Sustainability assessments highlight potential negative impacts in categories such as "Biodiversity and environment," "Material use and recyclability," and "Robustness and flexibility." Concerns centre around construction-phase impacts on biodiversity, soil, water, and air. Addressing the development of components resistant to embrittlement, a key concern, is crucial for reducing losses and enhancing network robustness.

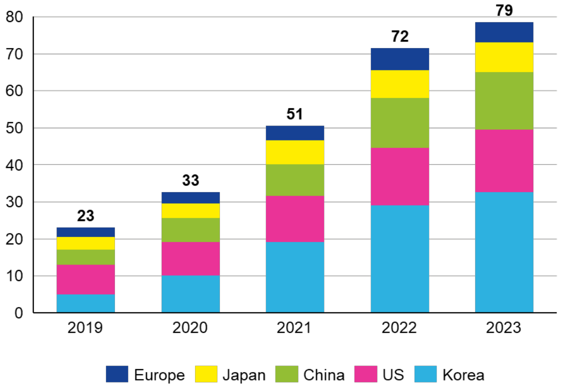
3.3. End-use technology supply chains

3.3.1. Fuel cell technologies

Fuel cell technologies constitute a sustainable approach in energy production, using hydrogen to generate electricity for a wide array of end applications. These advanced systems capitalise on chemical reactions to produce clean and efficient electrical power, diverging from conventional combustion-based methods. Each fuel cell variant exhibits unique operational features, catering to specific energy needs and applications. The most commonly used fuel cells as of today are PEMFCs and SOFCs, which have different applications, for instance for transport and combined heat and power for buildings, these being the most common uses in Europe.

The most common type of fuel cell for transport applications is the PEMFC. The fuel cell electric vehicle market is dominated by Korea, the US and China, representing ~80% of the market for the past 5 years. Europe's contribution to this market has not seen a major change in the last few years, remaining far behind Asia and the US.

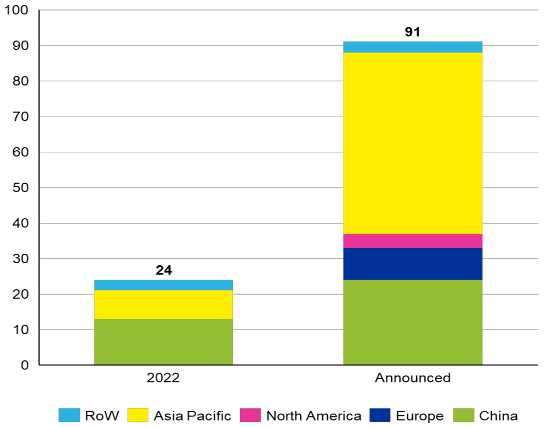
Figure 19 Fuel cell electric vehicle stock by region (2019-2023; thousand vehicles) [37]



Source: Global Hydrogen Review 2023; Monitor Deloitte

The analysis of the manufacturing capacity for these transport fuel cells is even more enlightening. Asia and, more specifically, China, are the leading players, accounting for the majority of the transport fuel cell market in 2022. In the future, the situation will remain very similar to that of today, with Asia as the leading player. However, Europe and the US will finally enter the market after the announcement of several projects for this decade.

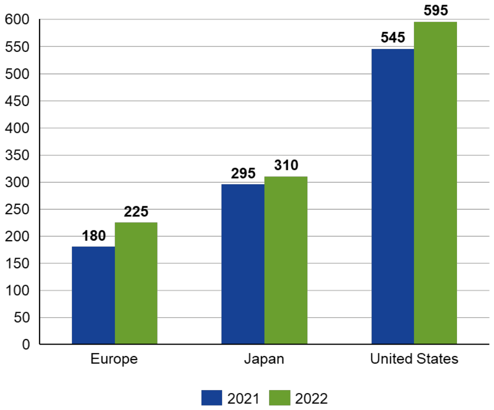
Figure 20 PEM fuel cell manufacturing capacity by region (2022-2030; GW/year) [37]



N.B.: based on announced projects; Source: Global Hydrogen Review 2023; Monitor Deloitte

For fuel cells in buildings (or CHP applications), SOFCs are more commonly utilised than PEMFCs as they are better-suited for this purpose due to their higher operating temperatures, enabling them to efficiently produce both electricity and usable heat. This characteristic aligns effectively with CHP applications where the heat generated can be captured and utilised for heating purposes and for enhancing overall energy efficiency. In this market Europe has a relatively higher presence than that for the other uses. However, it is still behind Japan and the US, which is the market leader with almost three times more installed stock than Europe, and double that of Japan.

Figure 21 Fuel cell stock used in buildings by region (2021-2022; MW) [37]



Source: Global Hydrogen Review 2023; Monitor Deloitte

3.3.1.1. PEM fuel cell (PEMFC)

3.3.1.1.1. Supply chain description

PEMFCs are devices used for electricity production, which is achieved using hydrogen as fuel and oxygen. They are currently commercialised and developed for transport and stationary use, mainly in transport and power applications. The scope of this technology is limited to the fuel cell stack, regardless of its application.

The criticality assessment yields the same results as the PEM electrolyser technology (see Section 3.1.1.1.1) since the components and their functionality are the same.

Table 21 Criticality assessment of (sub)components of a PEMFC

		PEM fuel cells (PEMFC)						
		Membrane Electrode Assembly (MEA)						
	(Sub) components	Electrolyte membrane	Cathode	Anode	Gas Diffusion Layer	Bipolar plates	End plates	Seal
Criteria	**Cost**	5	5	5	2	3	1	1
	Performance	5	5	5	3	2	2	3
	Technical development	5	5	5	3	3	1	1
	Results	**Critical**	**Critical**	**Critical**	**Semi-critical**	**Semi-critical**	**Not critical**	**Not critical**

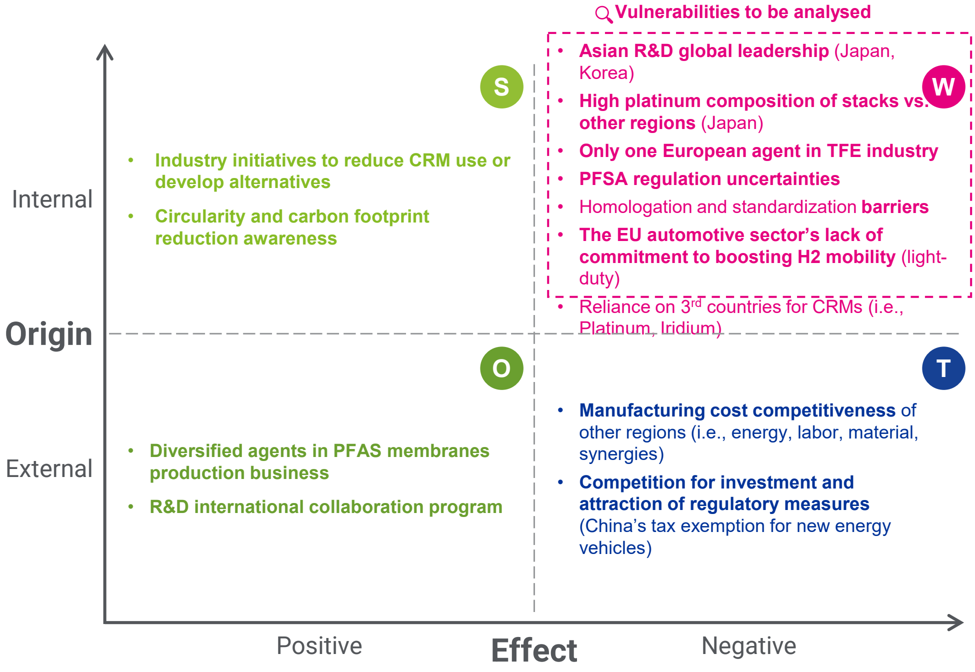
Source: SWECO; Industrial experts

3.3.1.1.2. SWOT analyses

Europe's main opportunities relating to this technology consist basically of its diversity of players in the PFAS membrane production business and the numerous existing international R&D collaboration programmes. The various different players in the PFAS industry represent a chance to develop European PEMFC solutions that are cost-efficient due to the competitiveness of the market and to avoid any possible supply chain issues regarding a component that is critical for the assembly of the final product. In addition, due to its collaboration in international programmes, Europe will be able to leverage the knowledge and expertise that other regions have already developed in recent decades.

There are also some associated threats that could have a negative impact on the evolution of European PEMFCs, namely the maturity and capabilities of Asian markets that offer higher manufacturing capacity and possibilities of attracting investment. China, for example, is offering a tax exemption for new energy vehicles which would allow them to become even more competitive in comparison with other international markets [57]. Other regions such as Japan or Korea have already demonstrated stronger manufacturing capabilities, which lead to better cost-efficiency. These are major concerning threats that could potentially make Europe merely an importer of this technology, as is already the case with light-duty hydrogen vehicles for example.

Figure 22 SWOT matrix of European capability factors for PEMFC



Source: Monitor Deloitte; Interviews with experts

European competitiveness in the PEMFC technology supply chain depends basically on the strengths derived from industry initiatives to reduce CRMs and sustainability awareness regarding carbon reduction:

- **Industry initiatives to reduce CRM use or develop alternatives.** The EU is aware of the barriers and dependencies that materials can create in the domestic industry. Nevertheless, European industries, in alignment with the EU Net-Zero Industry Act, have taken a proactive approach in this matter, by investing in the development of solutions to overcome potential issues that may arise in industrial upscaling.
- **Circularity and carbon footprint reduction awareness.** The upscaling of the manufacturing of net zero technologies produces environmental concerns. However, PEM industrial companies are working towards enforcing environmentally sustainable processes. The awareness created and the robust policies passed are clearly an EU strength. Not only do they force domestic industries to develop sustainable and low carbon solutions, but they also set a worldwide example by increasing the sustainability criteria to be met.

The vulnerabilities identified are rooted in technological knowledge and regulatory barriers or uncertainties (see Figure 22):

- **Asian R&D global leadership.** Besides all the supporting capabilities that Asian countries have regarding PEMFC (manufacturing, OEMs' commitment, etc.), these countries are also investing heavily in the development of this technology, as demonstrated by the patent issues in the last decade. Europe has yet to experience sufficiently significant growth in this aspect to become economically competitive vs. other regions.
- **High platinum composition of stacks.** Asian manufacturers have achieved reduced platinum-based stacks which European manufacturers are not yet able to produce.
- **Only one European player in the TFE chemical industry.** The high technical and economic barriers make it risky to locate the TFE chemical industry in Europe and there are concerns regarding the correct performance of the capacity expansion initiatives needed to satisfy current and projected PEMFC requirements.
- **PFSA regulatory uncertainties.** As explained, there is concern among some European chemical industries about the uncertainties regarding the use of PFASs, which include PFSA. EU approval is pending on the essential uses of fluorinated components and whether they will be allowed in PEM membrane manufacturing. There is the risk that other regions will get ahead in capacity expansions or in industry attraction measures, by creating a favourable regulatory and economic context, and, therefore, that there will be a dependency on third country imports of PFSA membranes if their use for PEM continues to be allowed.
- **Homologation and standardisation barriers.** The time to market and time for approval of new products or (sub)components for their commercialisation are considerably higher in Europe than for other regions due to strict regulations. Europe risks discouraging research by industrial players and also causing them to redirect the commercialisation of their new products to other regions with fewer bureaucratic barriers.
- **The EU automotive sector's lack of commitment to boosting H_2 mobility.** Whereas in Europe the focus on light-duty use by the mobility sector and its OEMs relates to battery electric vehicles, leading OEMs in Asia (Japan and South Korea) have been making continuous efforts to develop hydrogen mobility.

The evolution of the weaknesses is assessed using two variables: the importance of the sectors with shared supply chains, and technical development.

- **Asian R&D global leadership.** The evolution of this vulnerability is unknown at present since the role of Europe in PEMFC technologies in the medium term is yet to be established. Today Asian countries dominate the issuance of patents, and their automotive sector strongly supports the deployment of hydrogen mobility technologies. Europe is not taking the same approach and therefore the vulnerability could increase as the region becomes more and more dependent on imports from third countries. On the other hand, depending on the adoption of hydrogen mobility technologies in Europe, this increase in the vulnerability could be avoided. However, it does not appear that the vulnerability will decrease in the short term, due to Asia's leading position in both R&D and manufacturing capabilities.
- **High platinum composition of stacks.** Europe's high dependency on platinum-based components such as stacks is exerting stress on the technology supply chain. As a result of the current difference in expertise between Europe and Asian countries, this dependency has become even more evident due to a less developed PEMFC in Europe in comparison with these other countries. This dependency is expected to decrease due to new discoveries regarding the technology. However, it should also be considered that if the development of the technology is not sufficient, the supply chain will become more stressed as Europe

will become more and more dependent on imports from third countries for other PEMFC components as well.

- **Only one European player in the TFE chemical industry.** The possible regulatory restriction on fluorinated components is a barrier to the development of new plants or capacity expansion plans. Additionally, many operational barriers are not expected to be eliminated in either the short or medium term, so relocation of the industry to Europe or capacity increases do not seem to be a feasible option. All in all, this vulnerability is expected to increase in the short term given that alternative non-fluorinated membranes are still under research and are not widely commercialised.
- **PFSA regulatory uncertainties.** The competition from other industries is expected to be maintained or even increase in the coming year given the importance of Chlor-alkali products for the chemical industry [39]. Indeed, other technically viable alternatives are also subject to competition from other critical sectors. The technical development of other types of chemical-based membranes to substitute current PFSA is currently being researched, but there are still technical barriers to overcome. Therefore, this vulnerability will likely increase in the coming years as many PEMFCs are being assembled relying on PFAS membranes.
- **Homologation and standardisation barriers.** Competition for industry and knowledge attraction is only expected to increase in the coming years given the trend towards protectionism in strategic supply chains. Countries capable of developing and commercialising new improvements in short lead times will naturally attract industry developers and researchers. PEM technology and its associated (sub)components are also expected to evolve to a considerable degree. The evolution of this weakness is unknown and depends on Europe’s ability to retain talent and commercialise new discoveries in the future.
- **The EU automotive sector’s lack of commitment to boosting H_2 mobility.** The technological development of fuel cells and access to cheaper renewable hydrogen should result in the decrease of this vulnerability as OEMs would encourage the deployment of hydrogen mobility technologies for light-duty use.

3.3.1.1.3. Sustainability and circularity

A PEMFC operates under similar conditions to an electrolyser (see Section 3.1.1.1.1) and its components are built of almost all the same materials. This leads to a similar result in the sustainability assessment (see Table 22), except for certain characteristics such as feedstock purity requirements which, for a fuel cell, are applied to hydrogen. The fuel cell scores one point lower than the electrolyser in “Biodiversity and environment” since it does not give rise to water consumption. Like the electrolyser, the main concern centres around “Material use and recyclability” due to the dependency on PFAS-based membranes and PGM catalysts.

Table 22 Sustainability assessment of PEMFCs

Biodiversity and environment	• Dependency on PFAS-based membranes. • Contributes to air pollution if the electricity used to produce the fuelled hydrogen is not obtained from renewable sources.
Health and safety	• Use of PFAS. While not a threat to health or safety once configured into the electrolyser membrane, the production stage of the fluorinated polymer can be complex and hazardous. • The production, storage, and handling of hydrogen pose potential explosion and fire risks.
Material use and recyclability	• Use of materials classified as PFAS. • Use of, and dependency on, materials classified as CRMs (e.g., PGM catalysts). • Underdeveloped recycling procedures, particularly for critical parts like membranes/CRMs.
Robustness and flexibility	• Requires hydrogen with a high level of purity. • High maintenance requirements to maintain system performance and longevity.
Energy intensity and efficiency	• Operation of the stack generates a hydrogen output at up to approximately 50 bars, requiring a lot of energy to compress it for storage and some end uses (250-700 bars). • Potential energy losses during the conversion process of hydrogen to electricity.

3.3.1.1.4. PEMFC - conclusion

PEMFC technology has advanced to the commercialisation stage in both transport and stationary applications, including hydrogen vehicles and power systems. Despite this progress, Europe faces the challenge of lagging behind Asian countries, which currently dominate the market and exhibit superior PEMFC performance.

Several challenges lie ahead for Europe, including the need for technological enhancements, the utilisation of alternative materials to reduce dependency on CRMs, and the need to address regulatory concerns such as those for PFAS in the short term. There is also a lack of commitment from European OEMs in promoting hydrogen mobility solutions.

The MEA is particularly critical due to the use of precious metals that serve as benchmarks for their catalytic activity and chemical, thermal, and mechanical stability; crucial characteristics given the harsh conditions within the cell. The corrosive oxidising/reduction conditions and acidic environment necessitate careful material selection, impacting the performance and lifespan of the technology. The supply chain is also affected both by regulatory uncertainties regarding fluorinated chemicals required in membrane manufacturing and by equipment homologation requirements. These uncertainties contribute to a longer time-to-market vs. other regions.

Despite all this, Europe has the potential to compete globally in the PEMFC industry. This is due to ongoing efforts to reduce dependency on CRMs and the presence of leading players in PFAS membrane production.

The main concerns highlighted by the sustainability assessments, mirroring those for PEMEL, are in "Material use and recyclability", due to the reliance on PFAS-based membranes and PGM catalysts. However, there are exceptions, like feedstock purity requirements, where the assessment applies to hydrogen rather than water.

3.3.1.2. Solid Oxide fuel cell (SOFC)

3.3.1.2.1. Supply chain description

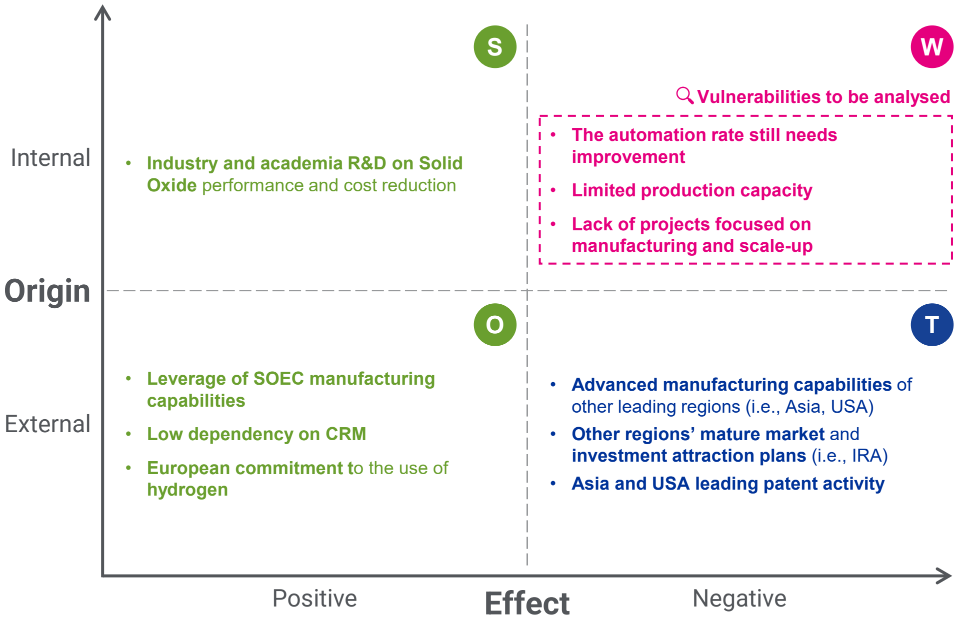
SOFCs are recommended for static industrial operations due to their lower power density requiring a larger size in comparison with PEMFCs. They are particularly useful as an alternative to Combined Heat and Power (CHP) systems since they produce both electricity and heat without the need to burn fossil fuels, thus avoiding emissions. Nevertheless, the scope of the study focuses on the technology itself, without an application context.

Due to the reversibility of the technology, and analogous subcomponents and materials, the criticality assessment yields similar results to those for SOECs. According to this assessment, the most critical components are the electrolyte, electrodes, and interconnectors due to their performance and technical development.

3.3.1.2.2. SWOT analyses

The analysis of European competitiveness has been performed using a SWOT matrix framework (Figure 23), showing that the main opportunities for this technology in the long term lie in the possibility of leveraging manufacturing capabilities for SOEC, which is gaining traction in the electrolyser industry; the lower dependence on CRMs in comparison with similar technologies; and the commitment to the use of hydrogen in the long term. If the industry is able to take advantage of these opportunities, European SOFCs will be able to compete at an international level and avoid the dependence on third countries that would result in having to import the technology.

Figure 23 SWOT matrix of European capability factors for SOFC



Source: Monitor Deloitte; Experts interviews

However, there are existing threats that could have an adverse impact on the development of the technology:

- **Other regions have more advanced manufacturing capabilities.** The US and Asian countries have developed larger scale SOFC units and have deployed more capacity in the markets. Europe is one step behind in manufacturing capacity, but the gap between Europe and Asia and the US is narrowing.
- **Global patent trends place the US and some Asian countries as the leaders** in the issuance of new SOFC patents over the last few years. This fact, in addition to their global manufacturing capabilities, makes it difficult for new European players to compete in the industry and gain recognition from end users.
- In addition to their greater maturity and manufacturing capabilities, the American and Asian regions also offer several **possibilities for attracting new investments** with the launch of new initiatives such as IRA.

European competitiveness in the SO (Solid Oxide) technology supply chain depends heavily on the R&D initiatives undertaken by the industry and academia to improve the performance of the technology and to reduce its costs. SO technology still faces many technical challenges related to real industry process integration and cost competitiveness. Research entities have been acknowledged for their collaboration with the industry in SO technical performance improvements, and EU manufacturers are working towards developing the scalability of the technology (both electrolysers and fuel cells) by leveraging Europe's leading knowledge capabilities.

Several weaknesses have been detected with respect to the SOFC industry supply chain in terms of the automation rate, the limited production capacity and the lack of projects focused on scaling-up (see Figure 23):

- **The automation rate still needs improvement.** As there are still very few commercial products and demand volumes are relatively low, European manufacturers have not faced any specific manufacturing bottlenecks so far. However, manufacturers note the required training time and rather manual manufacturing processes of the domestic suppliers on which they rely. Manufacturing training and quality assurance are challenges that Solid Oxide manufacturers face nowadays. The industry should continue making efforts to improve its automation as some companies are already making efforts in this direction [42].
- **Limited production capacity.** This vulnerability represents a potential bottleneck in the future if, when demand scales up, manufacturing capacities are not adapted. Currently, there are few European manufacturers and increasing competition to attract investment, especially in the US, where industrial and manufacturing capabilities are more mature, resulting in differences in scale of Solid Oxide products.

- **Lack of projects focused on manufacturing and scale-up.** A current problem is that Solid Oxide projects are not focused on manufacturing but rather on research into materials and components and the optimisation of their performance. This leads to a lack of competitiveness vis-à-vis major global manufacturing suppliers (e.g., Japan). Some European companies are making sustained efforts to expand their manufacturing capacity [43], but the industry in general lacks focus on new development projects geared towards scale-up.

The evolution of the weaknesses is assessed using two variables: the importance of the sectors with shared supply chains, and technical development.

- **The automation rate still needs improvement.** The mass production and assembly of Solid Oxide subcomponents will require EU industrial players to have higher automation rates. Automation will be needed not only to satisfy domestic demand, but also to reduce manufacturing costs and to achieve high quality products. This vulnerability is expected to increase due to the high barriers to the automation of the industry in the short term due to the learning curve required of European suppliers and competition with other industries for the knowledge and resources required for the automation of industrial processes.
- **Limited production capacity.** Solid Oxide technology expects a high level of technological development, which will give rise to the standardisation of Solid Oxide manufacturing processes and operating characteristics. Nonetheless, competition to attract or retain manufacturing and industrial processes will play a major role in the coming years. The extent of this vulnerability is unknown and depends on EU players' ability to support the scaling-up of industrial capabilities and on the development of a well-established domestic demand through the definition of Solid Oxide applications.
- **Lack of projects focused on manufacturing and scale-up.** As Solid Oxide technology increases its market size in Europe, new initiatives for the scaling-up of facilities should be incentivised. However, the extent of this vulnerability is unknown as it is highly dependent on the development of a well-established domestic demand through the definition of Solid Oxide applications.

3.3.1.2.3. Sustainability and circularity

Due to the reversible nature of this technology, the sustainability assessment (see Table 23) is almost the same for solid oxide fuel cells and for solid oxide electrolysers, except for certain impacts such as those resulting from water consumption in the electrolyser. For example, while the electrolyser required a certain level of purity, here in the case of the fuel cell the purity requirement in the feed is placed upon the hydrogen.

Table 23 Sustainability assessment of SOFCs

Biodiversity and environment	• Contributes to air pollution if the electricity used is not from renewable sources.
Health and safety	• High operating temperatures may pose safety risks during operation and maintenance. Risk of thermal burns during direct interaction with the system. • The production, storage, and handling of hydrogen pose potential explosion and fire risks.
Material use and recyclability	• Use of materials classified as CRMs (e.g., Nickel, Lanthanum). • Though components seem recyclable to a degree (on a small scale), no established pathways for component recycling have been demonstrated by companies at industrial level. • Experts interviewed state that the available techniques for recycling do not represent a viable business cost as opposed to sourcing new materials, due to the complexity and high cost of the process.
Robustness and flexibility	• Requires hydrogen to have a high level of purity. • Long start-up times due to the operation at high temperatures. The equipment is fit for continuous operation, not for switch on/off processes. • High operating temperatures reduce the lifespan of components, increasing maintenance requirements. At the current TRL the durability of interconnectors to sustain heating cycles is low. • The technology is currently underdeveloped, with a low TRL, and therefore still unreliable for industrial applications. Durability of the interconnectors is one of the main issues.
Energy intensity and efficiency	• Operation at high temperatures requires heat exchange systems. Some of the efficiency is lost if the waste heat generated by the cell is not repurposed. • Potential energy losses during the conversion process of hydrogen to electricity.

3.3.1.2.4. Solid Oxide Fuel Cells - conclusion

Solid Oxide Fuel Cells remain at an early stage of deployment, as indicated by their TRL of 7-8 (TRL of 9 for some specific applications such as residential use). This poses a critical challenge for Europe, where strategic hurdles within the supply chain must be addressed before commercialisation can be reached.

As of now, SOFC is a more cost-intensive technology than the alternative options. This is attributed to the current low level of automation in the supply chain process, a concern being addressed through the establishment of new, higher-scale plants. Additionally, limited production capacity among European manufacturers hampers the potential upscaling of demand, potentially leading to bottlenecks.

Compounding these challenges is the predominant focus of European support on R&D for technology performance improvement rather than on manufacturing and the scaling-up of existing or potential projects. This approach delays the arrival of cost reductions for the industry and diminishes the appeal for new entrants.

Despite these obstacles, SOFC technology holds the potential to compete globally with Asia and the US. Europe possesses substantial expertise in Solid Oxide performance and cost reduction, with opportunities to leverage SOEC manufacturing capabilities. Notably, SOFC is among the few hydrogen technologies with low dependence on CRMs, which presents a unique opportunity to establish a robust local supply chain.

The sustainability assessments, as with those for SOEC electrolysers, identify concerns in "Robustness and flexibility" in terms of the robustness of the cell concept design and the equipment's lack of flexibility. However, there are exceptions, such as feedstock purity requirements, where the assessment applies to hydrogen rather than water in the case of fuel cells. The technology's lack of maturity and its operation at high temperatures present additional challenges that may impact the lifespan of its components.

3.3.2. Industrial use technologies

3.3.2.1. Steel decarbonisation: Direct Reduction of Iron (DRI) method

3.3.2.1.1. Supply chain description

The iron and steel sectors are two of the main energy users and CO_2 producers within the industry. Conventionally, iron and steel are produced via a blast furnace/basic oxygen furnace (BF-BOF). In order to reduce emissions, new processes are being developed, the most promising of which is known as **direct reduction of iron (DRI) followed by an electric arc furnace (EAF)**. This process is preferred to others since it can function with hydrogen as a reducing agent and is used to produce steel from both ore and scrap [58].

Although the DRI-EAF method is described as a new alternative for steelmaking, it is not truly a new process. DRI-EAF plants are already in operation as lower temperature replacements for the BF-BOF method, which is considered to be the “conventional” option since it has historically been the most common method for producing iron. However, these DRI-EAF plants, which are reliant on the use of a reducing agent to produce the iron, generally use CO from natural gas. The novelty being proposed for decarbonisation is the adaptation of the process to change the reductant from natural gas to hydrogen. Therefore, the scope of this study is limited to the **DRI-EAF** technique, using hydrogen as a reducing agent, since it is capable of decarbonising steel production, has the possibility of fully running on hydrogen, involves a less energy-intensive process, and has a TRL of 6-8, which is higher than that of the alternative routes.

The criticality assessment highlights the shaft furnace as the main point of study in this report (see Table 24).

Table 24 Criticality assessment of the DRI-EAF steel production method

DRI-EAF steel production method				
	(Sub) systems	Iron section	Steel section	Balance of plant
		DRI shaft furnace	EAF	
Criteria	Cost	3	3	3
	Performance	5	5	2
	Technical development	5	2	1
	Results	Critical	Semi-critical	Not critical

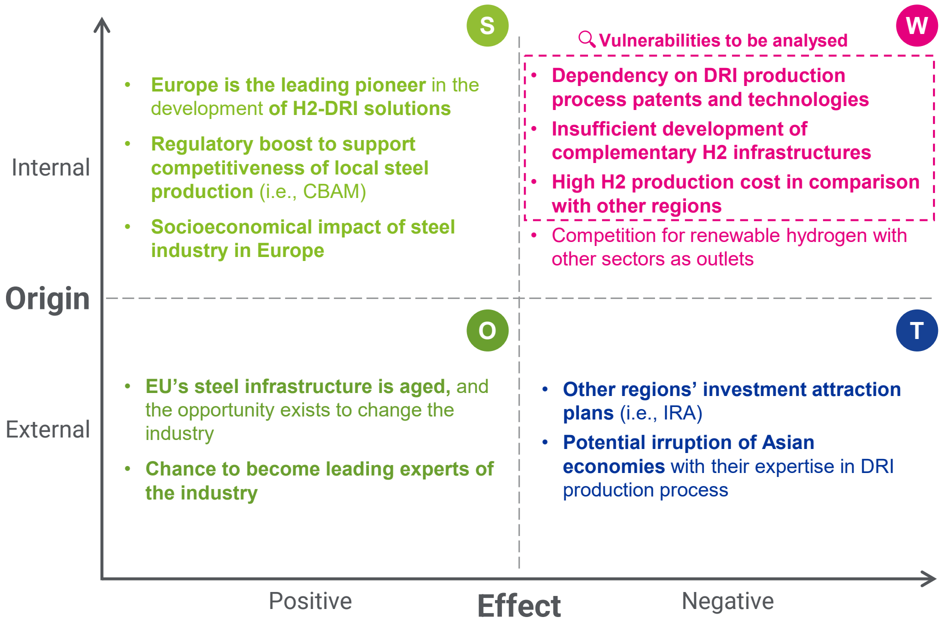
Source: SWECO; Industrial experts

3.3.2.1.2. SWOT analyses

European competitiveness was analysed using a SWOT matrix framework (Figure 24) which showed that the primary opportunity for H_2-DRI lies in the potential for the EU's steel infrastructure to be adapted for hydrogen integration. There is a unique opportunity for Europe to be a global frontrunner in the advancement of this technology. The infrastructure for steel production in Europe is aging and nearing the stage when it needs to be replaced with newer facilities. Capitalising on the current environment and the ongoing efforts to introduce hydrogen into Europe presents the sector with a unique opportunity to carry out both changes simultaneously, leading to a reduction in operating costs and further boosting industry decarbonisation. Given the maturity of the technology and Europe's position as the leading developer of H_2-DRI projects, Europe has the potential to become a dominant player in the steel decarbonisation landscape.

There are also potential threats associated with the European H_2-DRI technology supply chain that could hinder the progress of Europe's steel manufacturing industry in the short/mid-term. The introduction of new economic and regulatory incentive plans in regions with greater manufacturing capacity and the potential to attract investment (e.g., the US with its IRA) poses a significant challenge. This could potentially shift the focus of decarbonisation efforts in Europe's steel industry to other regions. Asia is a major potential disruptor in this regard. As the world's leading producer of DRI, and with its recent efforts related to the issuance of new patents in the iron and steel industry, Asia is in direct competition with Europe. This underscores the need for strategic planning and innovation to maintain Europe's competitive edge in the decarbonisation of the steel industry.

Figure 24 SWOT matrix of European capability factors for H_2-DRI technologies



Source: Monitor Deloitte; Interviews with experts

European competitiveness in the H_2-DRI technology supply chain depends basically on the strengths derived from being the leading developer of H_2-DRI projects globally, the existence of a strong and protected European market for steel production, and the socio-economic impact of the steel industry in Europe:

- **Leading developer of H_2-DRI projects globally.** Europe is at the forefront of H_2-DRI project development, accounting for over 80% of the total capacity committed globally. This gives Europe a technological and economic advantage over its competitors and provides the industry with the means to significantly reduce carbon dioxide emissions.
- **Regulatory boost to support the competitiveness of local steel production.** Europe has a rich history of steel manufacturing, which has been safeguarded by various regulations to ensure its cost competitiveness vis-à-vis other leading steel-producing regions such as India, Iran, and China. Currently, Europe is implementing the Carbon Border Adjustment Mechanism (CBAM) to extend the carbon price of the European Union Emissions Trading System (EU ETS) to iron and steel imported from outside the region. This strategic move aims to level the playing field for domestic producers adhering to stringent emission standards, further bolstering Europe's position in the global steel industry.
- **Socio-economic impact of the steel industry in Europe.** Indeed, Europe's long-standing tradition in steel manufacturing has fostered a robust industry that contributes significantly to job creation and the EU's budget. The steel industry serves as one of the pillars of the EU's economy, providing it with a

favourable position in future negotiations and decision-making processes. This advantageous position underscores the strategic importance of the steel industry in Europe's economic landscape.

Based on the SWOT analysis (see Figure 24), the vulnerabilities identified for the development of H_2-DRI technologies for steel decarbonisation are basically the licensing of the DRI production processes, the maturity and price of electrolysis and the insufficient existing transportation infrastructure for hydrogen.

- **Dependency on DRI production process patents and technologies.** EU manufacturers are indeed dependent on patents and technologies originating from third countries, such as the MIDREX process from the US, which is the leading process used for DRI production in the world. This dependence leaves them susceptible to potential disruptions or changes in licensing terms. It also restricts their control over vital technologies in steel production, which could impact their ability to adapt and innovate in a rapidly evolving landscape.
- **Need for competitive green H_2 production costs to achieve scalability.** One of the main bottlenecks for H_2-DRI relates to competitive renewable hydrogen production costs. Europe does not have the same capacity as other regions to produce large quantities of renewable hydrogen, due to the scarcity of renewable resources, thus leading to higher production costs and preventing the industry from achieving scalability.
- **Insufficient development of complementary H_2 infrastructure.** Europe does not have sufficient manufacturing and transportation capacity to cope with the present and future demand for renewable hydrogen. The potential demand for hydrogen for H_2-DRI plants in the next few years exceeds the projected hydrogen manufacturing capacity in Europe, thus creating an imbalance between supply and demand.

The evolution of the weaknesses is assessed using two variables: the importance of the sectors with shared supply chains, and technical development.

- **Dependence on DRI production process patents and technologies.** The H_2-DRI technology has not been fully developed technically/commercially and there is room for improvement over the next few years. This vulnerability is expected to decrease as technology evolves and new solutions/processes are developed.
- **Need for competitive green H2 production costs to achieve scalability.** With the increase in renewable energy capacity in Europe, cheaper renewable electricity should become more accessible and, as a result, the production of renewable hydrogen should be cheaper, which will lead to scalability in the sector. This vulnerability should decrease in line with the development of the European electricity system.
- **Insufficient development of complementary H_2 infrastructure.** As the hydrogen industry develops in the future, the expected infrastructure capacity of hydrogen production technologies should increase due to technical advancement and the investment of new funds in the industry. This vulnerability should decrease over time. However, the use and prioritisation of the hydrogen produced could be a potential concern.

3.3.2.1.3. Sustainability and circularity

The concerns regarding the technology are assessed through the sustainability assessment (see Table 25), which highlights issues across all the categories analysed. The highest score is in the “Robustness and flexibility” category, due primarily to concerns about the significant reliance on renewable energy sources to meet the substantial energy requirements and the availability of the hydrogen feedstock necessary for the proper functioning of the process. This reliance presents a challenge given the size of the industry and the current competitiveness of hydrogen resources. Furthermore, the flexibility of the process in accommodating different feedstocks requires further validation, particularly in terms of assessing the recyclability of certain metals through this route.

Table 25 Sustainability assessment of steel production using the DRI method

Biodiversity and environment	• Extraction of iron ore and other materials for DRI production can have environmental effects. • Risk of water pollution from process water and chemical spills. • If powered by blends of hydrogen and natural gas, there are still GHG emissions.
Health and safety	• High operating temperatures may pose safety risks during operation and maintenance. • The production, storage, and handling of hydrogen pose potential explosion and fire risks. • Respiratory health concerns due to exposure to particulate matter and gases during operations.

Material use and recyclability	• Dependence on ore extraction due to current low usage of recycled materials. • Generation of waste materials, such as slag, requiring proper handling and disposal. • Limited recyclability of feedstocks used in the DRI process, leading to waste generation.
Robustness and flexibility	• Potential limitations in adapting to varying feedstocks, affecting supply chain resilience. Dependence on production of large amounts of renewable hydrogen. • Certain alloying elements used in steel production may not be easily incorporated into the DRI process, limiting the range of available steel grades and applications. • Time-consuming start-up and shutdown processes, reducing operational flexibility. • Constraints on adapting the production process to different feedstocks or variations in H_2 quality.
Energy intensity and efficiency	• Energy-intensive process due to the energy requirements for H_2 and steel production. • Efficiency losses due to the conversion of H_2 and iron ore into steel, affecting energy efficiency. • Potential challenges in capturing and utilising waste heat or by-product gases to improve energy efficiency in the steel production process.

3.3.2.1.4. Steel decarbonisation DRI method - conclusion

Current steel facilities have improved their material and energy processes over time, operating at near-optimal levels. Despite this, the steel industry contributes 8% of global energy demand and generates 7% of the annual CO_2 emissions in the energy sector.

Among alternative steel production processes, DRI stands out as a promising decarbonisation method. However, its integration with hydrogen remains at an early stage.

The key concerns regarding the technology do not lie solely in materials but also in licensing, technology utilisation, and the complementary solutions needed for H_2-DRI production. Reliance on patents and technologies from third countries (MIDREX) exposes EU agents to disruptions and licensing limitations, hindering control over crucial steel production methods. Besides, the high cost of producing renewable hydrogen, coupled with Europe's limited capacity due to scarce resources, exacerbates the bottlenecks. Inadequate hydrogen infrastructure, manufacturing and transportation further compound these issues.

Europe is uniquely positioned to lead the H_2-DRI steel production sector globally. Its leadership in project development and the opportunity to replace aged steel infrastructure with H_2-DRI solutions bolster this potential, as does the strong regulatory support, exemplified by initiatives like the CBAM which boost the sector at a local level.

The sustainability assessments highlight potential adverse impacts across all categories, notably in "Robustness and flexibility." Heavy reliance on renewable sources to meet substantial energy needs and secure hydrogen feedstock poses challenges due to the size of the industry and the competition for hydrogen resources. However, the DRI-EAF technology allows steel recycling, reducing the impact of producing new steel.

3.3.3. Other technologies

3.3.3.1. Electricity generation (H_2-gas turbines)

3.3.3.1.1. Supply chain description

Gas turbines are commonly used to generate electricity. They drive air through a compressor that connects with a combustion chamber where a hydrocarbon is burnt to add more energy to the air in the form of heat and pressure. The combustion gas is led to the turbine where it moves through the blades producing mechanical work. By coupling the shaft of the turbine with a generator, mechanical energy is used to generate electricity.

Power plants with gas turbines come in two configurations: an open cycle configuration and a combined cycle configuration, in which exhaust gases from the open cycle power a steam turbine. The gas turbine remains identical in the two configurations. It consists of several subsystems: air compressor, combustion chamber, turbine stage (turbine blades attached to turbine discs) and auxiliary components (rotors, casings and other).

Traditional natural gas turbines currently stand at TRL 9 since they are used in traditional electricity generation power plants. Gas turbines using various hydrogen blends stand at TRL 7-8 as they are currently being offered by large turbine manufacturers but are still awaiting large-scale demand and standardisation. The industry is confident that it will be able to provide standard turbines capable of running entirely on hydrogen by 2030 [59].

Turbines running entirely on hydrogen or high hydrogen mixing blends are a pre-requisite for gas turbines to act as a feasible and plausible technology in a future low-carbon energy system. This is a result of the non-linear correlation between blending rates and the resultant CO_2 reductions. A mixing rate of 50% hydrogen to

50% natural gas only results in a small reduction of 25% gCO_2/KWh_{el} for a typical combined cycle power plant [60].

Lastly, the supply chain analysis in this report covers only land-based turbines for electricity generation.

The criticality assessment is applied to the most important components of the technology. The analysis indicates that the burner, turbine blades and turbine wheels are the most critical components (see Table 26).

Table 26 Criticality assessment of H_2-gas turbines

H_2-gas turbines						
	(Sub) components	**Air compressor blades**	**Combustion Chamber**	**Turbine blades**	**Turbine discs**	**Nozzle**
Criteria	**Cost**	3	5	5	4	3
	Performance	3	5	5	5	2
	Technical development	2	5	5	3	2
Results		**Semi-critical**	**Critical**	**Critical**	**Critical**	**Not critical**

Source: SWECO; Industrial experts

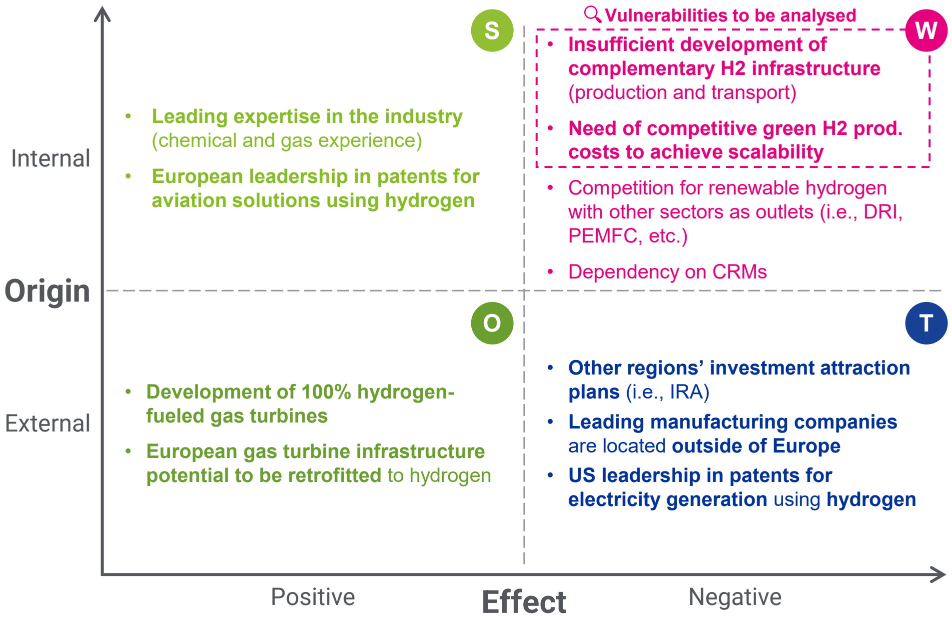
3.3.3.1.2. SWOT analyses

European competitiveness was analysed using a SWOT matrix framework (Figure 25) which showed that the main opportunities for this technology are basically the development of 100% H_2-gas turbines and the potential for European gas infrastructure to be retrofitted. The technology has yet not reached total maturity, meaning there is room for improvements, a higher acceptance of hydrogen blending, and a higher reduction of emissions. Hydrogen blending in state-of-the-art turbines has exceeded 50% [61] and a few pilot projects have achieved 100% hydrogen blending. Europe has an opportunity to become the leading region in terms of 100% H_2-gas turbines [62], but it faces strong competition from other regions and leading manufacturing companies.

Europe also represents a promising opportunity for this technology due to its long-standing tradition in gas turbines and its extensive related infrastructure, the existence of state-of-the-art gas turbines sitting idle and underutilised across Europe, and the fact that most of the components employed in traditional gas turbines can be repurposed for H_2-gas turbines with a few exceptions (e.g., the combustion chamber). The retrofitting of this infrastructure would not represent an issue and is a unique opportunity in comparison with other technologies.

There are also threats that could impede the development of the EU's supply chain. Several of the leading manufacturing companies (e.g., GE, Kawasaki, Mitsubishi) are located in regions outside Europe. Consequently, Europe functions as an importer of this technology, except for a few regional companies which drive local supply (e.g., Siemens, Ansaldo Energia). With the introduction of new industrial regulatory initiatives, such as the US's IRA, these other regions are emerging as potential frontrunners in the advancement of H_2-gas turbines. Viewed in a short-term perspective, these external regions, particularly the US, are also taking the lead in the hydrogen-based electricity generation industry in terms of patent issuance. This trend could position Europe as a secondary region in terms of development, potentially impacting its competitive edge in the global landscape. These are significant and concerning threats that have the potential to hinder the progress of Europe's manufacturing industry and, as a result, place the region primarily in the role of a technology importer.

Figure 25 SWOT matrix of European capability factors for H_2-gas turbines



Source: Monitor Deloitte; Experts interviews

European competitiveness in the H_2-gas turbine technology supply chain depends basically on the strengths derived from its knowledge and its leadership in patent activity for aviation solutions using hydrogen:

- **Leading expertise in the industry.** The chemical/gas industry in Europe has existed for decades and Europe has developed knowledge of these industries. The technology required to build H_2-gas turbines is similar to that used for traditional gas turbines and minimal alterations are needed. This results in significant opportunities to leverage synergies from the established traditional gas and chemical industries.

- **European leadership in patents for aviation solutions using hydrogen.** Other regions, such as the US or Asia, are home to leading manufacturing companies for H_2-gas turbine technologies. Nevertheless, when it comes to the specialised application of aviation solutions using hydrogen (H_2-gas turbines and fuel cells), Europe is at the forefront of R&I, closely followed by the US. The region could concentrate on this alternative to enhance its global competitiveness in the field of H_2-gas turbines.

Based on the SWOT analysis performed (see Figure 25), the vulnerabilities identified are mainly rooted in the lack of sufficient natural resources for the cost-effective production of renewable hydrogen. The dependence on CRMs should be monitored over the long term, but it does not represent a significant issue in the supply chain at present.

- **Insufficient development of complementary H_2 infrastructure.** Europe does not have sufficient manufacturing and transportation capacities to cope with future demand for renewable hydrogen in all its end-uses. H_2-gas turbines will demand over 50 TWh of renewable hydrogen by 2050 out of the ~2,000 TWh expected under the *REPowerEU* scenario. The access to renewable hydrogen will, consequently, be complex as other end-use technologies, which will already have been established in the market by then, will be competing for it. This, combined with the fact that only ~1,800 TWh of renewable hydrogen are expected to be produced under the same *REPowerEU* scenario, will create an imbalance between the projected local hydrogen manufacturing capacity and the end-user demand for this hydrogen.

- **Need for competitive green H_2 production costs to achieve scalability.** One of the main bottlenecks for hydrogen-gas turbines is the lack of competitiveness in the production of renewable hydrogen. Europe does not have the same capacity as other regions to produce large quantities of renewable hydrogen, due to the scarcity of renewable resources, thus leading to higher production costs and preventing Europe from achieving scalability in the industry.

The evolution of the weaknesses is assessed using two variables: the importance of the sectors with shared supply chains, and technical development.

- **Insufficient development of complementary H_2 infrastructure.** As the hydrogen industry develops in the future, the expected infrastructure capacity for hydrogen production should increase due to technical advancement and new funding. This vulnerability should not be a major concern and should decrease over time. However, the use and prioritisation of the hydrogen produced could be a concern.
- **Need for competitive green H_2 production costs to achieve scalability.** With the increase in renewable energy capacity in Europe, cheaper renewable electricity should be more accessible and, as a result, the production of renewable hydrogen should be cheaper, helping the industry achieve scalability. This vulnerability should decrease in line with the development of the European electricity system.

3.3.3.1.3. Sustainability and circularity

In the case of this technology, the sustainability assessment points to “Material use and recyclability”, “Robustness and flexibility” and “Health and safety” as the areas of concern (see Table 27). These categories receive the highest scores, suggesting the highest potential for positive impact.

Regarding the materials used, the presence of CRMs and the uncertainty surrounding their recyclability once integrated into a superalloy contribute to the potential impacts. Furthermore, the performance of this technology relies on the development of new materials that are resistant to embrittlement.

The health and safety concerns are a result of hydrogen being a flammable substance, posing significant risks such as that of explosion, particularly in the event of malfunctions or hydrogen flashbacks in the combustion chamber.

The interviews also reveal that this technology’s emission levels are only being addressed within the turbine system itself, reducing the emissions from the system by increasing the amount of hydrogen in the blend. Therefore, the analysis is independent of the type of hydrogen and disregards production-related emissions.

Table 27 Sustainability assessment of H_2-gas turbines

Biodiversity and environment	• High amount of NOx emissions without the use of adapted burners. • Currently requires combination with natural gas for combustion. • Contributes to air pollution if the electricity used to produce the hydrogen is not renewable.
Health and safety	• The production, storage, and handling of hydrogen pose potential explosion and fire risks. • Risk of hydrogen flashback in the combustion chamber.
Material use and recyclability	• Use of materials classified as Strategic Raw Materials (e.g., nickel, ruthenium). • The recycling and recovery rate of the superalloy materials are uncertain. • Need for new materials and coatings to counter hydrogen embrittlement.
Robustness and flexibility	• Low efficiencies for small-scale electricity production. • Difficulty for onsite hydrogen storage. • Potential limitations on applicability; the technology is only interesting in the context of reducing CO_2 emissions if it works with curtailed green energy.
Energy intensity and efficiency	• Efficiency related to conversion of hydrogen into electricity with gas turbines. • Efficiency difficult to improve in relation to exergy losses.

3.3.3.1.4. Electricity generation (H_2-gas turbines) - conclusion

H_2-gas turbines, a nascent power generation technology, face manufacturing scale immaturity in Europe, where only a few players engage in production. The leading expertise and manufacturing prowess resides in the US and Asia, leaving Europe striving to enhance technology efficiency and global competitiveness.

This technological immaturity presents several concerns for H_2-gas turbines since the equipment relies heavily on CRMs (e.g., nickel**,** titanium), rendering Europe reliant on third countries; also, the high costs of renewable hydrogen production, coupled with limited European capacity due to scarce material resources (e.g., aluminium, boron) exacerbate the existing bottlenecks. Yet, due to their long-standing tradition in the gas/chemical sectors, H_2-gas turbines emerge as an alternative for large manufacturers and users. Europe currently lacks competitiveness but holds unique opportunities.

Aging gas-based turbines in Europe offer immense potential for seamless retrofitting into H_2-gas turbines with minimal modifications. Additionally, the technology's immaturity presents unexplored applications, such as widespread commercialisation of 100% H_2-gas turbines or the use of this technology for aviation solutions. Seizing these opportunities could position Europe as a global leader.

The sustainability assessments flag concerns in "Health and safety," "Material use and recyclability," and "Robustness and flexibility." The technology's heavy reliance on CRMs and the lack of new embrittlement-resistant materials pose significant sustainability challenges. Moreover, combining hydrogen with specific elements, such as the combustion chamber, presents potential risks that need attention.

3.3.3.2. Synthetic methanol

3.3.3.2.1. Supply chain description

Methanol is one of the bulk chemicals with the highest global demand, since it is a precursor to a wide range of chemicals and fuels, with a current production of 98 Mt/year that is expected to increase in the coming decades [63]. Methanol can be considered as a carrier (LOHC), although, due to conversion losses it can be expected to be used mostly as an "end product" (e.g., fuel, chemical feedstock). Therefore, renewable methanol could be used as a fuelling solution with only minor technology adaptations (e.g., changes to existing fossil fuel engines) for the hard-to-abate sectors where electrification may not be possible (maritime transport).

Currently, methanol is produced using syngas sourced from natural gas or coal. The life-cycle emissions from global methanol production and consumption amount to 0.3 Gt CO_2 (~10% of total emissions from the chemical sector). New production methods are being investigated and they can be subdivided in two categories: **bio-methanol** (biomass) and **synthetic methanol** (CO_2 and hydrogen). Since the project focuses on the supply chain of hydrogen technologies, the scope is limited to **synthetic methanol.** In this category, several techniques for synthetic methanol production are currently under research, the most prominent of which are: **hydrogenation with heterogeneous catalysis** and the **electrochemical method**. The production method selected for inclusion in the supply chain analysis is CO_2 hydrogenation through heterogeneous catalysis, since it is hydrogen-specific and has a higher TRL of 8-9 and greater scalability compared with the alternatives.

Based on the sections identified within the process, the criticality assessment results (see Table 28) single out the reaction section as the critical part of the process, including both the reactor and the catalyst. The separation section is often run using traditional distillation columns which are not expected to undergo drastic technical development and, having only a certain impact on performance, influence mostly the end purity level. Nevertheless, separation sections tend to drive up costs in most processes, and therefore a higher score was awarded.

Table 28 Criticality assessment of the synthetic methanol production process

		Synthetic methanol production process			
	(Sub)Components	Reaction section		Separation section	Balance of the plant
		Reactor	Catalyst		
Criteria	**Cost**	3	2	4	2
	Performance	5	5	3	1
	Technical development	4	4	2	1
	Results	**Critical**	**Critical**	**Semi-critical**	**Not critical**

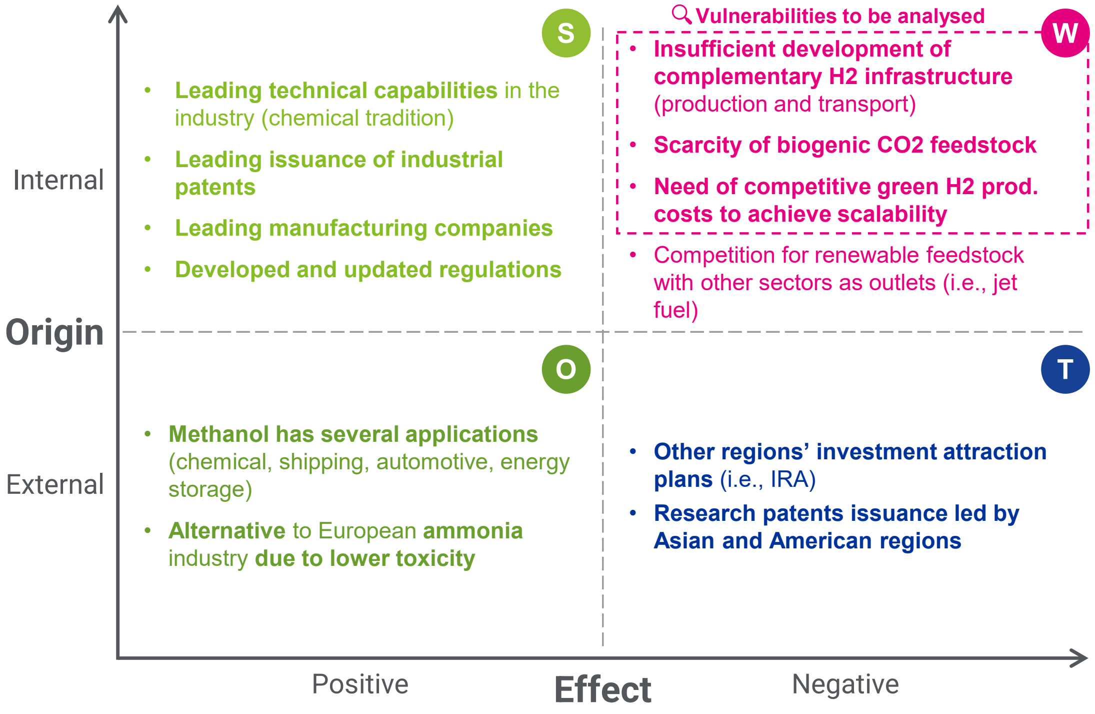
Source: SWECO; Industrial experts

3.3.3.2.2. SWOT analyses

European competitiveness was analysed using a SWOT matrix framework (Figure 26) which showed that the main opportunities for this technology are basically the use of methanol as a replacement for ammonia due to its lower toxicity and the numerous alternative applications in European industries (e.g., chemical, shipping). Methanol is toxic and flammable; however, as it is already used as a shipping fuel today, it has an edge regarding safety measures and technology advancement that ammonia does not. Therefore, wherever there are common applications, synthetic methanol can represent an alternative to ammonia, and vice versa. Moreover, although there are numerous applications for synthetic methanol in European industries, as it is being used in the chemical and automotive industries, the shipping industry is projected to become one of the largest drivers of global demand.

However, there are also some associated threats that could have a negative impact on the development of synthetic methanol in the EU. Even though the EU's synthetic methanol technologies are already mature due to Europe's tradition in the chemical industry, other regions are moving fast in the development of these technologies. Industry innovation is, as of today, located in Europe; however, the opposite is the case when considering research efforts. Once selected Asian countries and the US reach the technological advancement level seen in Europe, they will become major threats for the production of synthetic methanol. These regions offer higher manufacturing capacity and alternative possibilities for attracting investment (e.g., the US's IRA).

Figure 26 SWOT matrix of European capability factors for synthetic methanol



Source: Monitor Deloitte; Experts interviews

European competitiveness in the synthetic methanol technology supply chain depends on the strengths derived from the EU's technical, manufacturing and knowledge-based capabilities, its lack of reliance on significant components or materials, and the existence of a developed framework for the use of synthetic methanol:

- **Leading technical capabilities in the industry.** The methanol industry in Europe has existed for decades and Europe has been gathering technical knowledge and developing the latest innovations in methanol production. Producing synthetic methanol involves minimal alterations to components and materials, which results in significant opportunities to leverage synergies from the established traditional methanol industry. Europe is well-established to be a leading region in terms of knowledge/technical development.
- **Leading manufacturing companies.** Due to its extensive knowledge of the industry and the opportunity that the reduction of methanol emissions represents, Europe has become the major driver of synthetic methanol projects in recent years. The scale of these projects is not the result of more or less technical advancement, but rather of the lack of available resources in Europe, as will be explained later.
- **Developed and updated regulations.** As synthetic methanol is a derivative of methanol, the regulatory framework for the product is already in place. Owing to the use of methanol in the last few decades, Europe has issued new regulations and updates industry regulation regularly. The use of methanol is supported by European regulations, which helps the development and ultimate commercialisation of the product.
- **Leading the issuance of industrial patents.** EU manufacturers have attempted to develop the technology in the industrial sphere. Europe leads the issuance of new industrial patents, which guarantee the continuing efforts of European manufacturers in the development and scale-up of synthetic methanol technologies.

Based on the SWOT analysis (see Figure 26), the vulnerabilities identified for the development of the synthetic methanol supply chain are basically the insufficient existing transportation infrastructure for hydrogen, the maturity and price of electrolysis and the scarcity of biogenic CO_2.

- **Insufficient development of complementary H_2 infrastructure.** Europe does not have sufficient manufacturing and transportation capacity to cope with the present and future demand for renewable hydrogen. The potential demand for H_2-gas in the next few years exceeds the projected hydrogen production capacity in Europe, thus creating an imbalance between supply and demand.

- **Need for competitive green H_2 production costs to achieve scalability.** One of the main vulnerabilities that prevents synthetic methanol technology from developing faster is the lack of competitive production of renewable hydrogen. Europe does not have the same capacity as other regions to produce large quantities of renewable hydrogen, due to the scarcity of renewable resources, thus leading to higher production costs and preventing the industry from achieving scalability.
- **Scarcity of biogenic CO_2 feedstock.** Europe does not have the capacity to produce the amount of biogenic CO_2 necessary to cover the expected demand for synthetic methanol production in Europe in the next few years.

The evolution of the weaknesses is assessed using two variables: the importance of the sectors with shared supply chains, and technical development.

- **Insufficient development of complementary H_2 infrastructure.** As the hydrogen industry develops in the future, the expected infrastructure capacity for hydrogen production technologies should increase due to technical advancement and the investment of new funds in the industry. This vulnerability should not be a major concern and should decrease over time. However, the use and prioritisation of the hydrogen produced could be a concern.
- **Scarcity of biogenic CO_2 feedstock.** The production (or capture) of biogenic CO_2 could be an increasing concern in the future. As the European energy industry moves on to greener solutions, biogenic CO_2 could become less freely available, creating an issue for the production of synthetic methanol.

3.3.3.2.3. Sustainability and circularity

The sustainability of methanol production depends on improving efficiency and transitioning to renewable energy sources in the chemical and petrochemical sectors involved. Currently, these industries rely heavily on fossil fuels, resulting in significant CO_2 emissions. The use of carbon upcycling and renewable hydrogen in the production of methanol can mitigate CO_2 emissions during combustion, making low carbon methanol a viable low-carbon fuel option in the short term. However, achieving climate goals necessitates a reduction in emissions.

Another opportunity for obtaining carbon feedstock for synthetic methanol production lies in the synergistic combination of gasification and synthetic methanol production. The CO_2 generated through gasification can be repurposed to fuel the methanol process, offering a more sustainable short-term solution vs. blue methanol. However, it is crucial to ensure that biomass and organic waste gasification uses only waste materials and, therefore, the amount of CO_2 produced might fall short of covering the demand for methanol production. Depending on the feedstock and production processes involved, methanol can yield carbon reduction benefits ranging from 65% to 95%. The estimated CO_2 emissions from methanol produced via CO_2 recycling and renewable hydrogen sources are significantly lower, within a range of 1.74-33.1 gCO_2-eq/MJ, than for fossil fuels such as petrol (83.8 gCO_2-eq/MJ).

To highlight some of the potential issues of this technology, a sustainability assessment was conducted (see Table 29). The analysis revealed that the main areas of concern are "Energy intensity and efficiency", due to the energy-intensive production process, including hydrogen generation; "Robustness and flexibility", due to the dependence on developing technologies to ensure a steady renewable feedstock supply; and "Health and safety", due to the risks associated with operating chemical processes involving hazardous substances.

Table 29 Sustainability assessment of methanol as a hydrogen end-product

Biodiversity and environment	• Air pollution: potential emissions of unreacted CO_2, by-products (CO) and organic compounds. • Risks of water pollution resulting from the release of the methanol, by-products and wastewater generated.
Health and safety	• The production, storage, and handling of hydrogen pose potential explosion and fire risks. • Methanol is also a highly flammable substance. • Methanol is an irritant and is dangerous if it comes into contact with skin, or is inhaled or swallowed. • Operation at high temperatures and pressures (200-300°C, 50-100 bar).
Material use and recyclability	• Use of materials classified as CRMs (e.g., nickel in the catalyst). • Uncertainty regarding catalyst regeneration and material recyclability.

Robustness and flexibility	• Time-consuming start-up and shutdown processes, reducing operational flexibility. • Potential dependency on new, underdeveloped technology in order to obtain feedstock in sufficiently large quantities to cover demand (e.g., dependency on DAC to obtain the CO_2 feed). • Dependence on the availability and cost of green H_2, which are correlated with the availability of feedstocks or renewable electricity for electrolysis, thus impacting the reliability and flexibility of production.
Energy intensity and efficiency	• Efficiency losses resulting from the conversion of hydrogen into methanol and the purification steps. • Energy-intensive process due to the energy requirements for H_2 and methanol production. • Potential challenges in capturing and utilising waste heat or by-product gases to improve energy efficiency in the steel production process.

3.3.3.2.4. Synthetic methanol - conclusion

Synthetic methanol is emerging as an alternative in the EU fuel industry, particularly in maritime operations. Although the technology is well-established and mature, scaling up the industry presents intricate challenges. Europe has been a focal point for renewable methanol projects due to its institutional support and updated policies and has secured approximately 50% of global renewable methanol projects.

Projections estimate high demand for methanol, in excess of 500 Mt/year by 2050, which would require the construction of ~280 methanol plants. The TRL for synthetic methanol is high, supported by the industry's maturity and the minimal technological changes required. However, concerns remain in relation to the vulnerability affecting specific components, such as catalysts that use copper, and the scarcity of renewable resources such as hydrogen or biogenic CO_2. Europe lacks the manufacturing capacity to meet the demand for renewable hydrogen, as the various sectors have to compete for limited natural resources to develop competitive renewable electricity.

The European methanol industry also showcases several strengths that position Europe as one of the leading regions in synthetic methanol production today. Europe has extensive technical capabilities due to its long-standing tradition in the chemicals industry which, in addition to the robust regulatory framework present in Europe, has led the leading manufacturers to develop their methanol projects in this region.

Lastly, the sustainability assessment highlights potential negative impacts in the "Material use and recyclability" and "Robustness and flexibility" categories, but most notably in the "Health and safety" category. Synthetic methanol production faces critical challenges in terms of its energy-intensive manufacturing process, its reliance on the development of technologies for a steady supply of renewable feedstock (e.g., electrolysers, CCS), and the potential safety hazards involved in handling and storing hazardous substances that may cause explosions.

4. RECOMMENDATIONS TO STRENGTHEN THE EUROPEAN HYDROGEN SUPPLY CHAIN

The effort displayed in developing the hydrogen technology supply chain in Europe is promising, but improvements must still be made if the EU is to remain competitive vis-à-vis other regions. Many flaws have been identified in the supply chain for the technologies analysed in this study, as well as in the sustainability and circularity of those technologies, and also in the industry in general as a developer of hydrogen projects.

In this context, a set of recommendations can be drawn from the assessment of the European hydrogen supply chain, encompassing 3 main categories: strengthening the supply chain; enhancing the sustainability and circularity of the industry; and addressing the efforts required for the development of hydrogen projects.

4.1. Strengthening the hydrogen supply chain

The European hydrogen supply chain still faces immaturity issues in various areas, posing challenges in terms of maintaining competitiveness vis-à-vis other regions.

4.1.1. General recommendations to strengthen the hydrogen supply chain

1. **Intensify European R&D projects focusing on the discovery of new technologies and materials to reduce the reliance on CRMs** (e.g., Ni, PGMs, Al, Ti) **and other critical materials** (e.g., carbon fibre for hydrogen storage tanks). This will reduce Europe's dependence on third countries for their supply.
2. **Prioritise R&D projects focusing on manufacturing scale-up and automation processes of less mature technologies** (e.g., SOEC, AEMel, Waste-to-Hydrogen, SOFC). With new global competitors (the US) entering the market with mature industrial capabilities, Europe must reduce production costs and time-to-market for its products. The manual operation of testing, manufacturing and assembly processes has led to delayed R&D solutions, resulting in decreased investments in technology development.
3. **Create specific R&I programmes focusing on the development of complementary, and currently immature, solutions for the hydrogen technologies currently on the market.** Europe should promote R&D programmes centred on production technologies, including logistics and demand. Despite current cost challenges, these programmes are crucial for supporting the hydrogen production industry. For instance, to establish a developed hydrogen network, it is necessary to enable the transportation of green H_2 to end-use solutions.
4. **Introduce, review, or clarify hydrogen certification and standards (e.g., PFAS ban, ammonia safety procedures, H_2 blending rate).** Unclear, complex or underdeveloped regulations pose challenges for project developers. Rapid clarification and implementation of these regulations, aligning them with the specific needs of the European hydrogen industry, will help reduce time-to-market for end products.
5. **Promote specific supporting mechanisms for projects that target the development of the most underrepresented technologies in the European hydrogen landscape.** There is insufficient representation of some technologies, mainly in terms of the number of suppliers, in the European hydrogen industry, including AEM, Waste-to-H_2, NH_3 cracking, H_2-DRI, H_2-gas turbines, and synthetic methanol. Incentivising and supporting these projects will address gaps, prevent dependence on third countries, foster innovation, and ensure a comprehensive development of the European hydrogen industry.
6. **Ensure that funding programmes prioritise the distribution of subsidies based on the impact on emission reduction or energy consumption.** A potential approach involves locating major emission sources and prioritising solutions that minimise their effect, whether through greener alternatives to reduce emissions or alternatives to lower overall energy demand. However, it is crucial to strike a balance, considering both the sustainability of large companies and the sustainable development of smaller markets.
7. **Ensure that funding programmes focus on the diversification of Made in Europe technologies for energy independence based on the evaluation of potential synergies.** Diversification adds robustness and increases independence. Evaluating different scenarios on a case-by-case basis to maximize efficiencies is essential. For instance, in a highly electrified area, the addition of a gasification plant could be more beneficial than implementing an electrolyser, acting as a standalone hydrogen source with potential benefits for local markets. Therefore, it is important to take a look at the broad picture and look for potential synergies, evaluating different scenarios on a case-by-case basis to maximise efficiencies.

4.1.2. Specific recommendations for hydrogen production technologies

4.1.2.1. Electrolysers

Electrolysers are the technology with the largest investment among hydrogen technologies today and, as a result, the investment decisions made to develop the industry based on these technologies are critical to achieve the targets for decarbonisation set by EU.

- **Develop a standardised protocol for electrolyser performance rating.** The standardisation of electrolyser performance rating could involve creating consistent criteria and testing methods to assess efficiency, durability, and other key aspects of electrolysis systems. This would promote transparency and enable easier comparison of different electrolyser models and technologies, aiding stakeholders in making informed decisions and driving innovation in renewable hydrogen production.

4.1.2.1.1. PEM electrolysers

- **Create a programme focusing on the development of the European TFE chemical industry.** This industry is indispensable for PFSA production and there is only one European plant in the TFE chemical industry. The relocation of the TFE chemical industry to Europe is highly complex due to the operational conditions of the plants and the substantial financial investments needed.

- **Rapid clarification of the European PFAS regulation.** Several manufacturers are still awaiting clarification of the potential ban on PFAS materials by the European Commission, in order to make investment decisions, which is limiting the current development of the PEM industry.

4.1.2.1.2. Alkaline electrolysers

- **Establish a marketing programme that promotes the quality and customer service of European alkaline electrolyser manufacturers**. China holds a dominant position in global alkaline manufacturing, due primarily to lower production costs. However, consumers have raised concerns about the performance of their products (e.g., safety, post-sale services). This marketing programme would help highlight the advantages of European manufacturers, emphasizing the importance of reliability over lower production costs in the long run.

4.1.2.1.3. SOEC electrolysers

- **Develop programmes that integrate the use of SOEC in solutions designed for high-temperature conditions.** The high-temperature produced by SOEC is more suitable than existing solutions (e.g., PEM, ALK) for industries with high-temperature processes (H_2-DRI, H_2-gas turbines or synthetic methanol).

4.1.2.1.4. AEM electrolysers

- **Prioritise projects focused on manufacturing scale-up and the automation of plants.** New competitors are entering the market with more mature industrial and manufacturing capabilities. Europe needs to reduce costs and shorten the time-to-market for products, since most operations are conducted manually.

4.1.2.2. Waste to hydrogen

- **Implement a waste collection initiative within the agricultural sector with a collection cap in certain areas.** Social concerns exist in the agricultural sector regarding the obtainment of feedstock for the waste-to-hydrogen process. Excessive biomass collection may adversely affect the sector, leaving insufficient biomass for use as fertilizer. Given the limited agricultural land in Europe, it is crucial to achieve optimal biomass collection to satisfy agricultural needs while contributing to the development of a more robust hydrogen industry.

4.1.3. Specific recommendations for logistics technologies

4.1.3.1. Ammonia cracking

- **Launch new programmes to develop new ammonia offloading terminals and crackers**. To ensure that green H_2 can reach EU end-users in the next few years, Europe needs to build more ammonia bunkering, storage, and conversion facilities at ports. Existing capacity is largely concentrated around smaller ports near chemical manufacturers, and larger ports will need to build new ammonia off-take and cracking facilities in order to achieve their import ambitions.

4.1.3.2. Storage tanks

- **Update hydrogen certification and standards**. Current regulations are often suboptimal for the development of the European hydrogen industry as they do not align with the specific needs of the end product in Europe. Their swift clarification will contribute to reducing the time-to-market for end products.
- **Intensify European R&D projects focusing on the development of new technologies and the discovery of alternative advanced materials to reduce the reliance on critical materials** such as carbon fibre. Consequently, this will reduce Europe's dependence on third countries for the supply of CRMs.

4.1.3.3. Hydrogen refuelling stations

- **Promote new industrial initiatives to pursue economic solutions in collaboration with the leading European OEMs in the H_2 mobility sector.** Refuelling hubs are a practical solution, offering cost reduction and support for HDVs with lower CAPEX requirements. To optimise the development of this solution, it is crucial to strategically locate HRSs in main corridors, logistics centres, port and airport-serving areas and urban centres with long-distance bus services (i.e., to update the Hydrogen Backbone to prioritise these locations, and to develop regional plans focused on economic solutions in Europe). However, industry hesitancy persists due to underdeveloped large-scale technologies (e.g., electrolysers, compressors). European OEMs could potentially be incentivised to drive the H_2 mobility sector forward by providing assurances of their collaboration in future projects.

4.1.3.4. Grid infrastructure

- **Develop a functional hydrogen network, by ensuring non-discriminatory access to the network, without creating a higher usage fee for early adopters** while waiting for additional customers to join. Failure to meet these conditions would result in a lack of incentives for the development and use of new infrastructure, hindering the startup of the industry.

4.1.4. Specific recommendations for end-use technologies

4.1.4.1. Cross-cutting recommendations for end-use technologies

- **Develop a comprehensive framework for prioritising the utilisation of renewable hydrogen across various end-uses, structured according to their potential to abate CO_2 emissions.** During the initial years of technology adoption, the allocation of hydrogen among different end-uses should be based on factors like the CO_2 abatement potential (tCO_2/tH_2) of the off-taker, which must be previously specified by regulators. This approach would ensure greater transparency and visibility for projects in the future, reducing uncertainty and providing a stable environment for the development of these technologies.
- **Foster collaboration programmes where demand consortia and clusters of small and medium-sized customers are incentivised.** Consumption will be pooled, facilitating the production of hydrogen on a larger scale and encouraging producers to take advantage of the economies of scale of electrolysers, as well as to develop production and logistics infrastructure and jointly manage the operation of the electrolysers.

4.1.4.2. PEMFC

- **Encourage new initiatives to promote different H_2 mobility solutions in collaboration with the leading OEMs in the sector.** As in the case of the HRSs, European OEMs in the mobility sector are focused on battery electric vehicles, while Asian OEMs (e.g., Hyundai, Kia) have been making continuous efforts to develop H_2 mobility. OEMs could be incentivised by providing assurances as to their obtaining future projects.

4.1.4.3. SOFC

- **Prioritise projects focused on manufacturing scale-up and automation of plants.** To remain competitive globally, Europe needs to reduce production costs and shorten the time-to-market for products, since most testing, manufacturing, and/or assembly processes are manually operated.

4.1.4.4. Steel decarbonisation: H_2-DRI

- **Combine H_2-DRI with other solutions to maximise the decarbonisation of the steel industry.** Hydrogen requires a comprehensive strategy for decarbonising this industry. This involves a compendium of solutions such as reducing demand through optimised steel usage, raising recycling rates, and implementing technological solutions such as H_2-DRI and CCS in primary production.

4.1.4.5. H_2-gas turbines

- **Create specific programmes to prioritise R&D projects targeting 100% H_2-gas turbines to achieve a higher reduction of emissions.** It has been proven that the emission reduction for H_2-gas turbines is exponentially larger, the higher the hydrogen blend used in the fuel mix. Therefore, R&I should be focused on the development of solutions targeting 100% H_2-gas turbines.

4.1.4.6. Synthetic methanol

- **Create specific programmes focused on the development of complementary, and currently immature, solutions for the hydrogen technologies.** Europe should promote R&D programmes focused on solutions that complement synthetic methanol technologies and are centred on production and logistics. Considering their current cost curves, technologies such as CCS for the capture of biogenic CO_2 are not mature, as a result of which H_2 production costs are not competitive. For example, before establishing a developed H_2 network, it is crucial to enable the transportation of renewable hydrogen to end-use technologies.

4.2. Improvement of sustainability and circularity

While the European hydrogen supply chain still faces immaturity issues in various areas, the state of the art of the sustainability and circularity methods involved in the hydrogen technologies is even more immature. A set of recommendations to improve these methods has been prepared:

1. Ensure that the industry as a whole adheres to **new requirements when applying for European funding:**
   a. **Advanced ESG** (Environmental, Social and Governance) **reporting is crucial to fostering industry collaboration, enhancing transparency, and promoting sustainability.** Mandatory reporting increases accountability, aligns the industry with global goals and ensures long-term viability. Collaborative data sharing brings mutual benefits, improving insights, reducing waste, and enhancing accuracy.
   b. **New and clear sustainability guidelines must be implemented** to oblige all companies to pursue the circular design of hydrogen products.
2. **Develop a programme to facilitate the collection of residual materials and components from companies, especially small companies.** The volume of recycled materials is pivotal for economic efficiency in recycling processes. Small companies often struggle to meet the minimum volume required for cost-effective recycling. Companies could fund this programme, creating a reuse and recycle network on a European scale, where waste streams from some companies act as feed streams for others.
3. **In scenarios where alternatives such as direct electrification are feasible, assess whether the use of hydrogen technologies is crucial**, especially when they rely on grid-connected energy sources. Factors such as location, electricity mix, and grid capacity play a significant role. A thorough evaluation of the alternatives must be made before choosing hydrogen technology, considering potential emissions and adherence to relevant restrictions and laws.

4.3. Necessary efforts to develop hydrogen projects in Europe

As a result of the implementation of the recommendations to strengthen the supply chain and to improve sustainability and circularity, there will be a greater desire to initiate projects in the European hydrogen industry. However, several challenges still need to be overcome to ensure an optimal framework for growth:

1. **Projects should be granted both CAPEX and OPEX funding, enabling transparent, long-term planning by announcing grants for extended periods.** Providing this extended period will offer the industry a clearer pathway, reduce uncertainty and provide a stable environment for investment and innovation. By offering foresight to the companies within the sector, they will be better equipped to plan, invest, and scale up their operations with confidence, fostering a more rapid advancement in renewable hydrogen technologies.
2. **Demand-side subsidy schemes should be tailored to specific industries,** so that industries with higher costs compete amongst themselves, and each scheme must have a specific period for which it receives support.
3. **Facilitate and promote demand from off-takers by implementing a new framework that favours long-term HPA** (Hydrogen Purchase Agreement) **contracts.** This measure will provide stability and mitigate

long-term risks for hydrogen developers, which will attract higher investment from investors and foster technology development. This measure is key to supporting the transition to a hydrogen-based economy in the long term.

4. **Foster collaboration between the projects awarded and encourage knowledge-sharing to expedite progress, thereby enhancing the impact of the programme** on the renewable hydrogen sector in Europe. Industry collaboration is key to sustainable supply chain design. Businesses should expand their perceptions of the ecosystems in which they operate and embrace wider collaboration on data, information, and asset sharing. Collaboration does not need to compromise competitive advantages, but instead create mutual benefits through better insights, less waste, and greater accuracy.

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