Flagship Project
TransHyDE

Transport and storage infrastructure for green hydrogen

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and Research

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Dear reader,

Hydrogen represents our opportunity to link together energy security, climate neutrality and competitiveness. This is why we want to make Germany a "hydrogen republic".

Our National Hydrogen Strategy shows us how to reach this goal. A central aspect in this regard is the importation of hydrogen, because here in Germany, our potential to produce hydrogen is limited. Between 50 and 70 percent of the hydrogen we expect to need in 2030 will have to come from outside Germany. After that, this percentage is even likely to rise. Countries with plenty of sunshine and wind such as Namibia or Australia are especially good candidates for producing green hydrogen. This means we will need suitable infrastructure for transporting the hydrogen – both for importing it, and for distributing it within Germany.

And this is precisely where TransHyDE comes in. The aim of the project is to research and demonstrate exactly how hydrogen can be stored and transported: as a gas in pipelines and high-pressure tanks, in liquid form, or as part of compounds in the form of ammonia or LOHCs. Science and industry work hand in hand as part of the project, thus guaranteeing the direct transfer of research into practice. This is also the case in the two other hydrogen flagship projects. The H_2Giga project conducts research into how large-scale electrolysers can be mass-produced, while H_2Mare is all about producing hydrogen out at sea.

We, the Federal Ministry of Education and Research, are investing more than 700 million euros in these three hydrogen flagship projects alone. As such, we are paving the way and setting the pace for the creation of a "Hydrogen Republic of Germany" set to put its know-how to good use around the world. We want to become a lead market for hydrogen technologies, thus creating new export leaders with the label “Made in Germany”.

I invite you to read on and learn more about TransHyDE for yourself, and hope you will find this brochure informative.

B. Stark-Watzinger

Member of the German Bundestag

Federal Minister of Education and Research

TransHyDE

Organisational structure

Projects

Context of the TransHyDE hydrogen flagship project

The National Hydrogen Strategy envisages security of supply through intra-European production as well as diversification and securing international imports of hydrogen. This inevitably results in the need for a supra-regional transport and storage infrastructure for the energy carrier.

Key data

146.6 mio. euro funding
89 Partners
20 Associated partners
04.2021 - 03.2025 Duration

A total of 109 partners and associated partners are working on ten projects to overcome the technological and economic obstacles that currently hinder the efficient transportation and storage of green hydrogen.

Funding of the Federal Ministry of Education and Research (BMBF) for TransHyDE amounts to 145 million euros over a period of four years. The technical focus of TransHyDE is on four different transport options: gaseous hydrogen (gH_2), liquid hydrogen (LH_2), ammonia (NH_3) and liquid organic hydrogen carriers (LOHC). TransHyDE also analyses the regulatory framework and makes recommendations for an accelerated ramp-up of the hydrogen economy.

TransHyDE Coordinators

At the end of 2020, Prof. Robert Schlögl, Prof. Mario Ragwitz and Jimmie Langham designed the hydrogen flagship project TransHyDE and defined the project structure. Since 2021, they have been appointed by the BMBF as the three overall TransHyDE coordinators.

Prof. Dr. Robert Schlögl

The chemist Prof. Robert Schlögl is a key figure in the German energy transition. The results of his research projects form a multi-faceted foundation for his diverse advisory work for the German government and supranational organisations on energy policy issues.
Since 1994, Prof. Schlögl has been Director at the Fritz Haber Institute of the Max Planck Society and Honorary Professor at the Technical University of Berlin. In 2011, he was founding director of the Max Planck Institute for Chemical Energy Conversion in Mülheim an der Ruhr which he directed until 2022. Since 2011, he has been Vice President of the National Academy of Sciences Leopoldina in Halle, since 2013 Honorary Professor at the University of Duisburg-Essen, and since 2016 Chairman of the Advisory Board of the BMBF-funded Copernicus Research Initiative on Energy Transition. In 2019, the Center for Catalysis and Surface Science at Northwestern University in Evanston, Illinois appointed Prof. Schlögl as an Ipatieff Lecturer. In 2020, he received an honorary doctorate from the University of Darmstadt. He has been President of the Alexander von Humboldt Foundation in Bonn since 2023. During his career, Prof. Schlögl has received many awards for his scientific commitment, including the ENI Award in 2017 for his "Multifaceted Approach to Enabling the Transformation of Energy Systems", the Innovation Award of the State of North Rhine-Westphalia in 2016, and the Alwin Mittasch Price in 2015.

Prof. Dr. Mario Ragwitz

The physicist Prof. Mario Ragwitz focusses his scientific work on issues of energy system analysis, modeling and analysis of energy systems and infrastructures, as well as policy analysis and transformation research in the field of energy and climate.
Since 2014, Prof. Ragwitz has been Honorary Professor at the Albert Ludwigs University Freiburg at the Faculty of Environment and Natural Resources, and since 2017 Part-time Professor at the Robert Schuman Centre for Advanced Studies of the European University Institute in Florence. Since 2019, he is heading the Fraunhofer Institute for Energy Infrastructures and Geothermal Energy IEG together with Prof. Rolf Bracke. As Scientific Director of the Fraunhofer Cluster of Excellence "Integrated Energy Systems", he coordinates the joint research of eight Fraunhofer Institutes in the field of energy system transformation. In 2020, he was appointed spokesman of the Fraunhofer Hydrogen Network, which coordinates the work of 35 institutes in this field. As a professor at the Brandenburg University of Technology Cottbus-Senftenberg, he heads the department of "Integrated Energy Infrastructures" at the Faculty of Mechanical Engineering, Electrical Engineering and Energy Systems. In addition to the German Federal Government, Prof. Ragwitz advises the European Commission, the German Bundestag, the EU Parliament, the World Bank, national governments and companies.

Jimmie Langham

The former national table tennis league coach and chief executive of the German Table Tennis Coaches Association studied architecture and urban planning in Karlsruhe, Hamburg and London. After his studies, he worked for several years as a freelance project manager for various planning and engineering offices in Hamburg. In this context, he took up his consulting work in the energy sector in 2008.

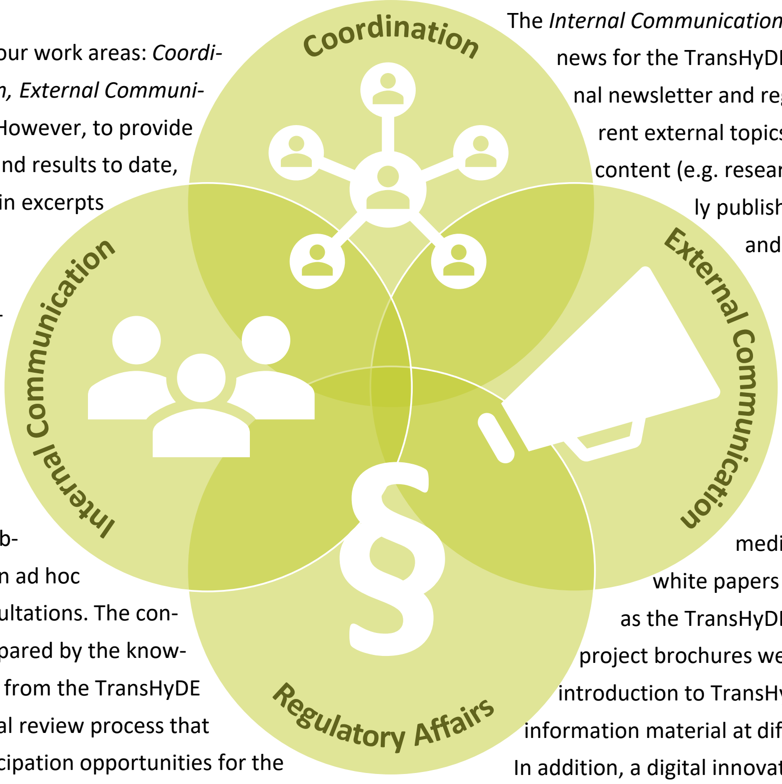
In 2012, he started working for E.ON in the field of project development Offshore Wind. From 2017 onwards, he was responsible for project development in Offshore Wind & Hydrogen as "Regulatory & Strategy Advisor". During the realignment of E.ON and RWE in 2019, he moved to RWE Renewables. As part of his advisory role he co-founded the AquaVentus initiative in 2020 – one of the largest planned hydrogen generation projects in the world.

As managing director of AquaVentus, he led the coordination office that became the **cru**h2**1** consulting firm in 2021, of which Langham is managing director. The company's consulting focus is on green hydrogen, sector coupling and the renewable energy system. For its research and development activities, **cru**h2**1** was recently awarded the "Innovation through Research" seal on behalf of the German BMBF.

Communication & Coordination

The TransHyDE project Communication and Coordination is part of the overarching project structure. It consists of the coordinators and an office, which supports the three TransHyDE coordinators in an administrative and advisory capacity and serves as the first point of contact for the project. In addition, the office is intended to strengthen the transfer of information between the TransHyDE coordinators and the TransHyDE projects as well as among the TransHyDE projects. The office is formed by staff from the Max Planck Institute for Chemical Energy Conversion, the Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG and the strategic project consultancy **cru**h2**1**.

The responsibilities comprise four work areas: *Coordination, Internal Communication, External Communication and Regulatory Affairs*. However, to provide an overview of the objectives and results to date, the individual tasks are shown in excerpts and by way of example.



Governance structures for publications were jointly established in *Coordination*, whereby the procedures created apply not only to regular publications (such as the white papers available on the TransHyDE website), but also to publications on ad hoc requests, such as political consultations. The content of the contributions is prepared by the knowledge and competence carriers from the TransHyDE projects, followed by an internal review process that enables commenting and participation opportunities for the indirectly involved experts. Another task of *Coordination* concerns the management of interfaces among the TransHyDE projects and towards the advisory board. The focus here is on exploiting synergies, avoiding duplication of work and receiving relevant impetus. In this context, the office organises quarterly virtual meetings, biannual hybride meetings with the advisory board as well as annual thematic workshops, plenary meetings and supports other TransHyDE projects with their external events. Additionally, the qualitative project reports to the Project Management Jülich and the BMBF are coordinated.

The *Internal Communication* continuously compiles detailed news for the TransHyDE projects. By means of an internal newsletter and regular project get-togethers, current external topics (e.g. events) as well as internal content (e.g. research and work results and recently published white papers) can be shared and discussed.

The results and progress of the TransHyDE projects are also made accessible to a wider public and the specialist community. The *External Communication* uses among others print media such as specialist journals and white papers as well as digital platforms such as the TransHyDE website and social media. Two project brochures were created to provide a broader introduction to TransHyDE activities, which are used as information material at different occasions like trade fairs. In addition, a digital innovation brochure was elaborated to illustrate individual innovations from partners that were developed as part of TransHyDE. New technological inventions are continually being added to the portfolio through the ongoing revision of the document.

A lively personal exchange with the public takes place through regular participation at trade fairs and visits at national and European level. The organisation of a TransHyDE scientific conference and participation in external events, including project presentations, workshop moderations and panel discussions, also strengthen the discourse with other active and interested stakeholders in the field of transport and storage infrastructure for green hydrogen.

The *regulatory affairs* work package focuses the legal framework supporting the green hydrogen ramp-up. A regulatory community was established to address the legal and regulatory issues across the entire spectrum of TransHyDE technologies and to develop optimisation proposals. This consists of experts from the individual TransHyDE projects. They draw up their own brief analyses and recommendations for action and commission external studies on specific topics. The results are continuously made available to political decision-makers and published digitally on the TransHyDE website. In addition, parliamentary evenings serve as a direct means of addressing the political level.

To always stay up to date with our activities follow us on **LinkedIn**

Link to **TransHyDE video**

Video of **Scientific Conference**

Further information regarding TransHyDE and all of our **Whitepapers**

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Total amount of funding:	5.1 mio. euro

System Analysis

The role of infrastructure in the energy system

Within the technology platform TransHyDE, the consortium of TransHyDE project System Analysis researches transport options of green hydrogen and its derivatives, including the relevant infrastructures. Major demand is expected to originate from the energy-intensive industries. Energy system models are based on macroeconomic cost optimisation.

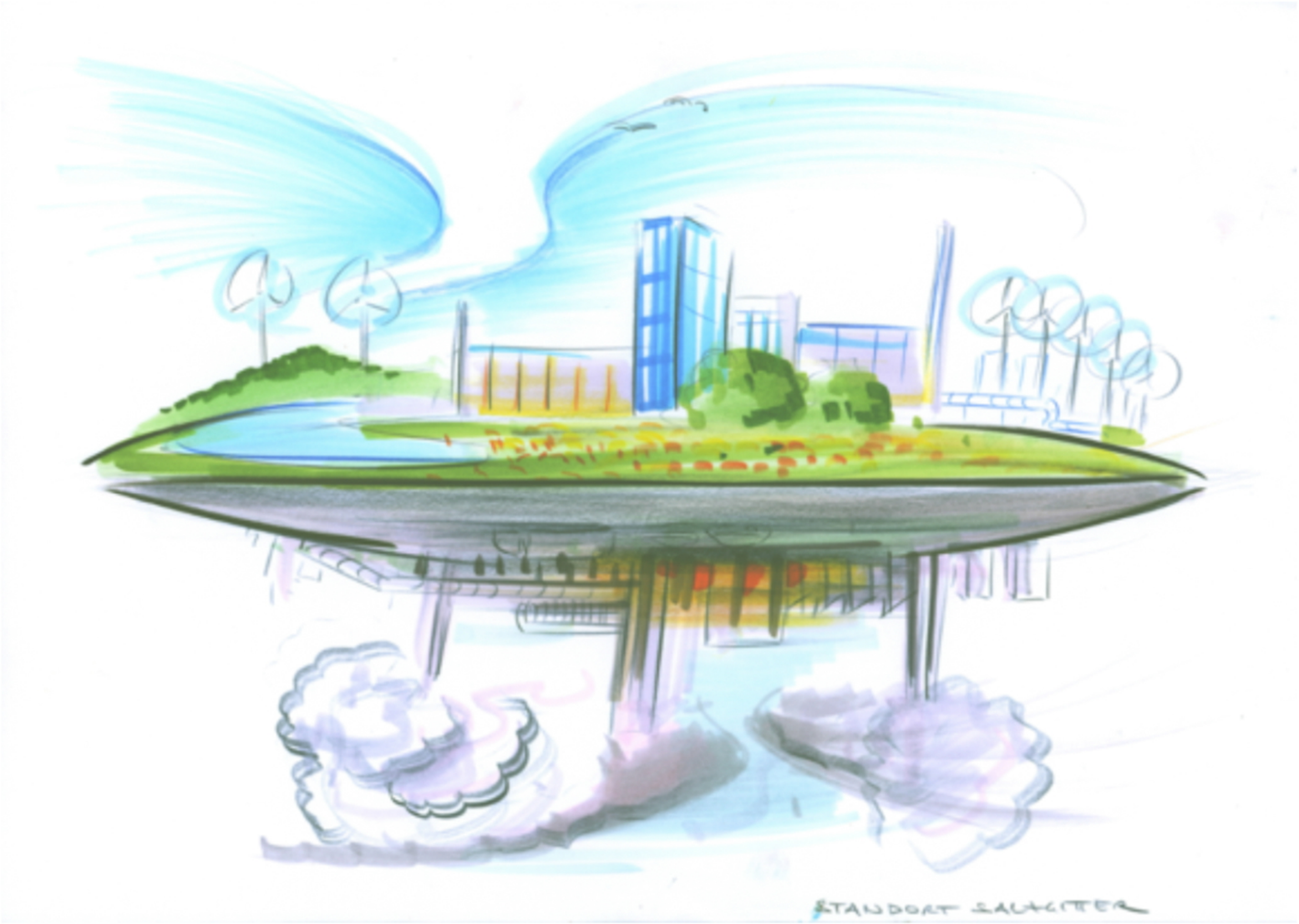
Link to **Project-Introduction**:
„TransHyDE project System Analysis: The pathways of hydrogen"

For the hydrogen import study of the TransHyDE project System Analysis, different transport options are analysed in terms of their technical feasibility. Currently, all future transport options contain processes that are not yet commercially available e.g., the cracking of ammonia to extract hydrogen. Available gas infrastructure could easily be used with green synthetic gas. However, this requires access to sustainable sources.

Furthermore, perspectives of different stakeholders are analysed within the project System Analysis as well. There are various political and industrial opinions as well as technical requirements within Europe. For example, TransHyDE System Analysis published a **media analysis** of hydrogen transport infrastructures and organised a stakeholder workshop in Salzgitter.

Part of the project System Analysis is the modelling of a potential future hydrogen grid. The project established a set of tools with which grid topologies and configurations can be modelled. These grids can be fed with the results of different hydrogen demand scenarios. Additionally, fluid mechanics in this system can be simulated. Next steps include increase of temporal resolution of the model, as well as the spatial expansion of the model network from Germany to Europe.

Link to **media analysis** (GER)



Artistic accompaniment to the stakeholder workshop in Salzgitter. Source: Fraunhofer ISI, drawing by Hyko Stöber

Comparisons of model methodologies and their results is also part of the project work. The resulting review “TransHyDE-Sys: An Integrated Systemic Approach for Analysing and Supporting the Transformation of Energy Systems and Hydrogen Infrastructure Development” has been published.

The results of all above mentioned works will be part of a roadmap, which will consist of scenarios, background information, framework conditions, and fields of research and action. The roadmap is currently under development.

A first comprehensive outline of the project results is presented in the flagship publication "European Hydrogen Infrastructure Planning". It provides the reader with a deeper insight into the analysis of the future development of hydrogen demand, supply, infrastructure and storage options and derives initial recommendations for decision-makers in industry and politics.

Flagship-Paper: „European Hydrogen Infrastructure Planning“

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Total amount of funding:	17.5 mio. euro

Safe Infrastructure

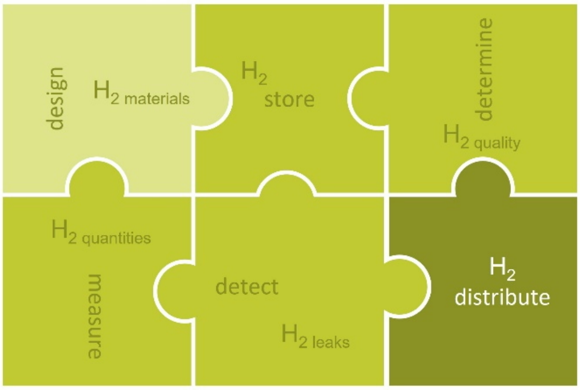
Securing the future with hydrogen transport and distribution grids

Upon a time, a simple question was raised »Can our current natural gas grid also be used for hydrogen?« Simple questions do not necessarily mean simple answers. Since April 2021, a consortium formed by industrial and research partners explores plenty of details to work together on a validated answer to this simple-sounding question – the TransHyDE project Safe Infrastructures.

Storing hydrogen safely and transporting it reliably to end customers is the key to success. The hydrogen infrastructure must be able to withstand these high loads. Existing natural gas grids and new components must therefore be thoroughly qualified for hydrogen use. In all areas of our project, standards, guidelines, and regulations play an important role. Therefore, technical regulations for materials design and storage must be analysed accurately, capacities of transport and distribution gas grids need to be calculated and safety concepts and risk analyses must be worked out.

Addtionally, knowledge of the quality and quantities of the hydrogen fed in and out the gas grid as well as the reliable and fast detection of leaks, which can also occur over long distances, are of great importance. Hence, existing or new sensor systems must be enhanced or developed for this purpose, so research is essential.

Further, hydrogen embrittlement must be understood in detail, a mechanism where atomic hydrogen can cause damages, cracks up to failures of components by penetrating crystal lattice structures of steel, for example. Therefore, the careful qualification of the many different steels used in the existing natural gas grid needs to be closely examined to be suitable for this new application.



Core tasks of the TransHyDE project Safe Infrastructure.
Source: TransHyDE project Safe Infrastructure

The 6 key tasks of the TransHyDE project Safe Infrastructure are:

1. Safe components and materials design for a reliable hydrogen infrastructure
2. Underground storage of hydrogen
3. Highly sensitive determination of hydrogen gas impurities
4. Calibration of flow meters for precise quantification of hydrogen quantities
5. Detection of gas leaks in the transport and distribution grid
6. Demonstrating the transformation process of a natural gas grid into a hydrogen gas grid

Our achievements of today

Salzgitter Mannesmann Forschung and **Fraunhofer IWM** were each able to set up innovative test infrastructures at their facilities to examine steels in hydrogen atmospheres in terms of their material-mechanical load capabilities. A round robin trial was started between the partners to confirm results, important for the conformity of results and thus for the safety of the hydrogen infrastructure.

In addition, standards and regulations such as AD2000, ASME 31.12, or DVGW-Leaflet G 221 were identified and the applicability for hydrogen was analysed. **Ontras Gastransport** accompanied the selection of steels by providing material information and boundary conditions for the operation of long-distance gas pipelines.

Fraunhofer IEG was able to compare existing and planned transport infrastructures with potential new storage sites for hydrogen. Evaluation criteria for underground hydrogen pore storage were formulated and storage and barrier rocks for hydrogen have been characterised. With the help of Monte Carlo simulations, they formulated storage capacities as examples.

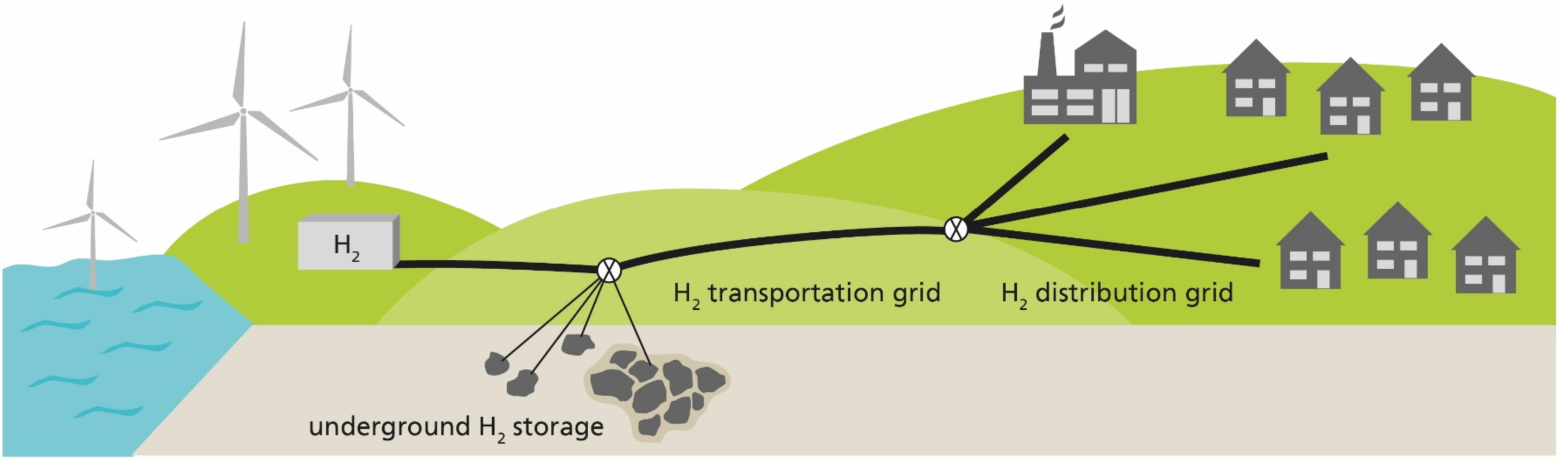
Endress + Hauser developed a prototype for the determination of carbon monoxide (CO) and water (H_2O). This sensor detects trace gases in hydrogen very sensitively. The detection limits in hydrogen are 15 ppm for carbon monoxide and 50 ppb for water.

A hydrogen test bench for calibrating flow meters for determining hydrogen quantities precisely and accurately was designed, manufactured, and put into operation in June 2023 at **RMA Rheinau**. It is expected to become an official test center of Germany's national metrology institute (Physikalisch-Technische Bundesanstalt, PTB). The H_2 test bench is located opposite the natural gas test bench, both together represent RMA's new TwinLoop.

Detecting leaks in components of the hydrogen infrastructure is anything but trivial. Infrared sensors are often used. Unfortunately, hydrogen is not infrared active. The **Fraunhofer IPM** therefore relies on Raman spectroscopy, an established technology for identifying and quantifying chemical substances, and has come a significant step closer to developing a cost-effective sensor for the selective quantification of hydrogen in any gas matrices.

Using hydrogen for space heating and water heating was the ambitious goal of **Thüga**, **Energie Südbayern** and **Energienetze Bayern**. The first hydrogen entry station has now gone into operation. An existing natural gas grid was successfully converted to a hydrogen gas grid. Through collaboration with Vaillant, who developed and delivered free of charge the H_2 heating systems, nine households and a commercial enterprise are now being supplied with hydrogen in a field trial for a period of 18 months.

The partners of the TransHyDE project Safe Infrastructure continue to face the challenges to give hydrogen a safe future and thus contribute to a successful energy transition in Germany and world-wide.



Store, transport and distribute hydrogen through safe materials and reliable leak detection.
Source: TransHyDE project Safe Infrastructure

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Total amount of funding:	12.0 mio. euro

AmmoRef

Reforming of ammonia to hydrogen

The aim of the TransHyDE project AmmoRef is to research and develop an application-oriented, industrially feasible, safe and cost-effective technology for the reforming of ammonia, i.e. the recovery of pure hydrogen, in order to ensure an environmentally friendly, economical and safe solution for a future energy supply. To date, no large-scale industrially applicable technology exists for this purpose. A comprehensive analysis of published data from international researchers shows that the precious metal ruthenium achieves the highest conversion rates.

However, ruthenium is characterised by low availability combined with high costs. Catalysts based on the more common metals iron, nickel and cobalt also show promising activity. Iron in particular stands out as a potential catalyst material, as its availability can be determined as non-critical. A disadvantage, however, is that the catalytic activity of iron only occurs at higher temperatures compared to the other elements mentioned.

Figure 1: Catalyst test rig at the Max Planck Institute for Chemical Energy Conversion (MPI CEC).
Source: Simon Ristig, MPI CEC

At the beginning of the project, catalyst test rigs (one example shown in Figure 1) were initially set up in order to be able to study ammonia reforming in detail under standardised conditions. Initial investigations were then carried out on selected catalysts known from other industrial catalysis processes. In addition to precious metal-based catalysts, catalysts used in other reforming processes (e.g. methane reforming) proved to be well suited. The catalysts developed in the project, which are based on iron, cobalt or nickel, among others, show different potentials depending on the other components they contain. Supported as finely dispersed nanoparticles on oxidic materials with a large specific surface area, such as magnesium oxide, cobalt and nickel have so far shown higher conversion rates than comparable iron-based catalysts (see Figure 2).

In contrast, iron and cobalt deposited on carbon materials achieve higher conversion rates than those with nickel. The most promising approaches are now being investigated in more detail and optimisation studies are being carried out. In addition to the highest possible conversion rate, the investigations will also focus in particular on long-term stability.

In addition, fundamental investigations of the catalytic processes are carried out using state-of-the-art spectroscopic methods and advanced computer modeling. With the understanding of the catalytic processes generated in this way, the catalysts can be optimised in a targeted manner.

Another key aspect of the project is the development of pilot plants and their components to ultimately demonstrate the industrial feasibility of energy-efficient ammonia reforming to hydrogen with a purity of >99.9 percent using the most suitable catalysts. The components that are under development are the appropriate reactor design for particularly high energy efficiency, gas purification by pressure swing adsorption, membrane process, or plasmalysis, and an overall heat integration of the system to achieve maximum energy efficiency. Plasmalysis will also be investigated as an alternative to thermal catalytic ammonia reforming.

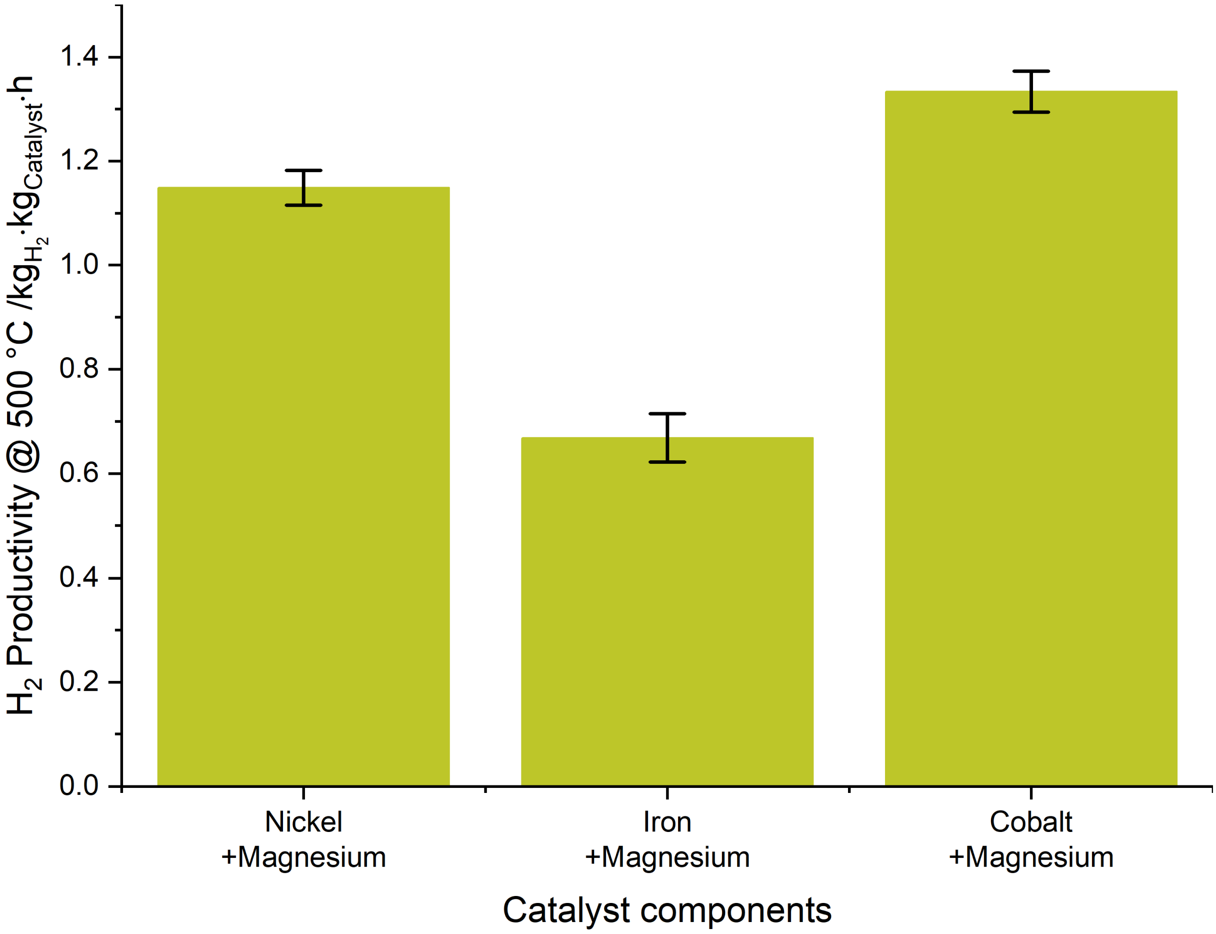

Figure 2: Comparison of hydrogen productivities in ammonia reforming by catalysts with different elemental compositions.
Source: Michael Poschmann, MPI CEC

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Total amount of funding:	14.7 mio. euro

AppLHy!

Storing, transporting and utilising LH_2 efficiently

The research of the TransHyDE project AppLHy! focuses on liquid hydrogen (LH_2). Due to its high energy density and purity as well as synergies with high-temperature superconductors, it offers great potential for a sustainable and efficient hydrogen economy. Since the start of the project, the researchers have been developing various technologies for the entire supply chain, from hydrogen liquefaction, storage and transportation to various application scenarios for LH_2.

Importing hydrogen in liquid form is energetically advantageous

The development status for the use of liquid hydrogen has so far shown promising results and further potential for improvement:

- LH_2 already has a very high level of technical maturity (TRL9) of the entire land-based transport chain and liquefaction capacities of up to approx. 30 tons per day.
- LH_2 offers the prospect of high energy efficiency when imported by ship. In addition, the energy required for liquefaction is only required once at the electrolysis site. There, large quantities of renewable energy are expected to be available that exceed the export country's national demand.
- In large-scale applications hydrogen losses caused by heat inleak into the LH_2 storage tanks, so-called boil-off, can be reduced to insignificant quantities through improved storage design and optimised transfer processes: at the export terminal, the boil-off gas is usually directly reliquefied, during transport by ship it can be utilised as fuel or reliquefied, and at the import terminal the gas is compressed and fed into the product pipeline.

Overall, the liquefaction of hydrogen is not only seen as a means of container-based transportation, but also as a flexible building block for the future hydrogen supply, which at the same time enables long ranges with high payloads in fuel cell-electric mobility applications. However, further developments in terms of increasing capacity, demonstration in Germany and market support are required for widespread commercialisation.

HyLiq – Solutions for efficient transportation and distribution of LH_2

As part of AppLHy!, the Dresden HyLiq consortium is working on the storage, transportation and handling of LH_2. One focus is on minimising losses and increasing the efficiency of the logistics chain – for example through efficient transfer pumps with wear-resistant bearings. Innovative sensor arrays also allow contactless determination of the LH_2 filling level, which introduces virtually no heat into the LH_2 tank. Highly efficient reliquefaction of boil-off gas further reduces losses, especially in the case of longer storage periods or if it is not possible to recycle the lost gas in the same location. Another important component for optimising the efficiency of the LH_2 supply chain is the recovery of parts of the energy for liquefaction by reusing the cold stored in LH_2 regardless of location and time. In addition to the development of the components required for this, a test environment has been created in Dresden that allows the investigation and testing of LH_2 under realistic conditions and serves as a demonstrator for stationary and mobile applications of LH_2.

Figure 1: LH_2 cryostat.
Source: Scientific Instruments Dresden GmbH

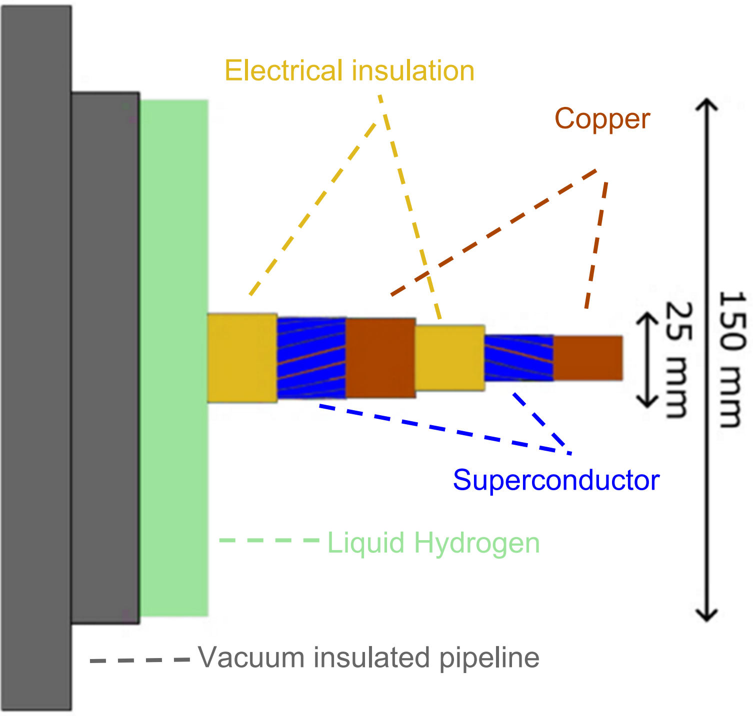
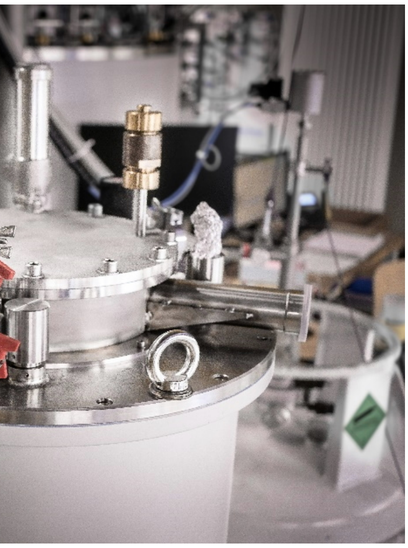


Figure 2: Schematic cross-section of a hybrid pipeline with LH_2 and electricity in a superconducting cable.
Source: Karlsruhe Institute of Technology – Institute of Technical Physics (ITEP)

Hybrid pipeline: LH_2 and superconductors

LH_2 is transported at extremely cold temperatures of around 20 Kelvin (-253 °C), an optimum operating temperature for high-temperature superconductors (HTS). This synergy is particularly interesting for simultaneous transport in a hybrid pipeline: in addition to chemical energy in the form of LH_2, electric energy is transmitted in a superconducting cable, and it does so in an extremely efficient, low-loss and space-saving way. The AppLHy! researchers have already developed initial application scenarios and components in order to demonstrate the feasibility of the concept in a test environment as the project progresses.



LH_2 increases range in mobile applications

Large vehicles with fuel cell drives benefit in particular from LH_2 as an energy source: its high energy density enables trucks, locomotives and ships to achieve long ranges with large payloads. This alternative to battery-electric vehicles is particularly attractive for regions with a limited electrical infrastructure and for sustainable aviation.

In addition, powertrains that are cooled with the intrinsic "free cold" of LH_2 are very efficient, as there is no need for separate cooling: for example, electric motors are limited in their performance diagram by three heating limits of components. However, if the LH_2 is regasified in the drivetrain itself, the hydrogen cools the surrounding motor. Also, as mentioned for the pipeline, this temperature range is ideal for components made of HTS. AppLHy! researchers are therefore developing LH_2-cooled, super-conducting motors – and calculating previously unattainable power densities of more than 10 kW/kg compared to less than 4 kW/kg for conventional motors.

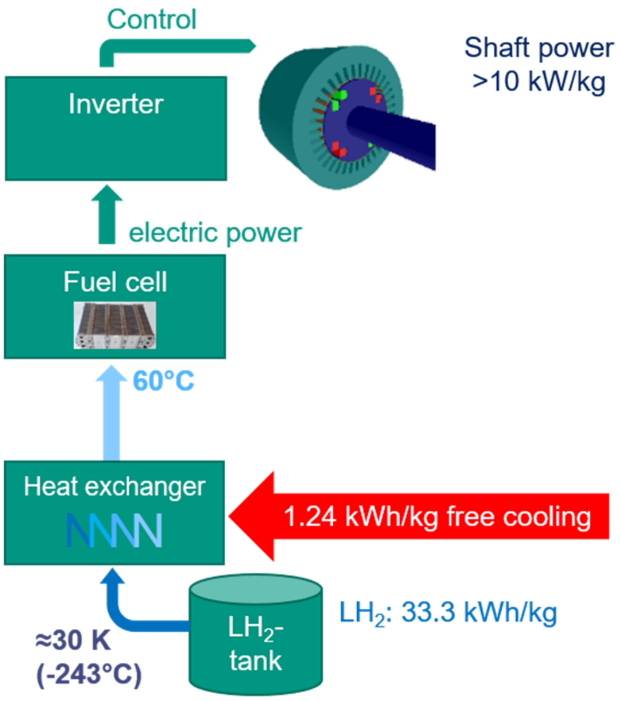


Figure 3: Fuel cell-electric drivetrain with HTS and LH_2 for vehicles (schematic).
Source: Karlsruhe Institute of Technology – Institute of Technical Physics (ITEP)

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Total amount of funding:	15.2 mio. euro

Norm

Technical standardisation for hydrogen ramp-up

In addition to technical and regulatory prerequisites, a rapid and successful hydrogen ramp-up also requires uniform specifications in the form of standards and certification programs. The TransHyDE project Norm investigates these aspects.

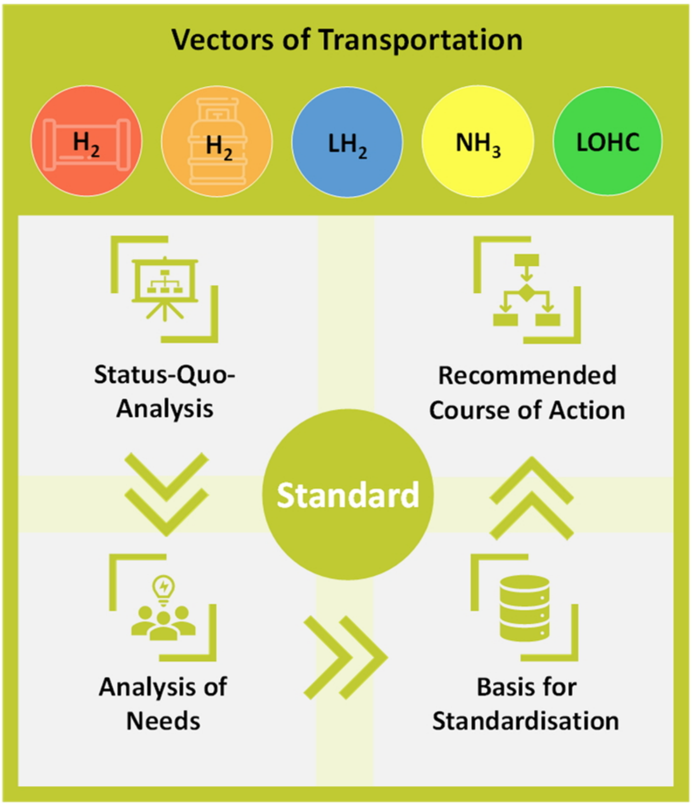

Figure 1: Overview of the contents of work packages 1 to 5
Source: TransHyDE project Norm

Technical standards form the basis with regard to safety, comparability and environmental compatibility. Here, the work within the project allows to identify deficits in standardisation for the transport vectors considered in TransHyDE

- compressed hydrogen (H_2) in pipelines,
- compressed hydrogen (H_2) in high-pressure vessels,
- liquid hydrogen (LH_2),
- hydrogen derivatives such as ammonia (NH_3),
- and Liquid Organic Hydrogen Carrier (LOHC)

to be identified and closed by clear recommendations for action. With regard to the envisaged new fields of application of the aforementioned transport vectors in, among others, industry, transport and the heat market, the standardisation of safety-relevant courses of action as well as technical processes and other aspects is indispensable due to their physical properties.

Inventory of the existing situation

In the first step, the currently existing technical standards and certification programs for the transport vectors considered were compiled in a database. For compressed H_2, transport and storage options in high-pressure gas containers and pipelines were considered. The focus was on national standards, although relevant European and international datasets were also included.

Over half of the datasets are already applicable to H_2. It should be noted that the proportions of H_2-ready rule sets and standards differ greatly among the various transportation vectors. A large part of the existing rule sets on established transport options, such as pipeline-bound or in high-pressure gas containers, as well as in the form of NH_3, are already H_2-ready or only need minor adaptation. In contrast, there are no specific standards for LOHC, for example. In the case of NH_3, it should be noted that existing regulations mostly apply to industrial applications and agriculture and not explicitly to NH_3 as an energy carrier.

Focus on experts

In the second step, a targeted survey of TransHyDE internal and external stakeholders from industry, research and associations served to identify gaps and adaptation needs. In the process, already initiated H_2 standardisation as well as the need for new developments were assigned to their temporal necessity. For NH_3, the legal adaptation needs were also included.

Exploiting synergies

In the third step, the recorded potentials for standardisation will be combined and evaluated. The necessary steps for further and new developments derived from this will then be formulated as recommendations for action in a roadmap.

From theory to implementation

In the course of the project, H_2HohlZug has joined as work package 6 with the aim of developing and standardise a flexible and cost-effective experimental method for the mechanical testing of metallic materials under high-pressure hydrogen. This method will play a critical role in assessing the H_2-readiness of materials used in the H_2 infrastructure.

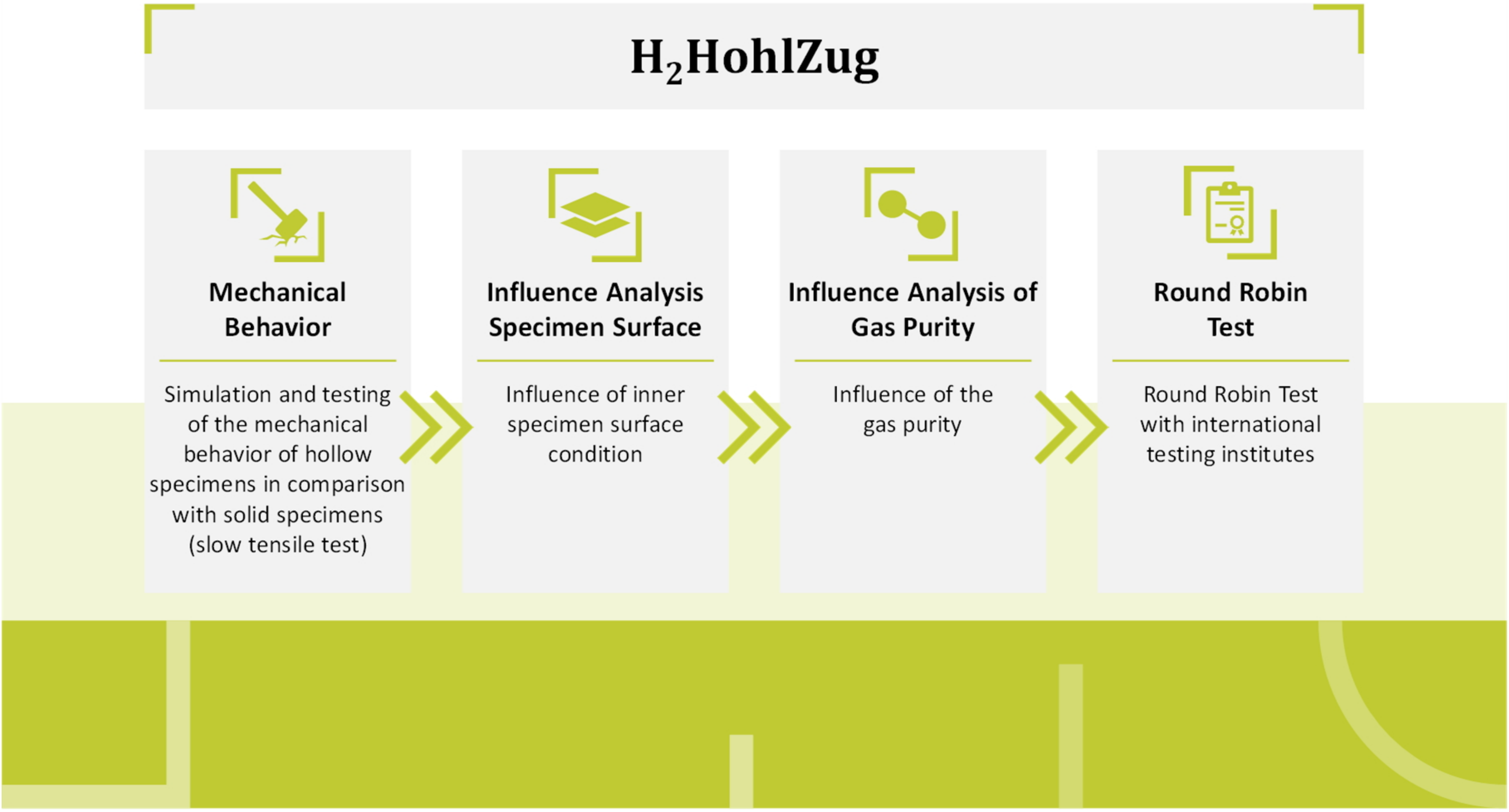

Figure 2: Overview of the content of work package 6
Source: TransHyDE project Norm

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LNG2Hydrogen

Sustainable use of liquid natural gas (LNG) Import Terminals

Forecast: demand for hydrogen and its derivatives trade in Europe and worldwide

Shipping is going to play a major role in the global transportation of hydrogen and its derivatives. It is assumed that more than 700 ships will be needed for maritime transport by 2050. Due to the high energy density of hydrogen and its derivatives, ships can transport large quantities and are most compatible with the existing LNG terminal infrastructures and those currently under construction.

As a study by McKinsey (Figure 1) shows, the global demand for hydrogen will almost quadruple by 2040 compared to 2020. In Europe, demand is expected to increase almost up to five times.

The future of hydrogen: climate neutrality and the LNG Acceleration Act (LNG Beschleunigungsgesetz)

The LNG Acceleration Act, which was passed on 24 May 2022, aims to accelerate the construction and use of stationary LNG terminals and the associated transport infrastructure in Germany.

Permits for such terminals require two main pieces of evidence: firstly,

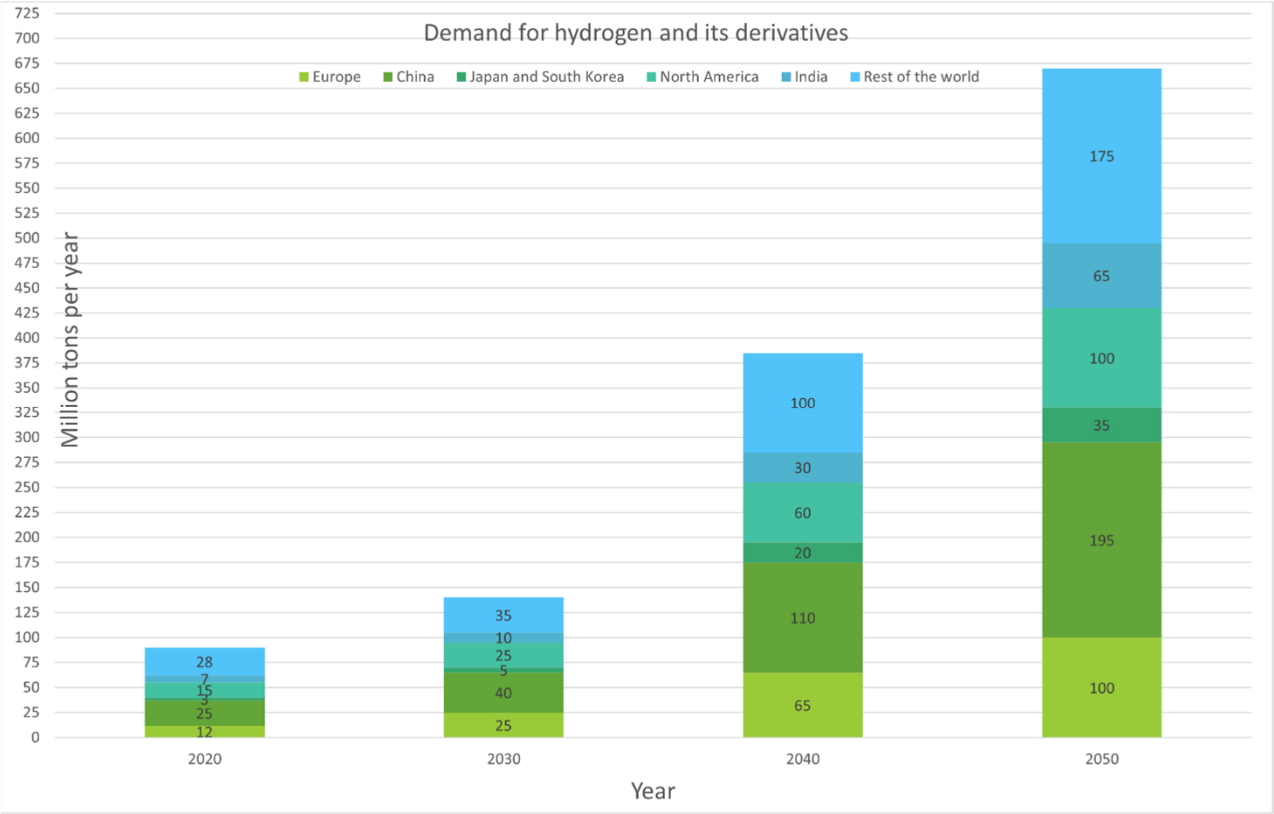

Figure 1: Demand for hydrogen and its derivatives.
Source: Global Hydrogen Flows: hydrogen trade as a key enabler for efficient decarbonisation Hydrogen Council, McKinsey & Company

the ability to convert to ammonia imports by 1 January 2044 at the latest, to ensure preparation for green hydrogen, and secondly, that the conversion costs do not exceed 15 percent of the original construction costs of the LNG terminal. The law also stipulates that a modification permit for the conversion must be applied for by 1 January 2035 at the latest. Until this date, hydrogen derivatives other than ammonia can be considered, ensuring flexibility and adaptability to new technologies in the hydrogen sector. The LNG Acceleration Act thus supports the rapid transformation of the LNG infrastructure.

Technological, logistical, economic and regulatory challenges

As part of the LNG2Hydrogen project, the technological, logistical, economic and regulatory requirements are being analysed. Several key aspects need to be considered with regard to the regulatory aspects of introducing new terminal types for hydrogen imports. These include the adaptation of shipping regulations at national, European and international level, the regulation of onward transport within Germany and the planning and authorisation law for terminals, in particular for multi-use terminals.

The specific properties of hydrogen derivatives are crucial in terms of technology and logistics. This applies to the design of the storage tanks, thermal insulation and the selection of structural materials to prevent damage. Equally important is the pump technology to ensure handling and safety. In terms of logistics, the properties of the derivatives play a central role, from ship transport and landing to storage, processing and further loading. The use of heat and cold from the processes rounds off the holistic approach and maximises the benefits of the hydrogen derivatives.

From an economic perspective, a number of considerations come to the fore. These include the timetable for converting the existing infrastructure and the economics of multi-purpose operation. It is important to consider in advance which elements can be implemented to minimise cost and effort.
The material and conversion costs, the availability of the required components and the follow-up costs along the entire logistics chain are key economic factors.

In addition, the organisational and temporal implementation of the transition from an old transport medium to a new hydrogen vector must be carefully planned and coordinated. These economic considerations are crucial for an efficient and cost-effective transition to sustainable hydrogen solutions. The question that arises is how is the transition from the old transport medium to the new hydrogen vector organised and timed?

LNG2Hydrogen: a research project as an answer

The LNG2Hydrogen research project is working on answers to the complex questions of terminal conversion. The aim of the project is to develop a database and recommendations as a basis for decision-making on the sustainable use of LNG terminal locations as logistical hubs for hydrogen and its derivatives (H_2 transport vectors).

The joint project is another important building block to achieve the TransHyDE goals, addresses several objectives of the National Hydrogen Strategy and thus makes a significant contribution to its implementation. The LNG2Hydrogen project will focus in particular on the following topics: analysis, presentation and evaluation of today's possible technical options for the sustainable use of LNG terminal infrastructures and an outlook on the necessary short-term research and innovation requirements – technology-open consideration of Synthetic Natural Gas, Liquid Hydrogen, Methanol, Ammonia, Liquid Organic Hydrogen Carrier and Dimethyl Ether as an alternative vector.

Status of the LNG2Hydrogen project

The project started in June 2023, has been running successfully for six months. The first step is to investigate what is meant by H_2 readiness and to define suitable transport vectors.
In a further step, detailed proposals for the conversion of LNG terminals and the process design of the terminal concepts for the various derivatives will be developed as part of a specification for future terminal concepts.

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Mukran

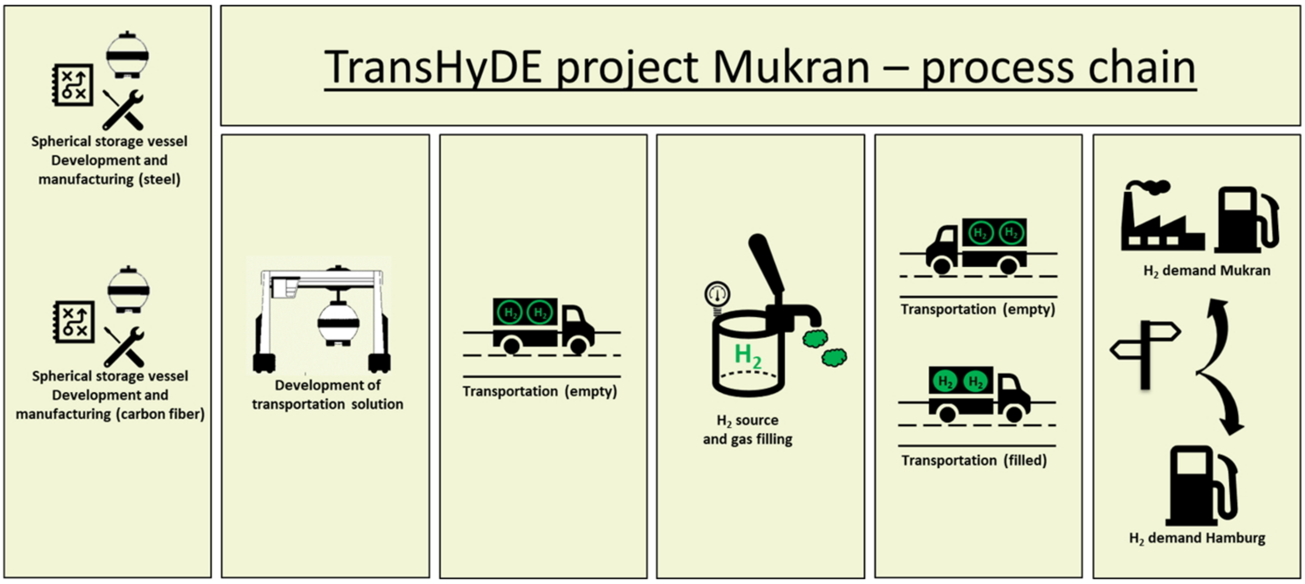
Trimodal H_2 transport and testing of the entire H_2 value chain using innovative high-pressure spherical vessels

The TransHyDE project Mukran has been exploring various development approaches in high-pressure hydrogen storage and decentralised hydrogen distribution since its inception in May 2023. The aim is to facilitate the establishment of regional hydrogen transportation solutions for the upcoming hydrogen market boom. The project goal is to implement and demonstrate the entire process chain, from container development and prototype construction to a mobile storage solution suitable for road, rail, and ship transport.

In pursuit of these goals, the project partners, including the Fraunhofer Institute for Applied Polymer Research IAP (division of Polymeric Materials and Composites PYCO) and the Brandenburg University of Technology Cottbus-Senftenberg BTU (Chair of Polymer-based Lightweight Design) are developing two variants of spherical hydrogen vessels with different material compositions. For the first spherical storage vessel, a combination of a steel liner with an outer skin made of carbon fibre-reinforced plastic (CFRP) is developed. In the second spherical storage vessel, two different steels are used. Here, high-strength alloys, new types of material-appropriate manufacturing processes as well as rule-based optimisation strategies are the innovation drivers and guarantee safety at high operating pressures despite minimised wall thicknesses. The partners expect decisive advantages from the choice of materials: on the one hand, cost savings that make the spherical storage vessels competitive, and on the other hand, a longer service life and improved recyclability.

In order to make the new types of hydrogen storage mobile, it is planned to install them in standardised container formats. To do this, a frame must first be developed that keeps the spherical storage units stable within the container during transportation.

In cooperation with the Sassnitz ferry port "Mukran Port" on the

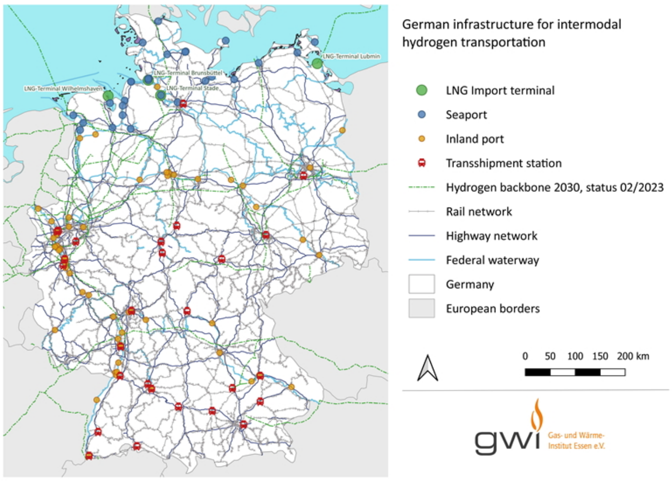


Overview of the transport chain with high-pressure storage tanks investigated in the TransHyDE project Mukran.
Source: TransHyDE project Mukran

Source: Fährfahren Sassnitz GmbH

island of Rügen and the European logistics company Hamburger Hafen und Logistik AG (HHLA), they discuss the requirements for transport as well as the filling and removal of the hydrogen. Data is being collected for this purpose, which assesses external influences during transportation and loading and unloading on the container. This data serves as the basis for the design of the vessels. These steps will then be tested in practice at HHLA's facilities in Hamburg and at Port Mukran.

To comprehensively examine the results of gaseous hydrogen transportation nationwide, an extensive literature and data review is being conducted at the Gas- und Wärme-Institut Essen e.V.. This review documents the current technical requirements for storage containers. This data, along with a georeferenced analysis of inland German trimodal transportation by rail, truck, and inland shipping, form the basis for a techno-economic comparison of different high-pressure gas storage systems based on customer and transportation structures, with an exclusion assessment concerning existing pipeline transportation.



German transport infrastructure for intermodal hydrogen transportation.
Source: gwi e.V.

The strategic project consultancy, **cru**h2**1**, is responsible for disseminating the results and searching for suitable investors. To facilitate this, a knowledge platform has been established to promote the exchange of information between research and industry and optimise the utilisation of potential synergies among knowledge providers.

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GET H_2

Conversion of natural gas transport grids to H_2 and safe operation of H_2 pipeline networks

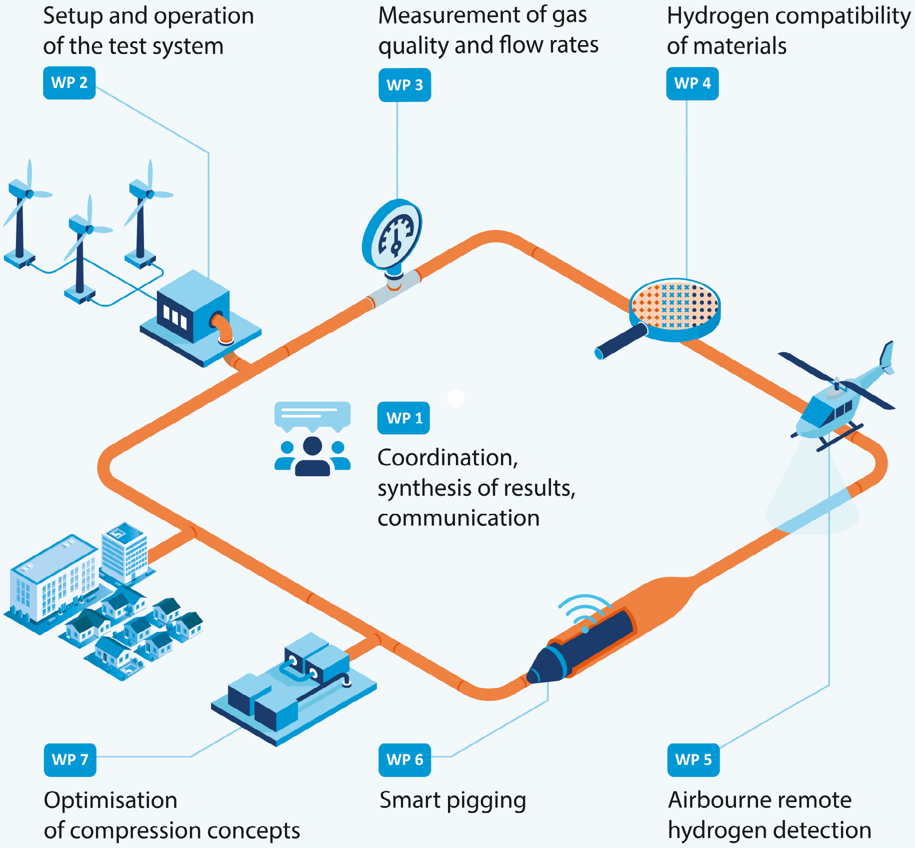
The existing natural gas infrastructure will be essential for importing and transporting hydrogen within Europe. Extensive planning is underway at both European and national levels for the development of a hydrogen transport network. A large part of this pipeline system will be the result of the conversion of natural gas networks, but new networks and facilities will also have to be built.

The TransHyDE project GET H_2 addresses fundamental technical and operational issues essential for developing and operating a safe and reliable gaseous hydrogen infrastructure.

For this purpose, a 130 m long pipeline loop will be set up (work package 2, WP 2) in order to investigate the metrological, operational (WP 3) and material-related (WP 4) aspects of pipeline-based hydrogen transport under realistic boundary conditions.

Safety issues will also be addressed with line monitoring using remote H_2 leak detection by air (WP 5) and intelligent pigging (WP 6).

Compressor concepts for hydrogen injection, transport and storage will also be developed and evaluated (WP 7).



The TransHyDE project GET H_2 develops operational strategies and safety standards for the safe and efficient operation of hydrogen pipeline networks.
Source: TransHyDE project GET H_2

So far, we have achieved the following results

In WP 2, a 250 kW high-temperature electrolysis plant was completed and commissioned at the Lingen gas power plant site to supply the test pipeline with hydrogen.

Micro GC system developed for H_2. Source: meterQ

For gas quality measurement, a micro gas chromatograph (GC) system was developed in WP 3 which is already undergoing the official approval and calibration process. Further commercially available measurement and analysis equipment was procured and tested in a specially designed laboratory. In addition, a purification vessel for the adsorptive removal of impurities was set up. Screening tests will be carried out to identify suitable adsorbents. The most promising adsorbents will then be tested in the purification container under realistic conditions. In addition, WP 3 will test turbine meters for official calibration and approval.

WP 4 will test the use of hydrogen in materials from existing and new plants. A review of the literature has shown that the influence of the operational loads in a hydrogen atmosphere has not yet been sufficiently evaluated. Therefore, a material test rig is currently being integrated into the test pipeline. It will compare operationally stressed pipe sections from existing pipelines with newly manufactured ones.

Airborne inspection of gas pipelines is an important component in the monitoring of gas transmission pipelines. In WP 5, a laser measurement system which can be integrated into an aircraft is being developed. It can detect leaks from a height of 100 to 150 m. The method used is based on the Raman scattering of UV radiation by hydrogen.

For the internal inspection of the pipeline in a hydrogen atmosphere (WP 6), a natural gas pipeline was inspected for corrosion and cracks using ultrasound with water as the coupling medium. No serious defects were detected. The pass ability of the pipeline was verified by a so-called zero-pigging using a geometry pig. A new Electro-Magnetic Acoustic Transducer ("EMAT") pig is being developed for reference inspection in an H_2 atmosphere. It must be capable of detecting crack-like flaws without the use of a coupling medium. An optimisation process will run in parallel for the construction and the operation mode. In addition, material tests have shown that the magnets installed on the pig need to be protected from the H_2 atmosphere.

Operating 250 kW high-temperature electrolyser.
Source: RWE Generation SE

As part of the development work, flow simulations were carried out using real pipeline data obtained by the zero-pigging, as the flow behaviour of hydrogen differs significantly from that of natural gas due to its much lower density. In order to connect an H_2 source to the transport system (WP 7), the gas quality and pressure level must match. This requires a gas pressure regulating and metering system (GDRM system) as a feed unit where the hydrogen is compressed and the flow rate is measured. Therefore, a standardised and modular hydrogen injection unit has been designed and an economic analysis has been carried out.

Another focus of the work is the conceptual design of compressor stations for H_2 transport. Based on network simulations, specifications for machines have been developed and product portfolios and expected developments over the next few years have been evaluated with manufacturers.
These studies provide an important basis for the construction and operation of both retrofitted and new hydrogen transport pipelines. The knowledge gained in-turn will be incorporated into DVGW regulations and operational practice.

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CAMPFIRE

Hydrogen carrier ammonia as a reliable energy storage medium and fuel

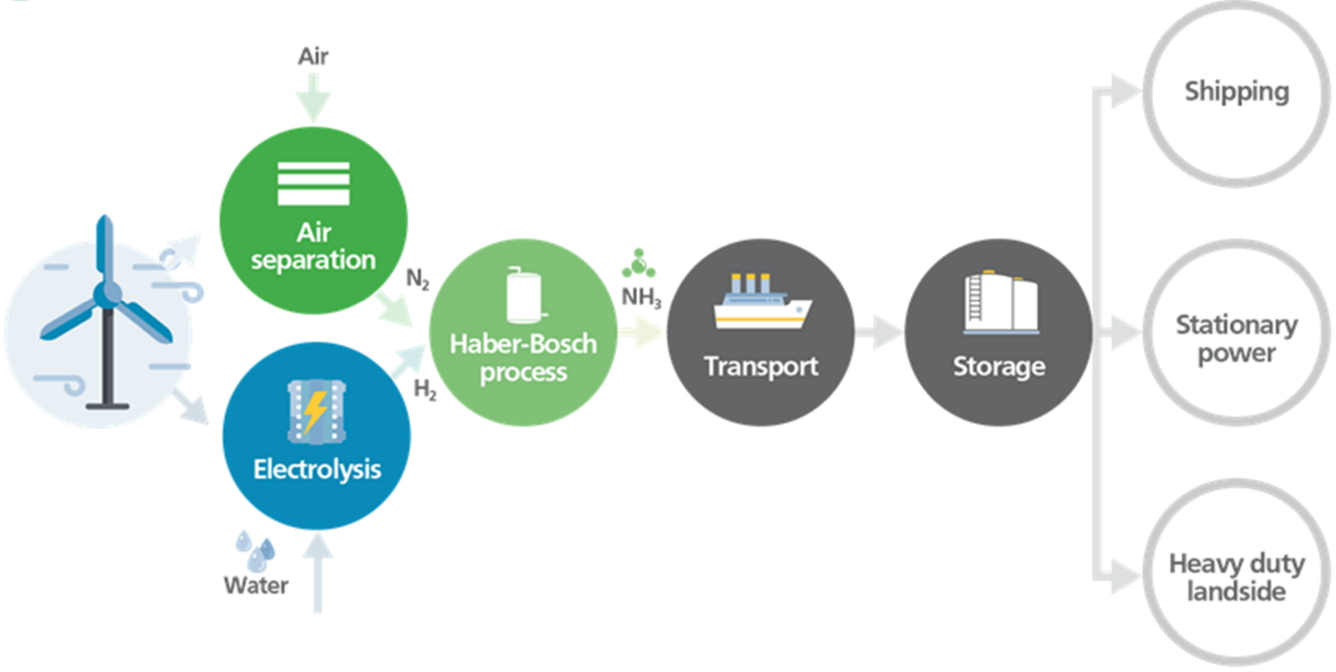
Ammonia is nitrogen-bound hydrogen that can be stored and transported easily and cost-effectively. It is increasingly recognised as a key building block for the roll-out of a hydrogen economy. The CAMPFIRE implementation project is developing technologies along the entire green ammonia value chain as part of the TransHyDE flagship project. Innovative technologies for the decentralised production of green ammonia for the storage of fluctuating wind and solar energy ("power-to-ammonia") are required for the development of logistics and infrastructures for the use of ammonia as a carbon-free hydrogen carrier. In addition, the partners are addressing the urgent need for new products for the flexible refuelling of ammonia-powered ships, for the use of ammonia as a fuel in ship engines, in land-based heavy goods transport, in work machines or for supplying combined heat and power plants and electricity filling stations ("ammonia-to-power"). New solutions are also being developed for the reconversion of ammonia to hydrogen using ammonia crackers. For each technical implementation, the legal framework conditions and acceptance issues are being closely analysed and developed. In view of the enormous demand for new technical solutions with global application potential, the companies in the CAMPFIRE alliance, which was founded in 2019 as part of the BMBF WIR! programme, the companies in the CAMPFIRE alliance want to exploit these enormous future opportunities for the German economy.

The infrastructural and technical supply conditions available at the YARA Rostock site are predestined for industrial technology development at relevant performance levels. Infrastructures and test benches are being set up by the CAMPFIRE Open Innovation Lab as part of TransHyDE in collaboration with the Poppendorf Technology Centre – Green Ammonia ChemPark, in order to create a suitable development environment that will give start-ups and young companies in the field of ammonia and hydrogen a competitive advantage in the global race.

In the course of the project to date, the 32 partners in the CAMPFIRE implementation project have addressed a number of development needs. Key results include the design of a bunker barge for the import and transport of 1,000 m³ of cold liquefied ammonia and a land-based refuelling system, including the design of the hose and coupling system, heat management, safety considerations and training documents. For the decentralised production of ammonia, the partners successfully developed the design of a 200 kW Haber-Bosch overall plant based on innovative flow control elements and catalysts for dynamic operation in different load ranges and are preparing the procurement and construction of the plant. Cracker engine hybrid systems for ship propulsion (350 kW) and for stationary combined heat and power generation (1 MW) based on ammonia are being developed.

The project teams were able to successfully carry out the combustion processes for ammonia-hydrogen fuel mixtures on the respective single-cylinder engines and achieve attractive efficiency levels. The combustion processes are currently being transferred to the full engines and coupled with ammonia crackers. The work also includes product safety evaluations and material compatibility analyses as well as the screening of exhaust gas catalytic converters.

CAMPFIRE



Core technologies and applicational fields for the future green ammonia energy system.
Source: CAMPFIRE Alliance / Makyo Studios

The partners are developing an infrastructure and logistics concept for ammonia and have carried out energy demand forecasts for modes of transport and a potential analysis as an overview of the current and future applications of ammonia. An interactive visualisation option was developed to provide an overview of ammonia transport capacities for sea and land transport.

The partners are also working on a cracker-based ammonia-to-hydrogen refuelling station for the future supply of hydrogen from ammonia. The focus is on the ultra-fine cleaning module, which is manufactured on the basis of a new type of screen printing process and an innovative laser welding process for the seals. The first module has been successfully realised and installed. The safety concept for the petrol station is being developed and a profitability analysis is being carried out. For the test operation of the new technologies, the partners are implementing the design and procurement of system components for the construction of test fields with energy and media supply and a central control concept at the YARA GmbH & Co KG site in Poppendorf. The focus is on the development of safety equipment and control concepts.

CAMPFIRE is closely interlinked with the technology developments and monitors and analyses current legal developments for ammonia by taking a holistic sustainability approach to supply chains, taking into account ongoing dynamic developments. Within the project, a communication concept for ammonia is being developed and refined. In-depth interviews were conducted with stakeholders and the requirements for formal public participation in relevant planning and authorisation procedures were defined. The focus of all work is the safe use of ammonia and investigations into regulatory gaps and obstacles with regard to safety are being carried out in order to derive proposals for legislation and standards.

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Helgoland

H_2 storage and transport with LOHC (Liquid Organic Hydrogen Carriers)

In the Helgoland network, nine project partners from science and industry have linked up with the island of Heligoland to research and develop a hydrogen supply chain from the offshore area in the Schleswig-Holstein coastal sea via the ports to hydrogen consumers on the mainland. In this supply chain, the example of Heligoland will be studied as a model location for hydrogen storage in LOHC (hydrogenation) and Hamburg as a location for hydrogen release from LOHC (dehydrogenation).

Within this research scenario, the green hydrogen produced at sea and shipped to the island of Heligoland via pipeline, is bound to LOHC – specifically the thermal oil benzyltoluene (BT) – in a hydrogenation plant. In this liquid carrier, it is transported by ship to the mainland and made available to hydrogen consumers. The goal of the project is to provide a reproducible and scalable blueprint for worldwide sites with similarly challenging conditions.

The focal points of the project at a glance

Within the modeled transport chain, each project partner has its own research and development areas. The focus is on LOHC-BT technology and the technical scaling of hydrogenation and dehydrogenation plants, logistical solutions for LOHC-BT transport and handling, feasibility and economic scenarios, as well as materials research for pipelines and the development of tank and maintenance concepts.

LOHC technology: packing hydrogen safely and efficiently

The TransHyDE project Helgoland relies on the innovative LOHC technology by Hydrogenious LOHC Technologies GmbH from Erlangen, Germany, which uses the thermal oil benzyltoluene as hydrogen carrier material. A major advantage of this technology is the high inherent safety of the carrier material used. Because it is flame retardant and comparatively uncomplicated to handle with existing liquid fuel infrastructure, it is particularly suitable for use in ports or urban environments. In addition, LOHC-BT can be loaded and unloaded with hydrogen many hundred times and is recyclable.

In the context of LOHC-BT technology, various development topics for the optimisation of hydrogenation plants are being investigated on a model basis, such as increased plant flexibility, reduced plant space requirements, intelligent modes of operation, etc. The focus is also on the technical scaling of hydrogenation and dehydrogenation plants. In addition, the technical scaling of the hydrogenation and dehydrogenation plants is a focus.

Visual inspection of LOHC-BT sample.
Source: Hydrogenious LOHC Technologies GmbH

Feasibility studies, business cases and operator models

Feasibility studies and analyses are used to examine the transport chain for its technical and economic realisation potential. These include studies on the location of the plants and the use or expansion of space within different logistical variants for LOHC transport and handling, as well as the use and integration of heat from different plant sizes during the hydrogenation and dehydrogenation process. Also case studies for decision making of later operator models. The main player in the field of "hydrogen logistics" is Hamburger Hafen und Logistik AG (HHLA). It is investigating possible locations in Hamburg for the implementation of a hydrogen import terminal.

Example of a storage plant.
Source: Hydrogenious LOHC Technologies GmbH

Materials research, maintenance and tank systems

The project partner Fraunhofer IFAM (Institute for Manufacturing Technology and Applied Materials Research) focuses on the area of materials research. Here, additional, innovative material concepts are being investigated as a possible addition to the existing infrastructure.

These include:

- Biocide-free anti-fouling coatings for marine pipelines and investigations into which substances are released into the environment by corrosion protection coatings.
- Special barrier coatings designed to reduce damage from pressurised hydrogen in metallic materials.
- Stationary and mobile tanks for LOHC-BT storage and transport: e.g., durable materials for tank construction and sealants and adhesives, or a new concept for LOHC tanks that cuts tank footprint in half.
- Investigations into whether LOHC-BT can be attacked by bacteria or fungi in a similar way to mineral fuels.
- Methods for monitoring the tanks: inspection by drones and continuous monitoring by integrated fiber optic sensors.
- Condition monitoring of LOHC-BT using inline spectroscopic methods.

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TransHyDE Technology platform

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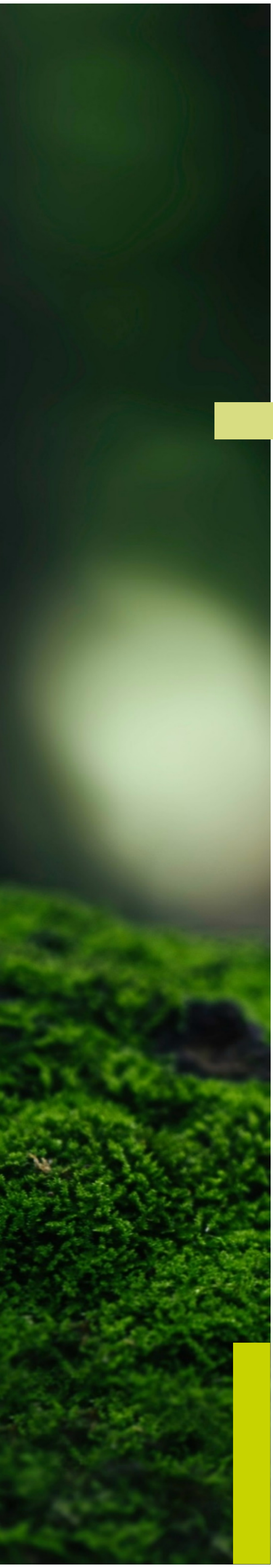

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