

Research and development needs – production paths for renewable and low-carbon hydrogen and its derivatives

INTRODUCTION

In addition to the economic and regulatory challenges for the hydrogen ramp-up, there are technical challenges in the provision of renewable and low-carbon hydrogen and its derivatives that need to be addressed through research and development. These challenges range from production, distribution and storage to the use of hydrogen and its derivatives. Hydrogen safety is a cross-cutting issue in this context.

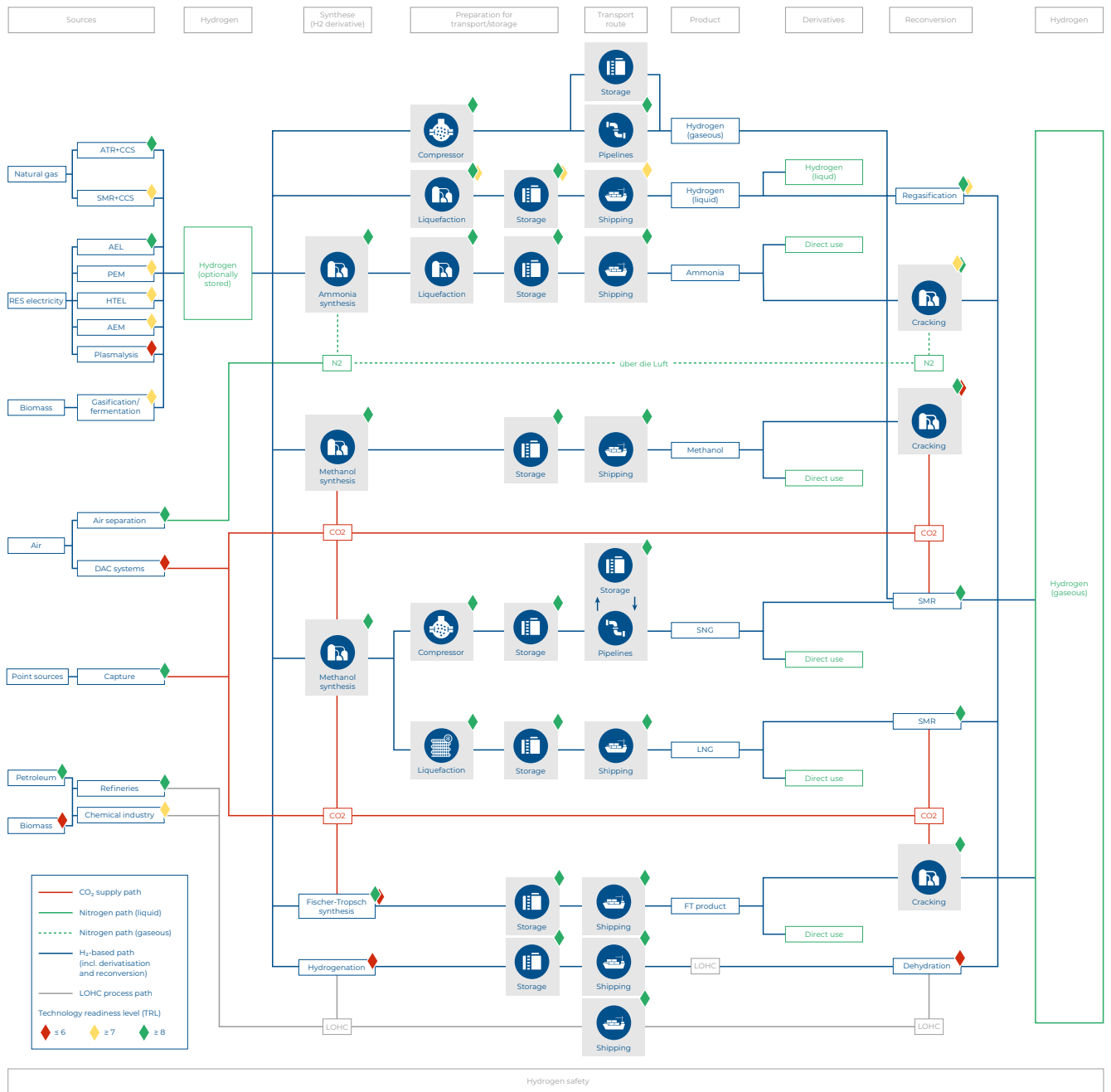
This whitepaper provides an overview of the various production paths according to current literature¹. The individual processes along the value chain are classified according to their technology readiness level (TRL) (see Table 1). This is shown in three colour categories in the graphic. Red indicates a TRL less than 6, yellow greater than 7 and green greater than 8.

Table 1: Technological readiness levels (TRL) as defined by PtJ based on the NASA definition

TLR 9	Qualified system with proof of successful use
TLR 8	Qualified system with proof of functionality in the area of application
TLR 7	Prototype in use
TLR 6	Prototype in operating environment
TLR 5	Test setup in operating environment
TLR 4	Test setup in the laboratory
TLR 3	Proof of concept for a technology
TLR 2	Description of the technology concept and/or the application of a technology
TLR 1	Observation and description of the functional principle

¹ Sterner, M. et al. (2024). 19 Import options for green hydrogen and derivatives – An overview of efficiencies and technology readiness levels. International Journal of Hydrogen Energy, 90, 1112–1127

Figure 1: Production paths for renewable and low-carbon hydrogen and its derivatives, classified by technological maturity



RESEARCH AND DEVELOPMENT REQUIREMENTS

Many production paths can already be classified as consistently green and are therefore technologically ready for industrial use (see Figure 1). However, individual processes and technologies still require further research and development in order to bring further production paths to industrial maturity. These technologies and the need for action are described and explained below in the form of fact sheets².

² The order does not imply any prioritisation of research needs.

DAC SYSTEMS ♦

Description	Direct air capture (DAC) refers to technologies that filter CO ₂ directly from the ambient air. The captured CO ₂ can be stored and used for the production of hydrogen derivatives (methanol, synthetic fuels) or as a feedstock for the chemical industry.
Challenges	The technical development of DAC technology is still in its infancy. It is unlikely to make a significant contribution to hydrogen derivatives by 2030. Only initial demonstration plants with major technical challenges currently exist.
Development needs	<p>Short-term (1-5 years):</p> <ul style="list-style-type: none"> ◆ Scaling of more mature technologies (e.g. sorption processes such as absorption and adsorption (selection of suitable filter materials and durable, selective and cost-effective sorbents), scrubbing (high-temperature regeneration), circulation of large air masses, space requirements, integration in CCU and CCS) ◆ Improvement in cost and energy efficiency (heat management, air circulation, reduced use of materials, integration of renewable energy sources) ◆ Long-term stability (corrosion, material research, fouling and ageing) <p>Long-term (> 5 years):</p> <ul style="list-style-type: none"> ◆ Basic research into more efficient, cost-effective and scalable approaches and concepts. The potential of new approaches such as electro-exchange adsorption and carbonate looping must be examined.

ELECTROLYSIS TECHNOLOGY: PLASMALYSIS ♦

Description	Plasmaproduction involves the conversion of natural gas/biogas/synthetic natural gas (SNG) to hydrogen and elemental carbon by means of thermal plasma (> 1,200°C) using renewable electricity. Other variants work with non-thermal plasmas.
Challenges	Both processes are currently being tested in initial pilots. The still young technologies require further testing and upscaling to demonstration and industrial standards.
Development needs	<p>Short-term (1-5 years):</p> <ul style="list-style-type: none"> ◆ Upscaling of various plasma technologies ◆ Possible uses for carbon and its application (storage behaviour, toxicity, storage, formation of by-products such as tar) <p>Long-term (> 5 years):</p> <ul style="list-style-type: none"> ◆ Improving the long-term stability of processes ◆ Utilisation of non-thermal plasmas

LOHC – HYDROGENATION/DEHYDROGENATION/BIO MASS ♦

Description	Liquid organic hydrogen carriers are a long-researched option for binding hydrogen to hydrogen carriers and thus making it easier to transport. The hydrogen is released at the point of use via a dehydration process.
Challenges	There is a lack of industrial dehydration plants. There is also a need for development with regard to the technical properties and cost efficiency of the carrier materials themselves.
Development needs	<p>Short-term (1-5 years):</p> <ul style="list-style-type: none"> ◆ Carrier material: Further development to achieve lower toxicity, long-term stability and cost reduction, comprehensive evaluation of the economic and ecological aspects of organic starting substances that are obtained from fossil sources and cause CO₂ emissions, increasing the proportion of hydrogen in the carrier material ◆ Dehydration: Scaling and improvement of cost and energy efficiency (reduction of temperature levels, etc.) <p>Long-term (> 5 years):</p> <ul style="list-style-type: none"> ◆ Sustainable production routes: aromatics such as toluene, which are currently produced from fossil fuels in the petrochemical industry, could in future be based on lignin-containing biomass, for example ◆ Increase product purity to hydrogen 5.0 without PSA (pressure swing adsorption)

FISCHER-TROPSCH SYNTHESIS FROM NON-FOSSIL CO₂ ♦

Description	Fischer-Tropsch synthesis (FT synthesis) is a chemical process for the production of liquid hydrocarbons such as petrol from synthesis gas (CO + H ₂) and was developed 100 years ago. Conventional FT synthesis is considered to be technically mature and has so far primarily used coal and natural gas as a carbon source, but can also be operated with non-fossil CO ₂ sources.
Challenges	The first pilot and test plants for converting to renewable synthesis gas are in operation. Two procedural methods are being pursued here: 1. with upstream conversion step from CO ₂ to synthesis gas (reverse water gas shift reaction, for example) and 2. direct synthesis of CO ₂ and H ₂ . The first variant is already more advanced, while the technical maturity level of the second variant with CO ₂ as feedstock remains low. The integration of FT synthesis into the refinery must be examined more closely (post-processing/further processing of FT hydrocarbons).
Development needs	Short-term (1-5 years): <ul style="list-style-type: none"> ♦ Further development of catalysts, for example, ♦ water-gas shift capability for processing CO₂ ♦ Long-term stability of the catalysts, also with regard to toxins, impurities ♦ Further development of reactor concepts, especially for smaller plants Long-term (> 5 years): <ul style="list-style-type: none"> ♦ Upscaling and demonstration of reactor concepts and systems

AMMONIA AS AN ENERGY SOURCE ♦

Description	Ammonia is being discussed as an energy source both in direct utilisation (as a fuel) and in reconversion to hydrogen (cracking) as a storage medium. Production from hydrogen and nitrogen is well known. Classic uses are primarily in the fertiliser sector. The production of ammonia with grey hydrogen and nitrogen from air separation plants is well established. Their conversion to renewable hydrogen is possible without any problems.
Challenges	However, there is a need for development in safe handling as a fuel, its use in engines and the purification of exhaust gases after combustion. Ammonia cracking is required when used as a hydrogen carrier. A need for development remains here as well.
Development needs	Short-term (1-5 years): <ul style="list-style-type: none"> ♦ Improving safe handling along the entire value chain ♦ Ammonia cracking: Development of more efficient catalysts and intelligent process control to reduce energy requirements and increase overall efficiency; scaling of the technology ♦ Fuel, engines, logistics: Improving energy efficiency and exhaust gas treatment in the optimisation of engines ♦ Materials research: Further development, for example, of seals for large-scale industrial applications Long-term (> 5 years): <ul style="list-style-type: none"> ♦ Materials research: Further development of low-temperature catalysts

LIQUID HYDROGEN – LIQUEFACTION, STORAGE, TRANSPORT BY SHIP, REGASIFICATION G ♦

Description	Hydrogen is liquefied for transport across the world's oceans in order to achieve a higher energy density and thus reduce transport costs. Initial pilot tests with grey hydrogen between Australia and Japan were successful.
Challenges	Importing liquid hydrogen by ship requires research and development to optimise and upscale liquefaction plants as well as the development of storage tanks and handling systems for large volumes on land.
Development needs	<p>Short-term (1-5 years):</p> <ul style="list-style-type: none"> ◆ Liquefaction: Further development and expansion of compressors, turbines, valves and pump technology for liquefaction plants ◆ Motors for heavy-duty applications (ship propulsion, etc.): Optimisation of the combustion process to reduce nitrogen oxide emissions. Development of improved exhaust gas treatment, including optimised catalysts. ◆ Storage and transport tanks: Reduction of the boil-off ◆ Regasification: Optimisation of waste heat utilisation <p>Long-term (> 5 years):</p> <ul style="list-style-type: none"> ◆ Energy optimisation of tanks, storage tanks and liquefaction plants (for example, insulation, catalysts)

STEAM REFORMING (SMR) WITH CCS ♦

Description	Steam methane reforming of natural gas is the leading technology for producing grey hydrogen. The technology is mature but has a large CO ₂ footprint. This can be reduced by capturing and storing CO ₂ (carbon capture and storage, CCS).
Challenges	CCS has not been used on a large scale in combination with SMR to date. While large-scale technical experience is available for the separation of CO ₂ in the process, there is a need for action in the capture of CO ₂ from the flue gas (exhaust gas). Large-scale long-term experience in continuous operation for flue gas capture (> 90 per cent CO ₂ capture) is not yet available.
Development needs	<p>Short-term (1-5 years):</p> <ul style="list-style-type: none"> ◆ Gathering experience in continuous operation ◆ Technical and economic optimisation and improvement of the process combination

ELECTROLYSIS TECHNOLOGY: PEM ♦

Description	In proton exchange membrane electrolysis (PEM), hydrogen is produced by electrolysis of water in a cell with a solid polymer electrolyte. It is established on a small MW scale and has the advantage of higher power density and the possibility of dynamic operation compared to alkaline electrolysis (AEL).
Challenges	Long-term experience with large-scale plants is lacking.
Development needs	<p>Short-term (1-5 years):</p> <ul style="list-style-type: none"> ◆ Reduction of PGM loading (platinum group metals) ◆ Gaining operating experience in the flexible, variable-load continuous operation of industrial plants (especially degradation) ◆ Technical-economic optimisation for cell stability ◆ Automated series production and scaling <p>Long-term (> 5 years):</p> <ul style="list-style-type: none"> ◆ Basic research into iridium-free stacks ◆ Development and optimisation of PFAS-free membranes including long-term tests and stability improvement to reduce environmental and health risks

ELECTROLYSIS TECHNOLOGY: HTEL ♦

Description	In high-temperature electrolysis (HTEL), water vapour is split into hydrogen and oxygen at high temperatures. The process is characterised by high efficiencies and is attractive when coupled with processes that generate waste heat (ammonia synthesis).
Challenges	HTEL is still in the development stage. The greatest challenge lies in the long-term stability of the stacks in an industrial environment. There are also optimisation issues relating to heat management and the integration of the heat source.
Development needs	Short-term (1-5 years): <ul style="list-style-type: none"> ♦ Optimisation of heat management ♦ Improved robustness against pressure fluctuations ♦ Improved long-term stability and safety Long-term (> 5 years): <ul style="list-style-type: none"> ♦ Further development of cells (larger cell surfaces, design for recycling) ♦ Material research on long-term stability/degradation ♦ Development of more cost-effective materials

ELECTROLYSIS TECHNOLOGY: AEM ♦

Description	Alkaline membrane electrolysis (AEM) is the latest water electrolysis technology and combines the advantages of alkaline and PEM electrolysis. It does not require precious metals, works in a mild alkaline medium and supports PFAS-free production.
Challenges	This promising technology is not yet ready for the market, so there is a lack of long-term experience. So far, it has had a relatively small stack size compared to other electrolysis technologies.
Development needs	Short-term (1-5 years): <ul style="list-style-type: none"> ♦ Upscaling and multiple scaling of the stacks ♦ Long-term tests of larger systems in an industrial environment ♦ Technologies for the automation of production Long-term (> 5 years): <ul style="list-style-type: none"> ♦ Improving the catalysts ♦ Developing membranes and coating processes ♦ Technical-economic optimisation of the process

HYDROGEN SAFETY (CROSS-CUTTING ISSUE)

Description	Hydrogen is the smallest element in the periodic table and has technical properties such as a wide explosion range and high permeability, which require special measures for safe handling. ³ Hydrogen is used on an industrial scale in refineries, the chemical industry, aerospace and other sectors. Handling in these applications is tried, proven and safe.
Challenges	Ensuring the safe handling of hydrogen in those areas where it will play a central future role is a challenge. The material compatibility of hydrogen and the safety of its large-scale application in particular require further research.
Development needs	Short-term (1-5 years): <ul style="list-style-type: none"> ♦ Materials research: Testing the suitability of all components in the supply path under real pressure and temperature conditions, development of a system for determining the hydrogen resistance of various materials, creation of binding testing and certification regulations ♦ Measurement and safety technology: Development for hydrogen content greater than 20 per cent by volume ♦ Pore storage: geological and geochemical questions on solubility or reactions of hydrogen in pore storage under storage conditions, geochemical interactions with the rock and gas losses during storage operation Long-term (> 5 years): <ul style="list-style-type: none"> ♦ Further development of the safety aspects of transport, storage and application technologies

³ NWR statement (2025). [Further strengthening safety culture in the hydrogen ramp-up.](#)



THE GERMAN NATIONAL HYDROGEN COUNCIL

On 10 June 2020, the German Federal Government adopted the National Hydrogen Strategy and appointed the German National Hydrogen Council. The Council consists of 25 high-ranking experts in the fields of economy, science and civil society. These experts are not part of public administration. The members of the National Hydrogen Council are experts in the fields of production, research and innovation, industrial decarbonisation, transportation and buildings/heating, infrastructure, international partnerships as well as climate and sustainability. The National Hydrogen Council is temporarily chaired by Felix Chr. Matthes..

The task of the National Hydrogen Council is to advise and support the State Secretary's Committee for Hydrogen with proposals and recommendations for action in the implementation and further development of Germany's National Hydrogen Strategy.

◆ **Contact:** info@leitstelle-nws.de, www.wasserstoffrat.de/en