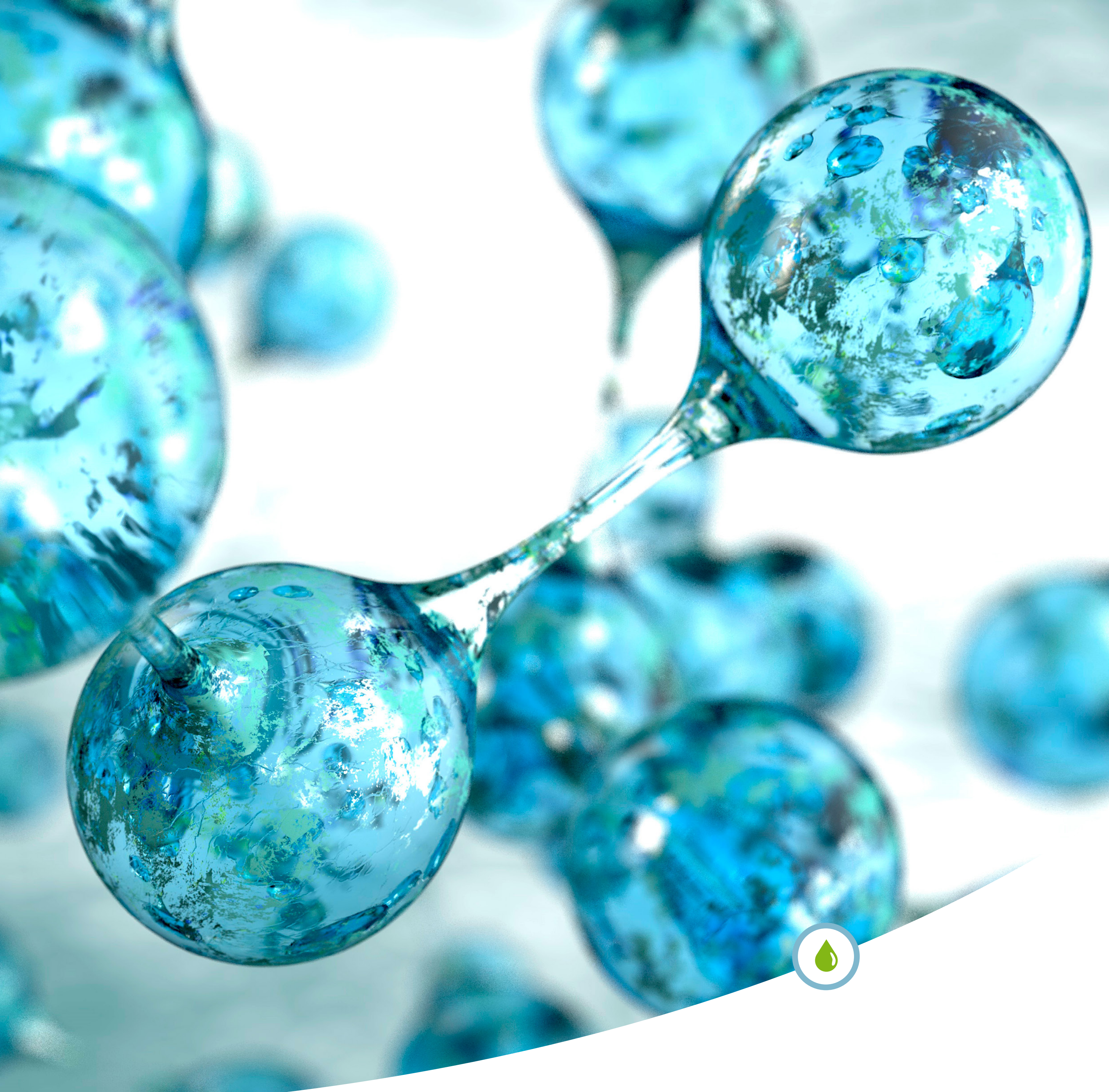

EXPERTS' RECOMMENDATION 2023
HYDROGEN RESEARCH NETWORK

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The revision of the Experts` Recommendation took place in an interactive dialogue process by the members of the Hydrogen Research Network in December 2022/January 2023.

The cluster spokespersons would like to express their sincere thanks to the topic mentors, moderators of the PLC and participants in the consultation process, without whose commitment it would not have been possible to produce this revision.

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SUMMARY

The Hydrogen Research Network has almost 1.350 active members from industry, science and associations and represents with its following four thematic clusters the full spectrum of hydrogen expertise in the field of applied energy research in Germany: 1) Production of hydrogen and downstream products, 2) infrastructure and system integration, 3) utilisation and 4) safety, acceptance and sustainable market introduction.

The first version of the Experts' Recommendation, summarising the research needs along the entire value chain of the hydrogen economy until 2025, was presented to the representatives of the German federal ministries in September 2021. In spring 2022, it was supplemented by a long version of the Experts' Recommendation, which refers to the topics mentioned in the short version, presents them in detail and categorises them in short, medium and long-term research needs.

The expertise bundled in this revised Experts' Recommendation will be incorporated into the consultation process of the 8. Energy Research Programme and show the German government the future need for actions and funding strategies.

The revision was produced in an interactive dialogue process by the members of the Hydrogen Research Network in December 2022/January 2023.

The cluster spokespersons would like to express their sincere thanks to the participants of the consultation process, in which science, industry, small and large companies and associations have been equally involved. Without this commitment, it would not have been possible to produce this revised Experts' Recommendation.

Production of Hydrogen and Downstream Products

Utilisation

Infrastructure and System Integration

Safety, Acceptance and Sustainable Market Introduction

1. PRODUCTION OF HYDROGEN AND DOWNSTREAM PRODUCTS

Motivation

The production of low-CO_2 hydrogen and hydrogen based downstream products are important pillars of the transformation of the raw material and energy system for a sustainable society. Overall, diverse processes exist for the production of sustainable, material energy carriers and basic materials that can play a decisive role on the path towards achieving climate neutrality in the long term or as bridging technologies.

In the case of hydrogen, the National Hydrogen Strategy focuses on the production of green hydrogen through water electrolysis, which uses renewably generated electricity. Furthermore, alternative photocatalytic, photobiological and solar thermochemical processes as well as techniques using biomass can be used for the production of hydrogen from renewable sources. Further paths for low-CO_2 production of so-called blue and turquoise hydrogen based on fossil energy carriers are currently being studied intensively.

In regard to related products, technologies for the conversion into other hydrogen-based energy carriers are being addressed, which increase the storage and transport capabilities. Particularly in the fields of aviation and maritime shipping, and to some extent also in heavy goods transport, sustainable liquid fuels are currently the only alternative for achieving climate neutrality in the foreseeable future. In the steel and chemical industries, too, existing production processes for the manufacture of intermediate and end products must be redesigned.

Research and development needs

According to the coalition agreement of the German government, hydrogen production facilities with a total capa city of ten gigawatts are to be built by 2030. This requires widespread industrialisation and the rapid implementation of viable technologies. The economic implementation of these processes essentially assumes that costs are reduced by increasing efficiency, scaling and longer service life. Furthermore, the automated large-scale industrial production of the components and cell stacks must established and optimised in terms of quantity and quality.

At the same time, there is an urgent need to pursue disruptive approaches with a low Technology Readiness Level (TRL) so far, but which offer the potential of a significant increase in efficiency. For all these processes, it is of fundamental relevance to develop and scale up new material systems (catalysts, membranes, electrode materials, other materials) promptly.

The development of individual technologies must also be complemented by systemic optimisation. This specifically encompasses the following aspects:

- The economic and ecological analysis of the entire value and supply chain.

- The holistic optimisation of the production processes for hydrogen and related products, including the integration of heat and material flows and dynamic operations management.

- The integration of the production facilities into the energy system through optimisation of the electrical system technology (cost reduction of the technology, grid-serving flexibility and improvement of the economic efficiency of the operation).

- Standardisation and harmonisation of components as well as the adaptation of existing norms and standards to future requirements and for worldwide application.

Production of green hydrogen via electrolysis

Various processes with different TRLs are available for the production of H_2 via electrolysis. Alkaline water electrolysis (AWE) ranks as one of the established processes with a high TRL. It requires virtually no critical resources and can already be produced today in large quantities with high output. R&D is needed on materials and components for high pressures and temperatures, adapted cell designs and on series and mass production. Alkaline membrane electrolysis (AEMEL) has a high potential to develop compact electrolysis units with high dynamics despite a low TRL. Here, it is necessary to continue developing components (membranes, catalysts) to increase long-term stability and to scale up cell stacks and facility concepts.

PEM water electrolysis (PEMEL) is currently being introduced to the market on a large scale. It features high flexibility and power density as well as low complexity of the overall system, but involves the use of cost intensive and partially critical materials. These must be reduced or substituted in the future. In this context, the development and establishing of recovery and recycling procedures play a key role. Those procedures accompany the ramp-up of the production and must be integrated into the existing and emerging manufacturing processes.

High-temperature electrolysis (HTEL) based on solid oxide cells or proton-conducting ceramic cells converts evaporated water into hydrogen or gas mixtures of water vapour and carbon dioxide directly into synthesis gas (syngas). R&D is mainly needed for the materials (increasing power density, robust-ness and service life), the scale-up of the stacks and for the development of fully automated manufacturing processes. Recycling options for the metallic as well as the ceramic components need to be developed.

Production of green hydrogen via alternative processes

Photoelectrochemical and photocatalytic processes as well as solar thermochemical and photobiological processes convert solar energy directly into hydrogen or other chemical energy carriers. They have the potential to produce green hydrogen particularly efficiently and cost-effectively. However, the processes generally possess a lower TRL. Research goals include increasing the efficiency and long-term stability of the processes. This can be achieved with the help of efficient and stable materials (absorbers), cost-effective concepts for the scalability of cells and reactors as well as by optimising photoelectric system aspects and the solar concentrators, or heat recovery in solar thermochemical systems.

Production of green hydrogen from biomass and biogenic waste materials

In the production of hydrogen from biogenic sources and waste materials, processes such as fermentation, reforming, gasification, pyrolysis and plasma analysis are used.

They can provide cost-efficient sources of hydrogen in closed regional material cycles and thus accelerate the ramp-up of the H_2 market. Connected technologies for CO_2 capture and storage as well as utilisation (CCS/CCU) result in effective greenhouse gas (GHG) reductions. There is a need for research in scaling up such plants to industrial levels as well as in the efficient processing and separation of the hydrogen reactant. Studies should be conducted simultaneously to detect residual material potentials and thus resulting production potentials as well as their carbon footprint.

Production of blue and turquoise hydrogen

Blue hydrogen is produced from fossil raw materials by capturing and storing the CO_2. Turquoise hydrogen is produced via methane pyrolysis from fossil natural gas or from biogenic sources (such as biogas), by which no gaseous CO_2 but solid elemental carbon is produced. The energy required for pyrolysis comes from renewable sources. Both approaches require relatively little energy, offer the possibility of a rapid ramp-up of an H_2-based energy supply and can contribute to GHG reductions within a short timeframe. R&D is needed to bring pyrolysis processes to demonstration scale and to develop CCU processes and techniques for the permanent and safe storage and/or utilisation of CO_2 and carbon.

Production of hydrogen-based related products

The production of sustainable synthetic base fuels and fuels based on climate-neutral hydrogen, carbon or synthesis gas (H_2/CO) is an important building block for achieving climate goals. Products such as methane, methanol, ammonia, olefins and ethers are key elements in the future chemical and fuel industry. More-over, as a hydrogen carrier medium, they can contribute to making the transport of hydrogen more efficient and safer as can liquid organic hydrogen carriers (LOHC). In aviation and maritime shipping as well as to some extent in heavy-duty transport, liquid chemical energy carriers will make an significant contribution in the medium to long-term due to their high energy density.

R&D for the production of hydrogen-based related products is therefore needed for the rapid industrial implementation of marketable overall process systems. For this purpose, different sub-processes must be ideally coordinated with each other to enable economical large-scale production. In addition to optimising established technologies, new types of disruptive processes offer the potential for significantly higher overall efficiencies despite a low TRL, such as the direct electrochemical synthesis of methane, methanol, ammonia and dimethyl ether (DME) as well as solar thermal, photochemical and biochemical syntheses.

2. INFRASTRUCTURE AND SYSTEM INTEGRATION

Motivation

As a link between the points of production and utilisation as well as a storage medium, hydrogen infrastructure will play a key role in a future energy system. The H_2 storage as well as the transport and distribution infrastructures must be redesigned at an early stage as the backbone of a hydrogen strategy in order to overcome from the outset the bottlenecks and delays which experience has shown have led to delay in the transition of the electricity sector.

Moreover, the potential of hydrogen to increase the flexibility and decarbonisation of the overall system can only be fully exploited through effective interaction between the electricity and gas or H_2 infrastructure. Therefore, it is of pivotal importance that the hydrogen infrastructure is optimally integrated into the overall system by means of sector coupling.

Since both infrastructure and the strategic overall system integration lead to early course-setting in the transition process, both fields have a high priority on the research side.

The smart conversion and utilisation of existing infrastructure such as pipelines and caverns are particularly important here. If these are strengthened through targeted upgrades for hydrogen, substantial cost savings can be achieved.

Research and development needs

The R&D needs in the field of H_2 infrastructure are divided into five thematic areas. The following applies to all areas:

- An openness to all technologies and an overall systemic approach ensures an optimal use of the technology options and their synergies as well as a fast market introduction and an effective ramp-up across the entire range of applications of H_2 infrastructure.

- The focus of the R&D measures is on increasing economic efficiency, conversion of existing installations, security of supply, sustainability and resilience through optimisation, further development and innovation as well as an improved understanding of future system design and operational management.

- Prompt implementation of the necessary R&D measures is necessary as H_2 infrastructure represents an essential basis for a hydrogen economy and early mistakes in setting the technical course can cause expensive lock-in situations for the economy.

- Market entry of first technology options is already given in all areas and should be pursued in parallel to necessary R&D measures.

- Compatibility and interoperability must be developed and optimised in order to fully exploit synergy effects.

- Clear definitions of standards and norms across all subject areas form the basis of technology solutions that are marketable.

The most important R&D requirements up to 2025 are summarised below for each of the five thematic areas.

Transport infrastructure for road, ship and rail-based H_2 transport

- Technical development of H_2 transport technologies (such as liquid hydrogen (LH_2), compressed hydrogen (CH_2), synthetic fuels, LOHC, metals and their hydrides, ammonia/methanol as H_2 carrier) with ongoing techno-economic analysis of the various process paths by means of specific use cases and demonstration projects.

- Further development as well as optimisation of mobile H_2 storage, refuelling technologies/processes and transfer technologies/processes (such as H_2 quality according to demand, H_2 pressure, controlled H_2 depressurisation, boil-off effects during transport of LH_2).

- New approaches for safety assessments of the elements of the process chain such as pressure vessels on road, rail and waterways.

- Development of methods for non-destructive testing of H_2 components such as storage tanks (material testing) and H_2 quality assurance.

Pipeline transportation distribution grid

- Analysis of the existing distribution grids and the user structure to identify cost-optimised and time-optimised transformation paths for private and industrial consumers.
- Materials research for the identification and development of H_2-compatible materials for pipelines, fittings and installations considering the main impacts (pressure and temperature cycles) and the permeation of hydrogen including the qualification of the materials.
- Development of materials for gas separation and of suitable coating processes for upgrading existing gas pipelines for hydrogen.
- Development of safe conversion processes and strategies for the transformation of conventional gas networks to hydrogen networks. For this purpose, not only pure hydrogen pipelines but also H_2 admixture to natural gas can be considered.
- Materials research on materials already existing in systems for qualification/requalification and determination of areas for application for operation with hydrogen.
- Gas quality measurements for monitoring the gas mixing ratio in the pipelines and gas detection without odourisation in the distribution system in the event of possible leaks.

Pipeline transportation transmission network

- Materials research to identify and develop H_2-compatible materials for pipes, fittings and systems, taking into account the parameters of pressure or cyclical pressure variation, temperature and the permeation of hydrogen.
- Further development to increase the TRL of relevant applications such as compressors (mechanical and electrochemical compressors), gas processing and sensor systems as well as measurement technology in order to achieve the necessary increase in scale and cost reductions.
- In the area of compressors and their drives, there is a need for development to meet the requirements of H_2 transportation with accordingly high delivery rate.
- Evaluation of grid topology with regard to suitable additional feed-in and landing points inland.

Medium and large-scale H_2 storage

- Conceptualising of geological reservoirs and development of transformation strategies into H_2-storage. Various aspects such as microbiology, suitability testing of underground and above-ground components, cementation/complementation and gas purification have to be considered.
- Development of measures to qualify existing H_2 storages facilities.
- Development and testing of operating strategies for H_2 storage facilities in order to take the changed boundary conditions in terms of dynamic operation and thermodynamic properties into account. In this context, an analysis of the expected operational management dynamics must be conducted with regard to market mechanisms, electrolysis hydrogen production, etc.
- Further development to increase the TRL of above-ground high-pressure, solid, LH_2 and other liquid storage as well as chemical storage and their interaction (multimodal storage) to achieve the necessary increase in scale and cost reductions.
- Technologies for the system integration of hydrogen storages in local electricity, gas and heat grids (waste heat, electrolysis, storage facilities and compressors, utilisation of pressure potentials).

Overall system integration and modelling

- Development of simulation and optimisation tools for integrated system planning and efficient grid operation with technology-open infra-structure modelling to address the four aspects of security of supply, economic efficiency, sustainability and resilience.

- Technologies and concepts for decentralised coupling of all energy sectors with the H_2 infrastructure including approaches to distributed hydrogen production and reconversion (such as H_2 combined heat and power (CHP), refrigeration reuse LH_2).

- Open science modelling of transport and distribution networks in combination with optimising modelling for integrated sector coupling (electricity, H_2, green hydrocarbons, heat, air conditioning) and energy demand (mobility, logistics, industry, commerce, buildings).

- Development of transformation strategies (global to local, centralised vs. decentralised) and road-maps that take different scenarios and market developments into account (such as sector coupling with H_2, transformation costs, operator models for H_2 infrastructure).

- Digital architectures and associated market designs for decentralised sector coupling.

- Grid-serving design of allocation and operational management of future electrolysis capacities.

To conclude and summarise, hydrogen distribution, storage and system integration are the lifeblood of resilient climate-neutral energy systems. For this reason, market entry can and should take place promptly by scaling up marketable and known technologies, while system-analytical research will simultaneously help to optimise system design to ensure the best possible course in the transformation process. The listed R&D needs are crucial until 2025 in order to raise the economic attractiveness of storage, transport and system technologies through further development and innovation.

3. UTILISATION

In principle, hydrogen can be used wherever fossil fuels are used today. However, the technical maturity of the applications varies significantly: While some are already fully developed and industrialised, others will only be ready for series production in a few years' time. The following table summarises the development status of the technologies based on the TRLs that are to be operated with pure hydrogen.

	Industry: Material use	Industry: Energetic use for process heat and steam	tationary: Use in trade and industry	Stationary: Use in households	Mobile: Use in cars	Mobile: Use in trucks	Mobile: Use in rail transport	Mobile: Use in shipping	Mobile: Use in aviation
H_2-based direct reduction and melting processes	TRL 7								
H_2-industrial furnaces	TRL 6	TRL 2-7							
H_2-furnace systems/ process heat/ condensing technolo-gy/steam generation	TRL 6	TRL 2-9	TRL 4	TRL 6					
Stationary H2 fuel cells			TRL 4-8	TRL 4-8				TRL 3-6	
H_2-gas turbines	TRL 6		TRL 4					TRL 4-6	TRL >4
H_2-combined heat and power plant			TRL 5-6	TRL 8				TRL 3-6	
Mobile H_2-fuel cells					TRL 3-9	TRL 4-7	TRL 4	TRL 3-6	TRL 1-6
H_2-storage systems				TRL 7	TRL 4-9	TRL 4-9	TRL 2-5	TRL 4	TRL 3-7
Mobiler H_2-combustion engines					TRL 6	TRL 4-6	TRL 4	TRL 5-6	TRL >4

Short and medium-term research needs

- Development of technologies for safe and efficient combustion of H_2 and derivations such as ammonia: burner development, engine development, flame monitoring, emissions, exhaust gas aftertreatment systems, waste heat utilisation.
- Material compatibility testing in H_2 atmosphere as well as gases from H_2 combustion.
- Measurement methods, controlling and regulating strategies for changing fuel compositions.
- Increasing service life, stress test scenarios for accelerated/standardised testing, for example for fuel cell system in industrial plants.
- Optimisation of system efficiency and integration of H_2 applications.
- Development of FC and CHP systems.
- Framework conditions and location factors for H_2 deployment, infrastructure development and security of supply.
- Socio-economic evaluation of process conversion to the H_2 application.
- Sustainability throughout the supply chain, such as recycling strategies of all stack components.

- Development and optimisation of tank systems for all mobile applications with regard to optimised system integration and reduction of investment and operating costs as well as crash safety.

- Development of sensor technology for monitoring and controlling H_2-carrying systems.

Industry: Material use, especially in metal production

- Material use for reduction (use of NH3 and synthesis gas) and for CCU.

- Raw material influence on product properties and process conditions in H_2-based production.

- System integration (process simulation, control power, recycling of H_2).

- Development of a strategy (including location analysis), as well as technologies for handling and long-term storage of CO_2 as part of the CCUS solutions.

Industry: Energetic use for process heat and steam

- Material investigations/developments for facility components and fireproof materials.

- H_2 use instead of natural gas/coupling gases in HT processes.

- Effects on product quality, product capacity, pollutant emissions, heat transfer, efficiency, facility output.

- Optimisation of the plant performance (gas turbines, industrial furnaces) with regard to load (minimum load/load change rates) when using H_2 and mixtures of H_2 and natural gas.

- Development of H_2-based systems for highly efficient process steam generation (including CHP).

- Flexibilisation of processes by switching energy sources (e.g. use of hydrogen in combination with other fuels and/or electric heating) to leverage demand response potentials.

Stationary: Use in trade and industry

- Optimised, cost-effective operational management, monitoring of combustion processes when using pure H_2 and utilisation of the waste hear.

- Electrochemical use (FC): Scaling to large-volume industrialisation incl. development of a supplier landscape; condition monitoring, interoperable system technology, service life-preserving/ grid-serving FC operation.

- Development of highly efficient and cost-effective hydrogen-powered gas turbine-based combined heat and power plants with low output (< 5 MW) through direct integration into process heat generation.

- Use in off-grid applications or for mobile power generation/emergency power supply.

Stationary: Use in households

- Cost-effective/socio-ecological H_2 applications in connection with heating, ventilation and air-conditioning technology.

- State analysis of the network structure and user structure in order to develop cost- and time-optimised transformation paths.

- Field test of hydrogen-powered heat generators as well as motorised and fuel cell powered CHP/ CHP plants under real conditions.

Mobile: Use in cars

- Simulation and optimisation of motorised H_2 combustion processes.

- Industrialisation and efficiency optimisation of FC stack and H_2 tank systems for gaseous hydrogen and their components.

- Materials research → Substitution of problematic compounds of scarce resources, Diaphragm, fluoropolymer-based cell sealing materials.

- Operating strategy/hybrid design/system design/TCO costs.

Mobil: Use in commercial vehicles and work machines (trucks)

- Overall powertrain/vehicle optimisation of FC and combustion engine systems (operating/hybrid strategy, cooling system).
- Combustion engine concepts for (sub)zero emissions.
- Efficiency optimisation (combustion engine: tribology, utilisation of waste heat, direct injection, combustion processes including simulation; FC: components).
- Reduction of noise emissions from H_2 combustion engine.
- Hydrogen-based refrigeration for transport refrigeration.

Mobil: Use in rail transport

- Investigation of railway-specific requirements with regard to the cost-effective use of Hydrogen.
- Methods and technologies for retrofitting and equipping existing and new vehicles.
- Simulation methodology for vehicle propulsion and cooling including hybrid energy management.
- Investigation of innovative H_2-technologies to increase and secure range as well as to increase efficiency for example through utilisation of waste heat or air conditioning/cooling.

Mobile: Use in shipping

- System comparison H_2 (carriers/mediums).
- Demonstrators in shipping (bunkering, tank/converter systems, fuel treatment, system integration, hybridisation of dynamic applications); cargo ships.
- Combustion in piston engines/direct use in FCs, H_2 generation from hydrogen-based derivatives on board.
- Closing the CO_2 cycle through CCS on board ships.
- Hybrid use with other fuels.
- Investigation of innovative H_2 technologies to increase efficiency for example through utilisation of waste heat or air conditioning/cooling.

Mobile: Use in aviation

- Aircraft architecture for H_2 and SAF: adaptation of piping systems and seals for LH_2/SAF, integration of LH_2 tanks (structural and thermal).
- Aircraft gas turbines for H_2/SAF combustion: adaptation of the combustion chamber and the expansion system.
- Fuel cells (FC): Increasing the power/energy density of FC powertrains (from tank to electric motor), scaling the power of FC systems into the range relevant for passenger transportation (> 1.5 MWel), Thermal management of the FC system.
- Infrastructure: provision of the LH_2/SAF, development of the LH_2 ground infrastructure including refuelling technologies.
- Cross-cutting issues for all new and further developments: Ensuring the reliability, service life and verifiability of flight safety.

4. SAFETY, ACCEPTANCE AND SUSTAINABLE MARKET INTRODUCTION

Motivation

The hydrogen value chain includes topics that cannot be attributed to neither production nor infrastructure or use, but have connecting points to all technologies in the respective areas. It is therefore important to consider the technical issues in the context of the thematic areas and to merge the research and development needs.

Research and development needs

Safety, climate impact, regulations, codes and standards (RCS) as well as acceptance, sustainability and the aspects concerning market introduction are to be understood as the overriding interdisciplinary topics. To address the interdisciplinary topics, project concepts that take into account the entire value chain are advisable.

Addressing safety-related questions and advancing concepts in a needs-oriented manner

- Leakage monitoring: Innovative methods for the monitoring of different areas, concepts for sensor selection, sensor combination and sensor distribution, also with the use of AI.

- Sensor development for operating measuring points.

- Protection concepts: Guidelines for specific protective measures and definition of protective areas (such as zones, safety distances, hazardous areas), especially for LH_2; QRA tools.

- Behaviour of H_2 in accident scenarios: Improve the understanding of corresponding scenarios to support the development of RCS; development of models for risk reduction potentials of different protective measures.

- Material suitability and compatibilities: Guidelines for the safe selection of suitable materials based on requirements along the entire life cycle; development of test methods for H_2 readiness and early damage detection; development of new material concepts; extension of existing test concepts and development of new test infrastructure to characterise the deformation and damage behaviour at high temperatures.

- Service life models and concepts for the design of components for H_2 applications, in particular the extension of known and established service life models to include the "damage parameter" hydrogen (e.g. pressure vessel directive AD2000 or FKM guidelines).

- Testing the suitability and long-term safety of additively manufactured components: Use and optimisation of additive manufacturing technologies for components as a production approach (such as fittings, fuel cells).

Better understanding and considering of climate impact of hydrogen emissions; quantifying and minimising hydrogen emissions

- Better understanding of the climate impact of hydrogen and basic atmospheric chemical processes and the hydrogen cycle.

- Development of measurement technique to quantify and localise hydrogen emissions (leakages and permeability) along the entire value chain: the measurement methods must be sufficiently sensitive in order to measure emission rates of less than 1% along the entire value chain.

- Quantification of non-technically cause hydrogen emission: „Factor human“.

- Development/Optimisation of methods to avoid hydrogen emissions, including material development and concepts for hydrogen recovery.

Necessary harmonisation for global quality standards

- Certification and release of products: Development of technical and regulatory frameworks for the internationally approved certification, acceptance and release of products; consideration of methods for risk assessment; combination of testing and simulation.

Fostering acceptance among the various stakeholders

- Knowledge transfer: Concepts for the education and training of experts; information for the general public to ensure a general understanding of safety; development of educational strategies; design of acceptance criteria.

- Development of communication strategies for negative, media-relevant individual cases in connection with hydrogen.

- Acceptance research with target groups, taking into account ecological and geopolitical issues as well as issues concerning development policy (such as on the issue of imports: acceptance and participation and development possibilities for the local population in partner countries) as well as changes in acceptance due to market ramp-up.

- Creation of a risk model for the introduction and analysis of acceptance criteria for risks.

- Transfer research from the energy and transport transition as well as innovation research.

Framework conditions for future business models

- Development of scenario models to discuss H_2 requirements with regular updates.

- Development of an EU-wide accepted market design for the ramp-up of a sustainable H_2 production and utilisation.

- Analysis of incentive systems taking aspects of safety, acceptance and an ecological and economic sustainability into account.

- Identification of economically attractive business models in short, medium and long-term.

- Identification of potential market areas with special dynamics for the market ramp-up.

- Facilitation of scaling and increasing the TRL through appropriate R&D policy measure.

- Transfer research from the energy and transport transition, innovation research and analysis of transferability to the H_2 value chain.

- Investigation of the influence of previous energy policy measures and assessment of the possibility of transfer (such as the German Renewable Energy Act (EEG)).

- Analysis of the compatibility of different regulatory conditions with international law.

- Analysis of the added value of the production of H_2 with regard to grid and system efficiency, taking into account applications in different sectors.

- Analysis of the expected cost development for the production of H_2 and its transport options.

- Analysis of the willingness to pay for green hydrogen as well as related products.

- Comparative policy analyses in the EU states and discussion of standardisation at EU level on particular topics (such as the certification of green hydrogen).

- Classification of different import strategies against the backdrop of geopolitical developments and potentially normative objectives: Monitoring of the international energy industry in the shift from extraction of raw materials to conversion, analysis of the role of technologies and technology leadership.

- Analysis of how the hydrogen value chain can be sustainably established in emerging and developing countries.

- Analysis of different scenarios for imports, national storage capacities and national production in the light of a cost-optimised transformation, taking into account increased resilience of the energy supply.

- Analysis of the role of the EU in an evolving H_2 economy with greater choice of potential partners (such as potential influence on standards and values).

Sustainability as a key driver in the H_2 economy

- Conduct life cycle assessments (LCA; sLCA; LCC) as a sustainability assessment method to map the entire life cycle.

- Investigation of all H_2 production pathways with regard to their greenhouse gas emissions and other environmental impacts (LCA).

- Conducting holistic sustainability analyses of imports from emerging and developing countries, in particular taking into account socio-economic and social aspects that go beyond environmental assessment.

- Further development of social criteria and creation of uniform data sets in the field of sLCA for the transparent assessment of technologies.

- Investigation of economic sustainability for stakeholders and systems (LCC), such as for the assessment of options for dealing with externalised costs.

Project formats modelled on the energy transition's living labs

- Creating project formats to examine the entire value chain in terms of environmental criteria and resources.

- Integration of the end of the project and thus aspects of the circular economy into the concepts of projects.

- Further strengthening of transdisciplinary research approaches, also in connection with non-technical areas such as the involvement of multipliers and educators.

- Integration of required training and further education of experts.

- Involving and educating society and the general public through Citizen science projects.

- Ensuring sustainable benefits by creating an open and accessible database for interested parties.

LIST OF ABBREVIATIONS

AEMEL	Alkaline Exchange Membrane Electrolysis
AI	Artificial Intelligence
AWE	Alkaline Water Electrolysis (AFC: Alkaline Fuel Cell)
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CO_2	Carbon Dioxide
DME	Dimethyl Ether
EEG	Erneuerbare-Energien-Gesetz (German Renewable Energy Act)
EL	Electrolysis
FC	Fuel Cell
GHG	Greenhouse Gas
GW	Gigawatt
H_2	Hydrogen
HT	High Temperature
HTEL	High Temperature Electrolysis
CCP	Combined Cooling and Power
CHP	Combined Heat and Power
CHPP	Combined Heat and Power Plant
LCA	Life Cycle Assessment
(s)LCA	Social Life Cycle Assessment
LCC	Life Cycle Costing
LH_2	Liquid Hydrogen
LOHC	Liquid Organic Hydrogen Carriers
MEA	Membrane Electrode Assembly
NHS	National Hydrogen Strategy
NH3	Ammonia
PEMEL	Proton Exchange or Polymer Electrolyte Membrane Electrolyser
QRA	Quick Reaction Alert or Quantitative Risk Assessment
R&D	Research and Development
RCS	Regulations, Codes and Standards
TCO	Total Cost of Ownership
TRL	Technology Readiness Level

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