Strategic Research and Innovation Agenda

Agenda Process for the European Research and Innovation Initiative on Green Hydrogen

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Content

Preface

With the European Green Deal, the EU is driving forward the energy transition to become climate neutral by 2050. The EU's intermediate CO_2 reduction target for 2030 is at least 55% compared to 1990. The imminent and far-reaching transformation of the energy system triggered by these policy goals will affect all sectors of the economy and society. Against this backdrop, green hydrogen[1] is gaining traction as a sustainable and universal energy carrier. Green hydrogen can help the energy transition succeed, maintain the competitiveness of key European industries and reduce dependence on fossil fuel imports.

The political impetus for hydrogen has come as the course is being set for a new energy policy. In many EU countries, national hydrogen strategies and action plans are currently being presented or under development. European hydrogen projects are being implemented and cross-border partnerships established. In addition to research collaborations, first industrial projects have also been launched by important players in the hydrogen industry. Swift, coordinated action is needed to spearhead the development and to allow for political decision-making that facilitates the industry's progress and is coherent across countries and sectors.

Ongoing European hydrogen initiatives

Several initiatives and policies exist at EU level, notably the EU's own **Hydrogen Strategy** (published in a Communication of July 2020, COM(2020) 301 final). It sets out a vision of how the EU can turn clean hydrogen into a viable solution to decarbonise different sectors over time, and identifies the challenges to overcome, such as the large-scale installation of renewable hydrogen electrolysers in the EU.

An accompanying European Commission **Staff Working Document**[2] on research and innovation investments provides insights into the European context in which the present document was created and in which the related policy actions will be developed.

The European Strategic Energy Technology **(SET) Plan**, launched already in 2007, aims at accelerating the development of low-carbon technologies through cooperation amongst EU countries, companies, research institutions and the EU itself. The revamping of the SET Plan, which the Commission intends to accomplish in 2022, will offer hydrogen a greater part to play as one of the means towards achieving the clean energy transition.

In recent years and months, Important Projects of Common European Interest **(IPCEIs)** in the hydrogen sector have been initiated, and the European Clean Hydrogen Alliance **(ECH2A)** has been set up.

Initiatives like the **Clean Hydrogen Joint Undertaking** with its own strategic research and innovation agenda (currently denominated as 'multi-annual work programme' - MAWP), the European Energy Research Alliance **(EERA)** as well as associations and networks including **Hydrogen Europe** and **Hydrogen Europe Research** also make a decisive contribution to the energy transformation. As the EU, hydrogen stakeholders and member states all seek to resolve open issues in research and innovation, coordination is needed to optimally utilise synergy effects.

Origin and key elements of the agenda process on green hydrogen

While such European-level action is vital, national policies also play a key role in implementing the Paris Climate Agreement and in shaping the energy transition. The groundwork for a European Hydrogen Union must be laid by member states. **Bottom-up processes are absolutely necessary for involving as many countries as possible** in order to respect the different national strengths and weaknesses and to avoid the fragmentation of measures. Recognising this responsibility, a European research and innovation (R&I) initiativewas launched in 2020 as a voluntary coordinated action in the European Research Area (ERA). During the German EU Council Presidency in 2020, research ministers agreed on a member state-

1 *The term 'green hydrogen' is used throughout the document as the ERA pilot was labelled originally for this. It should be noted that in EU publications such as the EU Hydrogen Strategy and the Renewable Energy Directive (REDII) it is recently referred to as clean hydrogen or renewable hydrogen rather than green hydrogen.*

2 *https://ec.europa.eu/info/sites/default/files/research_and_innovation/research_by_area/documents/ec_rtd_swd-era-clean-hydrogen.pdf*

led R&I initiative to build a European hydrogen economy. The action was started following the Competitiveness Council conclusions of December 2020 (13567/20) in which the Council invited the Commission and interested member states to conduct an agenda process for a green hydrogen research and innovation ERA pilot action in 2021, while ensuring consistency with other related initiatives and without prejudice to the relevance of a broader hydrogen R&I policy approach beyond this ERA pilot action. As a pilot measure, it is also intended to strengthen the new European Research Area by generating more commitment, dedication and scope for action on the part of the member states.

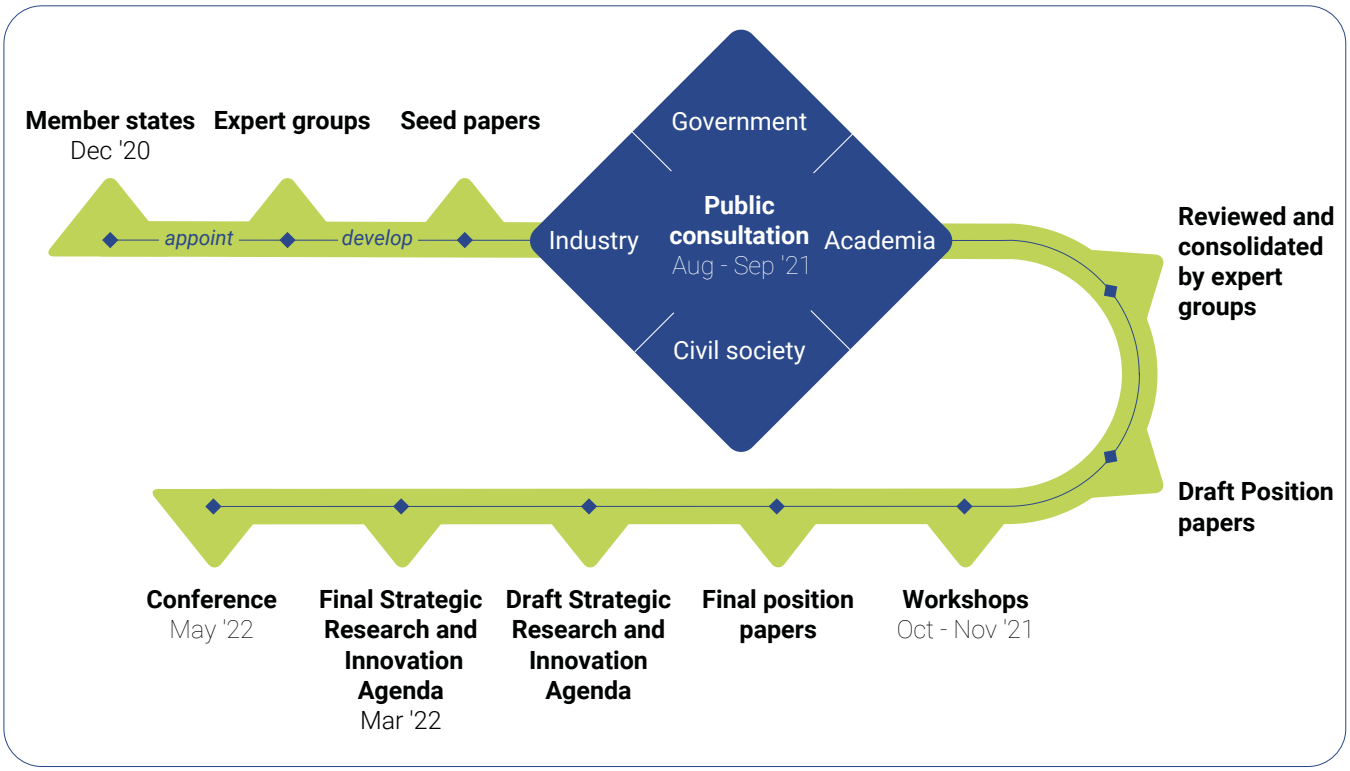
As a result, **25 interested member states and five third countries** have come together under the auspices of the German Federal Ministry of Education and Research (BMBF) to form a task force to jointly launch a pilot agenda process on green hydrogen, in close collaboration with the European Commission. The agenda process places a lot of emphasis on mutual coordination on an ongoing basis. This is particularly relevant in implementation, because the existing initiatives already offer very good programmes for an affordable future hydrogen economy.

In 2021, in a unique broad-based, science-led dialogue process, s**takeholders from industry, research, civil society and politics** were given the chance to express their perspectives on research and innovation issues and to name the priority research needs along the entire hydrogen value chain. The process put a lot of emphasis on **transparency, openness and low barriers** to participation – everyone could provide information and join the discussion. Another requirement for the process was its rapid implementation within one year.

As part of the agenda process (see Figure 1), three pan-European, transdisciplinary workshops on key challenges of a European hydrogen economy took place in autumn 2021, each organised under the leadership of one or more member states. The three workshops focused thematically on 'Production' (organisation: Italy and Bulgaria), 'Transport/Infrastructure' (organisation: Germany) and 'Market Stimulation' (organisation: Austria). In addition to technical issues, cross-cutting issues including regulatory, economic, ecological and social aspects were addressed in all the workshops.

Three **independent expert groups with representatives from various European countries** provided scientific advice for the preparation of the workshops and the evaluation of results. The experts' main contribution was to write 'seed papers' on the three main topics of the agenda process, on which the stakeholders and the public could comment in a Europe-wide online

Figure 1: Timeline and milestones of the agenda process on green hydrogen.



consultation. In the framework of thematic workshops in October, this feedback was taken up, discussed with high-level stakeholders from all over Europe and the initial seed papers were further developed into fully-fledged position papers. The results of the agenda process are summarised in this **strategic research and innovation agenda (SRIA) on green hydrogen** – the major outcome of the R&I initiative within the European Research Area.

Implications of the agenda process and next steps

The SRIA was finalised together with the task force and in close coordination with the European Commission in 2022. It will be officially presented in March 2022 and its implementation further discussed during a conference in May 2022. Due to the pandemic situation, the process could not be completed in December 2021 as originally planned.

The agenda process has been a **nucleus of member states' wider commitment to a European Hydrogen Union**. In particular for example, it integrates EU-13 states and stakeholders from society in order to enable a comprehensive exchange of views and information and to prevent a 'closed shop'. The agenda process is a true bottom-up exercise. Member states and third countries have identified experts, and experts themselves – via steering committees – have selected further experts to contribute. Using this approach, the responsibility for the process has been decisively strengthened.

More ownership will also mean more financial and political commitment from member states and third countries. This will ultimately have a positive effect on the support for research and innovation that already exists and thus accelerate the commercialisation of hydrogen technologies to better position Europe in global competition. We need **more awareness, strong collaboration and financial support** for this endeavour, which will have a decisive impact on European society.

The SRIA is only the starting point for further cooperation and coordinated action in the field of green hydrogen over the coming years. Now it is up to governments, the European Commission and stakeholders on all levels to follow up on the issues laid out in this SRIA. Where possible, tasks should be taken over from existing initiatives. Where gaps have been identified, new measures should be taken.

The energy transformation and the 1.5° C target can only be achieved with a strong joint European contribution, bringing together commitment and action at EU, national and regional level. The implications of climate change have a higher price tag than investments in a sustainable energy supply, which will therefore strengthen the European economy and its citizens in the long run.

Introduction

The years 2020 and 2021 have provided ample evidence that the impacts of climate change are already being felt in Europe: heavy floods in Germany, Belgium and the Netherlands; forest fires on an unprecedented scale in Greece, Italy and Turkey. In recent years, there have also been severe droughts and heat waves on the European continent, from which groundwater levels in many places have still not recovered. But the past year has also shown that ground-breaking research through a collective effort can provide solutions to global problems, most notably the rapid development of novel vaccines during the Covid-19 pandemic.

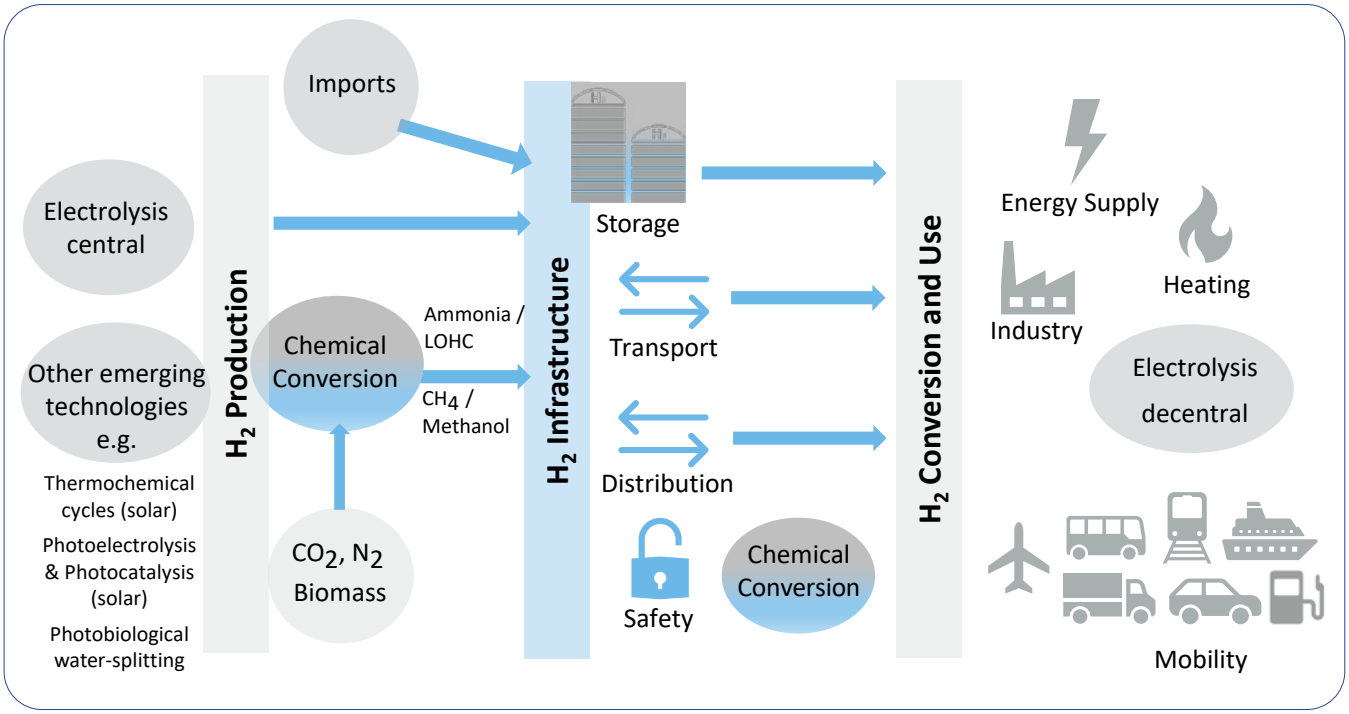
In the field of energy, green hydrogen holds great potential for a green recovery from the pandemic while also being a key element in achieving our climate goals. It is beyond doubt that rapid action is crucial to reach the 1.5° C target, and that industrialised countries have a special responsibility in this regard. This is why a number of European countries have joined forces with different stakeholder groups and have been in close exchange with the European Commission to develop this strategic research and innovation agenda on green hydrogen – a clear commitment for a green energy transition in Europe.

Europe's green hydrogen potential

The SRIA on green hydrogen deals with the urgent question of how societies can combat the impacts of climate change without compromising economic wellbeing. Hydrogen produced with renewable energies as well as renewable electricity offer **genuine alternatives to our current largely fossil fuel-based energy system**. They must therefore play an important role in future energy research to become the economic engine of a new, sustainable society.

Green hydrogen, in particular, can make a significant contribution for storing and distributing renewable energies and can be used especially in sectors where total electrification is not possible, for example in energy-intensive industries. In future, green hydrogen can also be deployed to a greater extent in other high CO_2-emitting sectors such as transport (air, maritime and heavy-duty road transport) or in the transformation sector (back-up for electricity generation and heat grids primarily based on renewable energies) to accelerate decarbonisation (see Figure 2). However, only if we produce green hydrogen cost-effectively and enable

Figure 2: Value chain of green hydrogen.



transparent certification globally will we achieve a complete decarbonisation of our economy. More research is needed in all segments of the value chain and on cross-cutting issues, as well as a bundling of European competences and financial resources to develop competitive green hydrogen solutions.

We must remain open to new technological approaches and at the same time scale up already known solutions to avoid as much carbon dioxide emissions as possible. 'Sustainable growth', as the EU has proclaimed within its European Green Deal, means nothing less than a ground-breaking transformation of our economy based on sustainable energy systems. Europe has to jointly seize the opportunity to **secure competitive advantages through technological know-how in green hydrogen solutions**. By intensifying its efforts, Europe can take a future leading role as a technology provider and market enabler. The economic and ecological advantages of green hydrogen will benefit society in the long term.

Voluntary initiative to identify the most important research needs

In order to unleash the full potential of a green hydrogen economy and to overcome challenges together, a coordinated approach involving industry, research, politics and civil society is needed at the European level. To complement existing hydrogen initiatives and platforms, many member states and other European countries therefore started the agenda process as a voluntary initiative in 2020 to jointly identify the most important research needs and items for action on green hydrogen, which are presented in this strategic research and innovation agenda. It transcends the format of a classic research and innovation agenda, proposing, beyond technological development, innovation measures, policy support and implementation actions to prepare for the realisation of a green and clean hydrogen economy.

The content was developed by dedicated European hydrogen experts from different stakeholder groups within this pilot initiative of the new European Research Area and is intended to kick-start targeted policy actions from 2022 onwards. The SRIA takes into account existing European polices, structures, priorities and initiatives, notably the multi-annual work programme of the Clean Hydrogen Joint Undertaking in order to identify synergies as well as distinguishing features.

Situation in Europe

Hydrogen has become an important driver for energy-related research and business collaborations in many European countries. This is not only reflected in various ongoing flagship projects or initiatives in green hydrogen involving a broad community of European researchers and practitioners. Many European countries have adopted national hydrogen strategies, are in the process of developing them or have included hydrogen in wider strategies and national plans. However, in some strategies and plans the value chain is not always completely covered. Moreover, different national views exist on how to shape the sustainable transition of the energy sector and primarily affected industries such as the basic chemical industry and heavy industry. This includes the issue of how far and how long the national hydrogen strategy will rely upon a transition period mainly using low carbon but not green hydrogen.

Respondents to the public consultation, conducted in August 2021 as part of the agenda process, were asked to describe the specificities of their country to the best of their knowledge. The main findings are depicted in Figure 3. It turned out that differences often arise from national particularities such as the available energy resources (fossil and renewable) and the respective national energy demand, which is related to the level of industrialisation and population size, as well as technological and financial capacities. Existing energy production and transport infrastructures are the result of historical developments and long-term investment decisions that influence the pace of transformation in the present and future. In addition, the individual geographical conditions such as topographic features and a peripheral or central location can also play a role when it comes to the evaluation of transport options for hydrogen. Mediterranean countries and those adjacent to the Atlantic have large renewable energy potentials (solar and wind energy) and can pursue export strategies for green hydrogen. In some central regions, energy demand often exceeds local supply or will not be satisfied without the development of other renewable energies. An overall approach to renewable energy demand and supply in the EU requires the search for cross-border/trans-regional renewable energy exchange capacities, for which green hydrogen can be a solution.

European countries with well-developed port facilities are crucial for the potential import of green hydrogen via long-distance ship transport from e.g. Australia, Japan or the MENA region. However, imports of green hydrogen into the EU should respect the two principles of being certified as renewable along the whole value chain (meaning that all steps from production to distribution, including maritime transport, should be green) and not distorting the local economy by not satisfying the local energy needs of exporting regions.

In the development and market preparation of interconnected hydrogen infrastructures and a common European hydrogen market, it is essential to **take into account the different starting conditions of the countries**, as well as the current lack of some common

standards (for instance on compression levels). This requires an integrated assessment approach of the national conditions and objectives in close coordination with member states and partner countries.

The document is structured with a preface, three main sections and an annex. The following section includes the research priorities identified by the respective expert group for the thematic blocks 'Production', 'Transport and Infrastructure', 'Market Stimulation' as well as cross-cutting issues. The last section gives an outlook on the future implementation of the SRIA and highlights first action points. A list of countries and experts involved in the agenda process as well as download links to the position papers, which have been taken as a basis for the SRIA, and to the technical report on the findings of the public consultation are provided in the annex.

Figure 3: Morphological box to demonstrate country particularities in Europe.

Variables	**Possible characteristics**					
Size of country	small		medium		large	
Climate	polar	subpolar	temperate continental	temperate marine	mediterranean	highland
Location on the continent	central		peripheral			
Sea connection	landlocked		at least one access to the sea		island	
Coverage of gas network	no gas grid	small		medium		extensive
Age of gas network	old, limited maintenance		well-developed and maintained			
Renewable energies	biomass	geothermal	hydro	photovoltaics	solar thermal	wind
H_2 demand	export		national production and use		import	

Thematic Areas

Essential research needs for green hydrogen are described in this section for the three thematic areas 'Production', 'Transport and Infrastructure', and 'Market Stimulation' which are oriented to the green hydrogen value chain and have been identified and elaborated by the corresponding expert group of the agenda process. Cross-cutting aspects were collected by all expert groups and form an additional subsection. The order of research priorities in each subsection does not imply any weighting.

1. Production

Challenge

Since 2020, we have been witnessing the rapid transition of hydrogen from an innovative niche technology into an important seed corn for the European Union's energy and climate policy and a key enabler in the EU's efforts for transition to a climate-neutral society by 2050. To fulfil the ambitious goals, hydrogen has to be 'green', i.e. to be produced from renewable energy, thus unlocking the full potential of renewables, ensuring sector integration and decarbonisation of our economy. Hydrogen technologies are under intensive development to enter the industry and transport sectors (especially heavy-duty road transport), to guarantee grid balancing and seasonal storage and thus to ensure high efficiency of the energy system. This process has to be accelerated by effective instruments which will make hydrogen technologies competitive with current technologies and well accepted by society. Since the agenda process involves research, industry and civil society (including ministries and public administration) in a common framework, it provides unique conditions to conduct analyses and organise activities based on the input of every member state.

Research priority: Supply and demand for green hydrogen

The fast and efficient deployment of green hydrogen in different areas of application requires a comprehensive analysis and mapping of existing and potential hydrogen production capacities in Europe. The EU-wide approach allows not only for the identification of hydrogen production capacities and locations in EU countries, but also for the development of support mechanisms for transporting hydrogen either produced in the EU or imported from other regions. The following aspects are of key relevance:

- Analyse and map the green hydrogen production on a national, EU and global scale required to meet the timeline of the European Green Deal (2024 and 2030)
- Analyse the future pan-European hydrogen supply and demand based on national supply and demand for different timelines (2030, 2040 and 2050)
- Elaborate a European green hydrogen production roadmap with respect to EU production and import/export among EU countries for different timelines (2030, 2040, 2050)
- Analyse the demand for hydrogen imports from outside EU comprehensively (costs, infrastructure, transport)

Research priority: Green hydrogen production – short-term research and technological aspects (2025)

Europe's transition towards a decarbonised energy system is underway with an ambitious roadmap for 40 GW of electrolyser capacity installed in Europe by 2030 (10 GW by 2025) and 40 GW installed outside Europe (using EU technologies). Project initiatives targeting 100 MW electrolysers have already started. In order to achieve these goals, we need an ambitious short-term programme focusing on the speedy development of electrolysers, in terms of technology and capacity.

- Foster technological development and deployment of electrolysers coupled with renewable energy for green hydrogen production, grid balancing and district heating and cooling grids
- Support research to enable scaling up of electrolysers' capacity: (i) at stack level by a factor of five and (ii) at systems level for large hydrogen hubs (100-500 MW)
- Develop offshore renewable hydrogen production, H_2 derivatives and related business models
- Develop an open innovation test bed and pilot line approach for materials and systems to accelerate the scale up of emerging technologies including new materials and components
- Apply an integrated approach in building new national infrastructures to support the industrial sector with scaling up hydrogen production and storage

Research priority: Green hydrogen production – medium-term research and technological aspects (2030)

In a medium-term horizon, the research activities should cover the whole range of feedstock for hydrogen technologies (e.g. waste biomass, direct use of photovoltaics and biomethane) and in particular should accelerate more mature technologies at research levels beyond basic research.

- Accelerate the development and scaling up of hydrogen production by electrolysis, co-electrolysis, sea water electrolysis, operation in reversible mode and integrated with recycling
- Investigate the reduction and progressive elimination of critical raw materials such as platinum group metals in electrolysers
- Scale up the most promising technologies to demonstrate cost-effective and reliable hydrogen production from waste biomass by thermochemical methods and exploit the potential of carbon negative hydrogen production by pyrolysis and gasification with appropriate environmental assessment
- Integrate different green hydrogen production processes (e.g. biomass and electrolysis) to increase efficiency and cost effectiveness
- Develop photoelectrolysis and photoelectrocatalytic devices (overall efficiency > 10%) and scale up the most promising technologies to 1-100 kW capacity
- Develop direct production of hydrogen vectors using renewable energy
- Develop carbon-negative hydrogen production technologies based on the utilisation of biomethane

Research priority: Green hydrogen production – long-term research and technological aspects (2050)

Next generation solutions for green hydrogen production are pivotal for the sustainable transition towards a hydrogen economy. However, longer time horizons imply increasing uncertainty in terms of the expected outcomes. Therefore, this research priority maps general expectations and important directions in the field of hydrogen production and will be amended after obtaining results from short-/mid-term research priorities.

- Support breakthrough research in all sectors of green hydrogen and hydrogen vectors production, in particular emerging production technologies, novel concepts for electrolysers, solar fuel production processes, etc.

- Develop a new generation of electrolysers in respect of costs, efficiency, active materials, durability, dynamic behaviour for coupling with renewables, hydrogen pressure (e.g. 70 bar for hydrogen injection into the gas network)
- Follow innovative approaches for hydrogen production from renewable waste/biomass, etc.
- Provide space for research and innovation for early stage research including topics beyond the predetermined applications in order to overcome scientific and technological challenges in hydrogen production through technological diversification

Research priority: Economic aspects of green hydrogen production

Economic analyses should cover geo-economic aspects for all EU countries ranging from coastal states with offshore opportunities to landlocked countries.

- Determine the most effective forms of financial support for accelerated scaling up and deployment of centralised and decentralised green hydrogen production technologies
- Set up a transparent database on the output efficiency of projects and ways to solve major issues (compare with solar and wind projects) to reduce the risk for investors and accelerate the decrease in financing costs
- Improve exploitation of project results
- Analyse geo-economic and geopolitical impacts
- Support expansion in order to enable self-sustaining business cases
- Support of OPEX-based business cases by removal of grid tariffs for green electricity for electrolysers (compare with Austria)
- Develop a common value chain related to hydrogen production to mutualise certain components
- Integrate efforts by EU member states and partner countries in the area of renewable energy generation
- Support smart system modelling to facilitate and economically optimise the planning and development of 'hydrogen valleys' to later form 'hydrogen corridors'

Research priority: Collaboration and partnership

European needs for large-scale green hydrogen production cannot be met without strong partnerships linking countries with huge renewable energy potential and countries that are more advanced in hydrogen production technologies. Collaboration is particularly needed for developing a common European legislation framework and fostering standardisation and certification procedures for green hydrogen production. International collaboration will also involve developing activities which have already started, e.g. through Mission Innovation.

- Coordinate bilateral and multilateral European partnerships for balancing hydrogen production with regard to exports and imports, first on an EU, and then on an international level
- Focus on hydrogen produced in Europe for import and avoid specialisation of a country or region to the detriment of its own needs and resources
- Support transnational partnerships on research collaboration along the value chain and foster collaboration between research and industry conducting both basic and applied research
- Foster the European Hydrogen Research Area through the integration of teams from different countries especially in new and emerging areas whose initial research efforts are usually fragmented
- Develop European criteria on sustainability certification over the whole value chain including transport of (imported) hydrogen
- Develop a common standardisation roadmap for hydrogen production with prioritisation of the urgently needed standards for a common hydrogen market (carbon intensity, quality, including overall footprint, and origin)

Research priority: Common simple and user-friendly digital platform for communication between industry, research and society

Effective pan-European cooperation on green hydrogen production requires the set up of a publicly accessible, user-friendly digital communication platform connecting research, industry and society. This includes a common database for sharing quantitative data as well as qualitative information from individual countries and would serve the joint interests within the European hydrogen research community. It should ensure:

- Effective collaboration between science and industry with regard to industrial needs and scientific support
- Effective research collaboration on different topics and technology readiness levels (TRL)
- Joint efforts of science, industry and active society in pan-European dimensions to implement joint activities highlighted in the other priorities

- Access to safety information, standards, key-performance indicators (KPI), profiles of experts and further relevant hydrogen stakeholders, administrative requirements, as well as data for investors and developers that need to better assess the risks associated with hydrogen technologies

The contribution and input of national programmes and project results to existing databases should be considered. This includes a database on European hydrogen projects developed by the Clean Hydrogen Joint Undertaking with a view to extend towards a European Union Clean Hydrogen Observatory (EUCHO).

Research priority: R&D (infra-)structures, organisation and instruments

- Identify ideal research conditions for improving electrolysis and increasing the rate of electrolyser capacity installations to 1-4 GW per year until 2030
- Investigate the requirements for successful research and market deployment of mid-term and long-term innovations such as hydrogen production from direct sunlight
- Foster the development of hydrogen production hubs and/or national 'hydrogen valleys' as starting points for a green hydrogen economy
- Integrate local 'hydrogen valleys' into pan-European green hydrogen corridors

Conclusion

Green hydrogen production can be environmentally and economically beneficial, ensuring effective introduction of the renewable energy in our industry, energy, mobility and heating, which makes our economy clean, low carbon and climate friendly. To achieve these goals, we need to foster international cooperation on the levels of basic and applied research, e.g. through participation in Mission Innovation actions. We also need to further develop synergies between actions at European level and at national level to set up an effective European hydrogen economy. If we are successful in this, we can expect economic growth and many new jobs for the citizens of Europe.

2. Transport and Infrastructure

Challenge

This section describes the research needs identified in terms of hydrogen transport on a European level as well as regarding imports to Europe. For the transport of hydrogen and its derivatives, different infrastructure types are envisaged such as repurposing existing natural gas pipelines, building (up) new hydrogen pipelines and large-scale subsurface storage as well as establishing hydrogen transport by road, rail and ship.

Research priority: Implications of different hydrogen sources on transport options

Requirements for hydrogen infrastructures depend on several factors. One of these factors is distance. Thus, a decisive question is whether the hydrogen is produced in Europe – close to the customer – or imported. Moreover, for hydrogen import solutions, the definition, certification and labelling of renewable hydrogen should include the full delivery chain, to ensure accurate tracking of the emissions associated with large-scale hydrogen delivery chains. This results in the following research needs:

- Evaluate hydrogen production by national and European sources and how much hydrogen has to be imported to Europe in the time horizons 2030, 2040 and 2050 and via which entry points
- Analyse how much of the total European hydrogen demand can be covered by green hydrogen and to what extent by low carbon hydrogen production (e.g. blue hydrogen via steam reforming with Carbon Capture, Utilisation and Storage (CCUS), pyrolysis of natural gas)
- Investigate which offshore infrastructure has to be built up depending on the distance to the coast (wind turbines connected to an electrical grid or offshore production connected to a hydrogen network)
- Analyse the techno-economic aspects of different hydrogen import routes (including ecological aspects, e.g. carbon footprint) which should consider several regions in the world and be based on different transport options and transport quantities

Research priority: European hydrogen backbone

There are two driving forces which can contribute to building up a hydrogen infrastructure. One is following a bottom-up approach by creating local 'hydrogen valleys'. The other is based on a top-down approach by establishing a pan-European backbone.

- Investigate whether the integration of green hydrogen should be based on a European hydrogen backbone infrastructure or whether decoupled national hydrogen infrastructures are sufficient and more adequate for the initial period until 2030
- Evaluate if and how 'hydrogen valleys' and a pan-European backbone can be connected and complement each other – look at how to further develop 'hydrogen valleys' to increase the visibility of the benefits of hydrogen and accelerate its use in various economic sectors
- Support R&I on underground storage of hydrogen, e.g. in aquifers, salt caverns, depleted natural gas reservoirs and porous rock stores and examine how other storage possibilities (LH_2, NH_3, LOHC, etc.) can contribute to the total storage capacity requirements

Research priority: Transition from natural gas to hydrogen pipelines

One option for the ramp up of the hydrogen backbone is the transitioning of the existing natural gas pipelines and natural gas storage systems to hydrogen transport infrastructures. For this purpose, research is urgently needed in the following areas. These concern the technological solutions of retrofitting and the transition phase which is characterised by the transport of both natural gas and hydrogen.

- Assess the level of hydrogen readiness (i.e. readiness for both 100% hydrogen transport and hydrogen blending) and the age structure of assets for established technologies
- Assess the capability and scale of regional or national grid infrastructure that can be fragmented to dedicated hydrogen microgrid valleys
- Improve gas separation and purification technologies to increase the flexibility of the transported gas mixtures in natural gas networks
- Research on and improve appliances, processes and metering devices
- Outline the adaptation measures for current long-term contracts regarding the transmission of natural gas
- Investigate on the addition of a safety smell to hydrogen different to methane smell
- Address the challenge of planning transport infrastructures to cope with growing hydrogen demand without compromising secure natural gas supplies

Research priority: Hydrogen transport in tanks

In addition to pipelines and depending on regional characteristics, such as geography, flexible options for transporting hydrogen and its derivatives on land and water are vital. Among other reasons, hydrogen transport in tanks is crucial for overseas import and thus needs to be addressed on a European level.

- Characterise the role of transport by rail, ships and trucks versus transport via hydrogen pipelines in a diverse European context until 2030 and in the long term
- Find business cases for the short-term implementation of transport by rail, ships and trucks
- Address technology specialisation and make-or-buy decisions in the shipping sector (e.g. buying ships from Japan for transport of liquid hydrogen)
- Identify the main challenges for transport options based on liquid hydrogen and hydrogen derivatives such as ammonia within research, development and innovation
- Investigateon the technological, economic and ecological aspects of alternative energy carriers besides ammonia

Research priority: Integrated energy infrastructures

A future hydrogen supply system will be embedded in the entire energy supply system with interconnections to the other sectors, in particular to the electricity grid. For integration of hydrogen into the existing energy infrastructures, supply, demand and different regional aggregations need to be considered alongside the following research topics:

- Perform integrated infrastructure modelling to assess if electrolysers and storage options should be located close to the centres of renewable energy supply or rather in the vicinity of demand or large-scale storage infrastructure
- Assess the interaction of electricity grid connected vs. non-grid connected electrolysers on the economics of green hydrogen production
- Assess the interaction of electricity grid imbalance with curtailment, constraint and electrolyser implementation
- Create distribution maps for supply and demand in various regional scales

- Develop infrastructures within regional clusters in the short term and investigate how these clusters can be interconnected on a national and European level in the long run

Research priority: Coordinated planning

Stakeholders in a future European hydrogen economy face many uncertainties and wish for coordination and efficiency. The centralised coordination of initiatives, transparent decision processes and analytical tools and methods are needed in order to set up a Europe-wide hydrogen infrastructure and integrate hydrogen into the energy system.

- Find the best way to coordinate the integration of hydrogen into the energy system efficiently, e.g. through coordinated infrastructure planning on a European level or an integrated decision process for infrastructural development
- Design a decision process for hydrogen network planning that accounts for both the uncertainty in demand, production and import routes, and the mid- and long-term role for decarbonisation
- Create integrated analytical tools and methods to provide decision-making support for building up a new hydrogen infrastructure

Research priority: Safety in hydrogen transport

Safety is one of the major topics when it comes to social acceptance and a critical issue in large-scale hydrogen transport across urban and rural regions. This results in the following research needs for hydrogen and its derivatives:

- Identify and solve the main challenges for safe hydrogen infrastructures within research, development and innovation, in particular regarding material development and sensor technologies
- Develop models to spot critical areas in large scale hydrogen-related storage and transport infrastructures

Conclusion

As the scale of green hydrogen increases, more infrastructure will be required to manage and transport it. At the moment, it is unclear in what form (liquid, high pressured, or as a part of an aggregate) and by what mode and route hydrogen is to be transported to the end user or be stored, and this uncertainty hampers related investment decisions. Therefore, research efforts shall be directed to creating modelling tools for simulating various situations as well as to setting harmonised standards for safe hydrogen transport to Europe, considering the activities and experience of past projects, e.g. of the Clean Hydrogen Joint Undertaking. The standardisation of related activities will be done in close cooperation with the established European bodies on standardisation and with international fora like the International Partnership on Hydrogen (IPHE). In view of the large quantities of green hydrogen to be imported to Europe and transported across the continent, it is crucial to determine the right size and place of infrastructure facilities and to balance investments in harbours and pipelines. Given the technological challenges and the high industrial demand for green hydrogen, the focus should be on Europe for piloting individual and interconnected transport solutions.

3. Market Stimulation

Challenge

We understand market stimulation as any support measures which help to move from a situation of little or no supply and demand to a fast-growing green hydrogen market, finally replacing fossil-based energy carriers and feedstock. Based on the input of our experts, the public consultation and the workshop, we have identified types of measures, innovation needs and concrete research questions derived from them. All the types of market-stimulation measures identified are equally important and the order in which they are listed does not reflect a particular hierarchy. In most cases, measures complement each other or are requirements for other measures and it is important to emphasise at this point that a multi-layered, effective and concerted set of measures is necessary to quickly and sustainably embark on the path to a green hydrogen economy.

A hydrogen market already exists, dominated by industrial applications and fossil hydrogen. In existing markets, the non-energy use of hydrogen is predominant because of its specific chemical properties, however, there are other possible future markets that are expected to absorb large volumes of especially green hydrogen. In order to present the advantages of green hydrogen in the best possible way, the systemic advantages of hydrogen should be presented holistically in addition to individual aspects such as production costs or decarbonisation potential. To promote the use of hydrogen, a paradigm shift from hydrogen production to its use in specific areas is necessary. We should distinguish between the costs of hydrogen production and the market price on the one hand and its competitive price as part of the system solution in different use cases on the other hand.

The following types of measures and research needs will help to pave the way for a green hydrogen economy.

Research priority: Level playing field with fossil energy carriers and feedstock

The price of green hydrogen depends heavily on the geographical region, its primary energy sources and prices, the possibility to use existing infrastructure and a supporting policy framework. Due to these circumstances, general valid price statements are difficult to make. In many cases, the pure production costs of green hydrogen are currently higher than those of fossil hydrogen and financial measures can support the ramp-up of green hydrogen. Financial support in order to cover the costs of green hydrogen as well as a coherent green procurement policy and stronger carbon pricing mechanisms are crucial requirements for becoming more competitive compared to fossil fuels and feedstock.

Market prices for energy carriers and feedstock should reflect all costs holistically, e.g. from drilling/mining to climate costs, in order to create fair market conditions.

- Link support measures clearly with the expected effective benefit (e.g. CO_2 reduction) based on suitable assessment technologies
- Deepen and broaden knowledge on carbon pricing mechanisms' positive effects on the development of green hydrogen-based solutions in order to maximise the desired output
- Identify the most efficient, effective and sustainable hydrogen-specific support (e.g. exemption from grid charges) for a rapid and sustainable market introduction (especially with regard to the initial start-up phase). The positive effects of subsidies (e.g. tax incentives, investment subsidies) for the ramp-up phase and as well as CO_2 cost measures (e.g. carbon pricing) need to be understandable and transparent to everyone.
- Develop mechanisms to incorporate positive externalities into the economics of green hydrogen e.g. energy security, renewable expansion, etc.
- Improve the evaluation mechanisms of green hydrogen's potential by developing methods to make visible the holistic benefits of hydrogen energy systems (including storage) compared to other systems

Research priority: Energy system, integration and sector coupling

Renewable energies should be used in the best possible way to achieve the overarching goals set out in the European Green Deal. This means that the energy system is undergoing a multi-faceted transformation. More and more (volatile) renewable energy sources (RES) are being integrated into the system, different sectors are becoming more interconnected and vertically nested, and supra-regional supply chains are being complemented by energy regions and horizontal 'prosumer' relationships. In addition to increasing difficulty in guaranteeing access to RES in order to source green hydrogen production, the different applications are in competition with each other in terms of the use of the main primary RES for green hydrogen: solar radiation, wind energy, hydro power and biomass, which depend on local resources (in the case of biomass) and limited load factors (solar radiation, wind energy).

- As renewable energy supply to green hydrogen value chains is increasing the stress on local resources, strategic energy systems design is required in order to integrate different dimensions (e.g. integrating offshore RES and cross-border approaches)
- Develop and introduce clear metrics with proper methodologies that enable evaluation of the impact of comparative uses of renewable energies for the supply of green hydrogen
- Integrate RES into the energy system. This often causes a temporal and/or spatial discrepancy between energy generation and consumption, which emphasises the importance of transport and storage.
- Deepen the knowledge about the added value of hydrogen production, hydrogen vectors and storage systems in the deployment of low carbon energy ecosystems
- Improve the competitive factors of storage systems when integrated in the design of green hydrogen value chains
- Further harmonise the electricity market system in order to stimulate concentrated and dispersed renewable energy production and enable cooperation of local energy communities within Europe
- Illustrate the benefits of hydrogen-driven ecosystems in model energy regions (e.g. 'hydrogen valleys'), where innovation and social interaction/partnership building are key enabling factors for economic and social development
- Identify possible national and EU-wide hydrogen-hindering regulations as well as necessary technical and regulatory adaptations
- Link the EU Emissions Trading Scheme (EU ETS) to the development of green hydrogen technologies as it has enormous potential for promoting the energy transition

Research priority: Market conditions, business models and financing

Investments in the energy system are traditionally long-term projects and the market and its participants need a stable environment to develop credible and financially viable (bankable) business models. Especially in the transition of the energy system, long-term investments with a need for long-term return of investment come up against the uncertainty of change. Governments and authorities should create certainty and other enabling conditions – namely through legislation stimulating both the supply and demand sides and reducing policy risks in order to support the market. On the other hand, the market for green hydrogen is still at the very beginning and we need to identify those levers which can lead to the greatest possible positive impact in the creation of the market.

- Identify the best business models that can be replicated as examples
- Study and publish the performance of hydrogen systems in order to develop reliable, shared knowledge on key performance indicators (lifetime of equipment, output, efficiency etc.). Investors need to understand (hydrogen-)systems and resolving uncertainty will make financing easier and less costly.
- Develop support measures in order to stimulate energy communities, citizens' communities and different 'prosumers' to invest in hydrogen systems as part of the local green energy supply system
- Identify local strengths in Europe and work out a concrete catalogue of measures in order to maximise the benefit from cross-border cooperation

Research priority: Trade and trade barriers

A global market for the trade in hydrogen and its derivatives is expected to develop, in order to connect areas of production/demand surplus and deficit. It is anticipated that significant quantities of hydrogen will need to be transported across borders. The removal of trade barriers and common robust certification systems with countries from outside the EU play a crucial role in enabling cross-border trade of hydrogen and the development of a global hydrogen economy.

- Quantify the environmental and social impact of hydrogen trading with proper methodologies
- Create uniform international and European framework conditions in order to provide the best possible support and not hinder a rapid development of green hydrogen delivery (e.g. harmonise standards and guidelines, safety regulations, purity/pressure/flow speed definitions, rules for access to infrastructure, etc.)
- Identify appropriate and effective guarantees of origin (GO) and certification schemes as a basis for traceability and credibility (e.g. transparency regarding the carbon foot print, the hydrogen production technology, carbon intensity, etc.) Evaluate how best to introduce border adjustment mechanisms to create a level playing field with regard to the import of products from regions with less stringent regulations

- Identify all WTO rules applying to hydrogen and hydrogen carriers and make suggestions for an alignment between the different substances if necessary

Conclusion

Green hydrogen and the technologies behind it will certainly make a decisive contribution to a future sustainable energy and feedstock supply. The aspects to be considered are numerous, the change requires great investment and the market ramp-up should take place as quickly as possible. The implementation of the suggestions in these sections will help to fully develop the potential of green hydrogen in the best possible way and as quickly as possible.

4. Cross-cutting topics

Challenge

Energy systems consist of complex interrelated energy production-consumption chains that have implications for the design and implementation of enabling frameworks for the sustainable energy transition. The particular challenges of the energy transition will have to be tackled and the forces related to competition, consolidation, convergence and carbon emissions understood in terms of how they will be (i) shaping the power mix as well as the next wave of power systems transformation, (ii) reshaping the energy markets in the years ahead, and (iii) scaling up the energy innovations and their respective diffusion curves. Cross-cutting approaches for green hydrogen, as described in this section, aim to address this complexity. They include the production, conversion, delivery and use of energy as well as the underlying aspects ranging from business and financial models to the behaviour of consumption.

A green hydrogen economy will not only influence the entire energy system but also society. What does the transition mean for the use of and expenditure on household energy and public and private transport? How can regulation, standardisation and certification enable the acceptance and diffusion of green hydrogen in Europe? To answer these questions, one must move away from the technology focus and pursue an interdisciplinary and holistic research approach. Public acceptance of hydrogen will not only depend on its technical safety and price as an end product on the market, but rather on its value in achieving climate goals. The enabling framework needs to ensure that energy systems which deliver manifold energy services do this in a way that aligns with the international and national policy objectives.

Cross-cutting issues that deal with the socio-economic and environmental implications of hydrogen technologies as well as the legal framework are related to all three thematic blocks and are therefore described in this separate section.

Research priority: Establishing a common European framework for standards and regulations

Standards and regulations are basic requirements to create a common understanding about products, equipment, processes, quality and analytical methods. They provide the information needed to safely build, maintain, and operate systems. The infrastructure and mobility sectors, in particular, depend on uniform requirements across borders. Therefore, EU-wide

harmonisation of the common legislative framework and administrative requirements for hydrogen production, storage and transport is needed as a prerequisite for a competitive hydrogen market. Also, international activities such as those carried out by the IPHE should be considered.

- Establish a common technical, regulatory and legislative framework on integrated energy systems based on principles recognised throughout Europe to ensure consistency and provide predictability
- Analyse the existing national and regional regulations, codes and standards and rank the most urgent global actions
- Accelerate the process by defining and updating the regulatory framework, including standards, and developing technologies simultaneously
- Develop a roadmap for European standardisation with prioritised harmonised standards for a fast scaling up of hydrogen production technologies and their coupling with renewable resources
- Develop innovation-driven standards to maintain flexibility in regulation (for co-existence with natural gas, following electricity and pipeline solutions)

Research priority: Certification and tracking of green hydrogen and its derivatives along the whole value chain

A globally recognised certification system for green hydrogen has to cover the entire supply chain, including production, transport and import of hydrogen and its derivatives (Chain of Custody). This system is a prerequisite to calculate the right CO_2 price of nationally produced and imported hydrogen and its derivatives. Only by ensuring a high level of transparency and control can we build the trust necessary to create a strong green hydrogen market and thus achieve our climate goals.

- Introduce a common European taxonomy with a clear definition of green hydrogen and other 'colours of hydrogen'
- Develop a harmonised terminology at European level for hydrogen production technologies considering the climate neutrality of H_2 produced
- Apply a unified European system for Quality of Hydrogen and Hydrogen Guarantees of Origin for the establishment of a common hydrogen market (Certification of Origin)
- Perform life cycle assessments (LCA), develop life cycle inventories (LCI) for new hydrogen technologies and facilitate the exchange of environmental data
- Measure the carbon footprint of hydrogen in each step of the value chain, including the relevant parts of company footprints, and compile all greenhouse gas emissions in order to calculate the CO_2 product footprint for end customers
- Establish a platform on best practices in certification throughout Europe

Research priority: Transparency on external costs of fossil fuels

Ensuring a level playing field for green hydrogen can only be achieved if energy prices reflect the true costs of energy carriers including environmental and social costs that have so far been borne by society (polluter-pays principle). The recognition of an intact natural environment as a scarce resource in pricing leads to a valorisation of green hydrogen, as no carbon dioxide or other pollutants are emitted during its production and consumption.

- Develop mechanisms to increase the competitiveness of green hydrogen in the future energy system by internalising negative externalities in energy prices
- Develop concepts to return money to people and communities while encouraging environmentally-benign consumer behaviour (nudging)

Research priority: System analysis to allow well-informed decisions

Given the complexity of an integrated energy system based on hydrogen and renewable resources, a systematic analysis is needed to understand the interrelationships between individual elements. This allows for better prediction of future developments and early detection of trade-offs in decision-making.

- Apply systems analysis approaches to identify synergies, resource use and environmental and social impacts and to derive recommendations for high-quality business cases
- Improve methods for technology analysis to better address the readiness and the decarbonisation potential of hydrogen technologies

Research priority: Security of infrastructures

The greater the relevance of hydrogen in the energy system, the more important the protection of infrastructures for the production, storage and transport of hydrogen becomes. An effective security management not only includes the systematic identification

of vulnerabilities in the overall system, adequate precautionary and emergency measures, but also intensive cross-border cooperation.

- Develop a common European normative framework about safety topics for large-scale hydrogen production, storage and transportation, including coupling with renewable resources
- Disseminate existing fire protection programmes developed with EU firefighter training centres to expand relevant knowledge throughout EU fire crews
- Establish cyber-safe infrastructure through more collaboration in cybersecurity subjects on a national, European and global level

Research priority: Public acceptance of hydrogen and hydrogen infrastructure

Among the most crucial aspects of a successful transition towards green hydrogen is the challenge to make the transition socially acceptable and fair. Everybody will be affected by the transition and we must ensure a fair distribution of profit and transformation costs. Therefore, the energy transition must be considered holistically as a socio-economic challenge.

- Develop an effective common European policy for public acceptance of hydrogen
- Demonstrate clear and transparent national hydrogen strategies involving policy makers at national and European level
- Implement dedicated and coordinated pan-European demonstration activities and information campaigns making the benefits and safe use of hydrogen in our personal daily life more visible (e.g. in public transport and households, employment opportunities, etc.)
- Pursue an interdisciplinary approach for the development of hydrogen technologies including economic and social sciences to achieve public acceptance
- Promote knowledge transfer between behavioural science and public policy, as behavioural public policy is key to sustainable transitions and transformations
- Develop concepts in order to support the establishment of local energy communities

Research priority: Education and skills

The interest in hydrogen and fuel cell technology is increasing, but there remains a lack of awareness and knowledge of hydrogen as an energy carrier and feedstock as well as of fuel cells and electrolysers. From a market perspective, well-trained, internationally experienced and versatile employees are a prerequisite for rapid growth.

- Foster education in hydrogen technologies at all levels (from primary school to university programmes including PhD) in a coordinated way including student exchange
- Foster European doctorates on next generation carbon-negative H_2 technologies
- Develop a European network for upskilling and reskilling training programmes in the field of hydrogen (e.g. via a digital platform)
- Develop pan-European educational programmes to increase the knowledge of policy makers and public administrations in the field of hydrogen
- Develop a database for new green hydrogen jobs in Europe (e.g. via a digital platform)

Research priority: Organisational change

Overcoming silo thinking and increasing the efficiency and speed of decision-making are essential to create a swift transition to a green hydrogen economy. This implies the need to change well-established organisational structures in industry, research and public administration to better serve the specific requirements of hydrogen technologies.

- Develop new models to interact with, evolve and change to modern sustainable organisational structures
- Identify the requirements for institutional changes for regulating production, storage and transport infrastructures (e.g. institutional resources, new regulatory arrangements)

Conclusion

The overarching themes presented can be integrated into individual technology research projects or implemented as accompanying research. Better networking between Europe's best engineers, legal experts, economists and environmental and social scientists not only supports the exchange of information and application of state-of-the-art methodologies, but also the early consideration of critical aspects that could hinder the future diffusion of green hydrogen.

Outlook

There is no doubt that green hydrogen will become a key element in the energy transition. A multitude of hydrogen strategies and initiatives have emerged throughout the world, illustrating the momentum this energy carrier has gained in recent years. Europe is called upon not only to keep up, but to take the lead in this transformational period through the new European Research Area and the European hydrogen strategy. Given the magnitude of the challenge, only a combination of national, EU, bilateral and multilateral activities can lead to success.

While this will be no simple undertaking, whether for policy-makers or science and industry, a couple of steps have to be taken quickly. Optimising research conditions while at the same time taking a coordinated approach to existing and upcoming measures and regulations is the most pressing matter at hand. An important step in this direction is the European agenda process for green hydrogen developed in 2021.

The R&I initiative stimulated by the European Council in the framework of the new European Research Area and initiated under the trio presidency of Germany, Portugal and Slovenia is intended to improve cooperation as well as coordination between European member states, third countries and the European Commission. It **brings together stakeholders from industry, research, politics and society** (figures are provided in the annex). The SRIA is the key outcome of this wide-ranging cooperation and should also serve as an orientation and impulse for countries that have not yet developed their own hydrogen strategy or who are revising or updating their national strategies.

The SRIA includes recommendations for action to pave the way to a European hydrogen economy taking into consideration current European activities. It is the foundation for a European implementation plan on green hydrogen which will be jointly discussed during the conference in May 2022 with all participants. However, there can be no doubt that the **implementation of the SRIA is a joint task of the member states, third countries and the European Commission**. The implementation plan to be developed will be complementary to other action plans and coordinated between the task force of the agenda process and the European Commission.

The SRIA contains aspects going beyond classic research and innovation actions. These concern the mapping of hydrogen production and demand at national level as well as import/export among EU countries, the creation of national infrastructures, geo-economics and geopolitical impact analysis, transnational partnerships, market simulation at national level, etc.

To optimise the European research conditions and unlock the full innovation potential of green hydrogen, the implementation of the following action items is recommended:

Action point 1: Innovation ecosystem for green hydrogen

In order to meet our ambitious targets in the near future, we urgently recommend to all stakeholders to facilitate building a strong innovation ecosystem for green hydrogen and use respectively optimise European structures that already exist. This includes **making adjustments in the organisation of research funding** and the revision and widening of funding criteria (e.g. to stimulate cross-sectoral research projects and public-private partnerships). National deployment programmes must be used to advance green hydrogen solutions to the market. By building large cross-sectorial consortia, we can accommodate the input of different stakeholders and realise useful synergies. Of great importance for the process is the early involvement of all relevant actors of the value chain in research and decision processes (e.g. logistics companies). In this competitive global environment, we need to **accelerate processes by defining the regulation and developing technologies simultaneously**.

Action point 2: European digital platform

A catalyst for speeding up the creation of a profitable green hydrogen market could be a European digital platform which **serves to support transparency and interconnectivity on multiple levels**. It should contain:

- Overview of hydrogen projects and market players in Europe
- Market analyses regarding volumes and technologies used in projects
- Benchmarking of technology trends
- Compilation of official documents on EU member states legislation, strategies and programmes to support meta analyses
- Support tool box to create blueprints for projects
- Possibility to track green hydrogen along the value chain (proof of origin)

Key requirements that ensure the success of such a platform are simplicity and user-friendliness. The data has to come in different spatial and temporal resolutions (per sector and technology) to account for the diverse application needs. And finally, the data needs to be open access and include models for integrated system planning and knowledge sharing on a country and an EU level. If done in a responsible manner regarding data and knowledge security, this can enable mutual information and trust.

This activity could be linked with the hydrogen projects database TRUST[3] developed under the Clean Hydrogen Joint Undertaking. TRUST and its subsequent Observatory will be developed further to **integrate all R&I European projects and national projects** with a view to set up a European Union Clean Hydrogen Observatory (EUCHO), which will also be aimed at serving researchers, innovators, industry and the wider public. Furthermore, this activity could be linked to the Mission Innovation Hydrogen Valleys Platform to keep an updated overview of projects and provide a support tool for project blue-prints.

Action point 3: European and international partnerships

Strong European and international partnerships are necessary to establish a green hydrogen economy in Europe. More impact and efficiency of bilateral and multilateral activities can be achieved through coordinated action. However, it **requires a critical mass of European and international cooperation and joint action by countries to leverage funding and increase visibility**. At the same time, it must be taken into account that countries have different areas of innovation strength, different market shares and opportunities within the green hydrogen value chain and different starting conditions for the transition. For instance, the global potential and demand for renewable energy are distributed very unevenly and coordination of national support measures is therefore desirable.

International partnerships are expected to provide a significant input to a rapidly growing hydrogen economy. The agenda process on green hydrogen is a starting point to enable lasting and trusting partnerships. But we should ensure security for investments in potential exporting countries in order to have a real prospect of import partnerships. The H_2 Atlas Africa[4] exploring the potentials of hydrogen production from renewable energies within the Sub-Saharan region in West Africa is a good basis for further research in this area.

In order to improve the European coordination of funding programmes, the agenda process will inform the State Representative Group of the Clean Hydrogen Joint Undertaking, allowing an optimal analysis of the existing and planned national hydrogen research programmes and partnerships. This analysis can also provide reference points for synergies, cross-border cooperation and further harmonisation possibilities of the energy market system. The agenda process may also develop synergies and feed into the work on hydrogen within the SET Plan.

Action point 4: Involvement of member states and national authorities

To ensure the continued success of the agenda process, the member state holding the presidency should be responsible, in co-operation with the Commission, for the implementation of the SRIA, e.g. by organising at least one higher-level meeting, or delegating this responsibility to another participating member state. The involvement will also mean supporting communication between the national authorities and the research community and industry (through joint events, etc.) and addressing the need for investments in non-profitable parts of

3 TRUST (Technology Reporting Using Structured Templates) is an online database and tool for projects financed by the Clean Hydrogen Joint Undertaking to report on progress and status.

4 https://www.h2atlas.de/en/

the infrastructure with subsidies and other financing instruments .

Action point 5: Parallel coordination of R&I activities and infrastructure setup

Time is of the utmost importance in 'the switch' to green hydrogen across Europe. The timing of all action taken needs to be synchronised so that European countries **converge on a shared timeline when implementing research projects, setting up infrastructures and delivering or exporting hydrogen**. A coordinated approach allows for bridging regional 'technology gaps' and distributed responsibilities borne by hydrogen centres of excellence. Duplication of efforts can be avoided if priorities and actions are coordinated among countries.

Conclusion

To continue working on the realisation of the SRIA in 2022 comprehensive action needs to be taken. Leadership and competitiveness thrive on innovation and cooperation. Moreover, it is important to link countries across Europe and beyond and to stimulate the development of excellent and diverse consortia. In order to benefit from existing structures, this should be coordinated with other existing initiatives such as the SET Plan, which will be revamped in the coming months, the Clean Hydrogen Partnership and its State Representative Group, EUREKA and, on the international level, Mission Innovation and the IPHE.

Working together within the ERA should remain a priority along with an elaborated innovation ecosystem. This also means that industry partners need to be included, for several reasons: to widen their scope and network, to exploit new technologies and research findings, to learn from other perspectives and knowledge, to gain insights in real applications etc. Integrated R&I projects on hydrogen are needed covering the whole value chain as well as economic, environmental and social implications.

For the overall coordination and timing of all the different actions and initiatives, a joint platform should be set up based on already existing and planned initiatives while being compatible with the needs as outlined above. From now on, **R&I on green hydrogen can be coordinated via the governance mechanisms of the European Research Area**, where member states and the EU Commission work closely together. This includes the development of a more concrete implementation plan (including reference to funding opportunities, a budget and concrete EU and national member state activities on a European and bilateral level) and the evaluation of the endeavour to accelerate the green hydrogen market. It is important to monitor the implementation of the SRIA on a regular basis and to make adjustments, whenever needed in order to ensure that we achieve the ultimate goal of climate neutrality. Green hydrogen can be a game-changer, if we continue on this promising path of joint research and innovation.

Annex 1 – List of stakeholders

Table 1: List and role of stakeholders involved in the agenda process.

	Task force	Expert groups	Coordinating countries	Third countries
Austria (AUT)	x	x	x	
Belgium (BEL)	x			
Bulgaria (BGR)	x	x	x	
Croatia (HVR)	x			
Cyprus (CYP)	x			
Czech Republic (CZE)	x	x		
Denmark (DNK)	x			
Estonia (EST)	x			
European Commission	x			
Finland (FIN)	x	x		
France (FRA)	x	x		
Germany (DEU)	x	x	x	
Greece (GRC)	x	x		
Iceland (ISL)		x		x
Ireland (IRL)	x			
Israel (ISR)		x		x
Italy (ITA)	x	x	x	
Latvia (LVA)	x			
Lithuania (LTU)	x			
Luxembourg (LUX)	x			
Netherlands (NLD)	x	x		
Norway (NOR)				x
Poland (POL)	x			
Portugal (PRT)	x	x		
Romania (ROU)	x	x		

	Task force	Expert groups	Coordinating countries	Third countries
Slovakia (SVK)	x			
Slovenia (SVN)	x	x		
Spain (ESP)	x	x		
Sweden (SWE)	x			
Switzerland (CHE)		x		x
United Kingdom (GBR)				x

Table 2: Expert groups of the agenda process.

	Production	Transport and Infrastructure	Market Stimulation
Coordinating country	**Italy, Bulgaria**	**Germany**	**Austria**
Science	**Dr. Antonino Salvatore Aricò** (Steering Committee, ITA) **Dr. Angelo Moreno** (Steering Committee, ITA) **Dr. Carmen M. Rangel** (PRT) **Dr. Sonya Calnan** (DEU) **Dr. Stanko Hočevar** (SVN)	**Prof. Dr. Mario Ragwitz** (Steering Committee, DEU) **Prof. Dr. Robert Schlögl** (Steering Committee, DEU) **Dr. Elena Carcadea** (ROU) **Prof. Dr. A.P.C. Faaij** (NLD) **Prof. Pantelis Capros** (GRC)	**Dr. Alexander Trattner** (Steering Committee, AUT) **Dr. Katrin Goldammer** (DEU) **Juliane Arriens, M.Sc.** (DEU) **Prof. Gabriele Centi** (ITA) **Dr. Paulo Partidário** (PRT)
Industry	**Dr. Nikolaus Fleischhacker** (AUT) **África Castro** (ESP) **Dr. Ervin Tal-Gutelmacher** (ISR)	**Dr.-Ing. Karin Stehlík** (CZE) **María Sicilia Salvadores** (ESP) **Dipl.-Ing. Stijn van Els** (NLD) **Dina Lanzi** (ITA) **Peter Koop** (DEU)	**Prof. h.c. Dr. Peter Prenninger** (AUT) **Dr. Antti Arasto** (FIN) **Raphael Schoentgen** (FRA) **Dr. Zoran Marinšek** (SVN)
Civil society	**Julian Popov** (Steering Committee, BGR) **Prof. Dr. Vasco Amorim** (PRT)	**Dr. Tom Kober** (CHE)	**Dr. Günter Simader** (Steering Committee, AUT) **Prof. Dr. Brynhildur Davíðsdóttir** (ISL)

Annex 2 – Participation in numbers

10x task force meetings with 30 participating representatives of the member states on average – virtual events.

Expert pool with 155 hydrogen experts, nominated by 20 countries. Of these, 57 for the thematic area 'Transport and Infrastructure', 57 for the thematic area 'Production', and 41 for the thematic area 'Market Stimulation'.

Public consultation from 20 August until 1 October 2021 with 170 valid surveys from 22 countries, which corresponds to a response quote of ~15%.

Three thematic workshops:

- Workshop 'Transport and Infrastructure' on 7 and 8 October 2021 in Berlin with about 60 participants on site and 60 virtual participants – hybrid event.
- Workshop 'Market Stimulation' on 22 October 2021 with more than 80 participants – virtual event.
- Workshop 'Production' on 4 and 5 November 2021 in Rome with about 30 participants on site and 70 virtual participants – hybrid event.

Adoption event of the SRIA 'Towards a European Green Hydrogen Union – Presenting a Strategic Research and Innovation Agenda' on 18 March 2022 in Berlin – hybrid event.

Conference 'Green Hydrogen for a Sustainable European Future' planned for 16 and 17 May 2022 in Berlin – hybrid event.

Annex 3 - Supplementary materials

Position papers of the expert groups

- 'Production' (DOI https://zenodo.org/record/6366032)
- 'Transport/Infrastructure' (DOI https://zenodo.org/record/6365765)
- 'Market Stimulation' (DOI https://zenodo.org/record/6365999)

Technical report on the public consultation (DOI https://zenodo.org/record/6366108)

agenda process on green hydrogen