Seed Paper

➢ Definition of scope for Green Hydrogen Production

On 1st December 2020, the Council conclusion of the European Union has invited the Commission and interested Member States to carry out an agenda process for a green hydrogen R&I 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. In this context, green hydrogen production represents, undoubtedly a field in which significant research and innovation efforts are needed.

1. Description of status quo

European Strategy for hydrogen production

On 8th July 2020, the European Commission communicated the "Hydrogen strategy for a climate-neutral Europe" to the European Parliament, the Council, the European Economic and social committee and the committee of the Regions. The strategic document presented by the European Commission focuses on the production and use of green hydrogen. The EU strategy indicates, as priority, the installation of electrolysers in Europe between 2020 and 2024 with a capacity of up to 6 GW to produce hydrogen with renewable energy. Producing 1 Mt of green H_2 will facilitate the introduction of the hydrogen vector in several industrial sectors and for sustainable mobility. In this phase, a large increase in local clusters of H_2 and "Hydrogen Valleys" is foreseen. The second phase (2025-2030) foresees 40 GW of electrolysers and 10 Mt of green H_2 production to extend its application especially to the steel sector and heavy mobility (trucks, ships, trains). The third phase concerns a period beyond 2030. The goal for renewable hydrogen is to reach maturity in order to be applied on a large scale. The planned investments until 2030 are of the order of 24-42 billion euros for electrolysers, 220-340 billion euros to connect the production of renewable energy and another 160-200 billion euros for uses in the application sectors.

Actual EU initiatives related to hydrogen production

The EU research and development programs focusing on hydrogen in the past Horizon 2020 framework program were supported by the Public Private Partnership named **Fuel Cells and Hydrogen Joint Undertaking (FCH JU)**. The FCH JU is made up of three partners that is the European Commission, the **Hydrogen Europe** association and the **Hydrogen Europe Research** association. Hydrogen Europe brings together diverse industry and research players, large companies and SMEs, who support the delivery of hydrogen and fuel cells technologies. Hydrogen Europe Research is an association of universities and Research & Technology Organisations that are active in the hydrogen and fuel cell fields. In the new framework program, Horizon Europe, the **Clean Hydrogen for Europe Partnership** in Cluster 5 Climate, Energy and Mobility will replace the FCH JU. The new partnership aims to accelerate development and deployment of European clean hydrogen technologies, contributing to a sustainable, decarbonised and fully integrated energy system. It will focus on production, distribution and storage of clean hydrogen to supply sectors, which are hard to decarbonise such as heavy industries and heavy-duty transport applications.

The **Strategic Research and Innovation Agenda** (SRIA) of the Clean Hydrogen for Europe Partnership forwarded by Hydrogen Europe and Hydrogen Europe Research, consists of several strategic objectives and horizontal activities. The three pillars on which the roadmap is structured are (i) production, (ii) storage, transport and distribution and (iii) end usage. The SRIA reports detailed analyses and forecasts for each of the strategic goals, as objectives of the partnership based on what was achieved by FCH-JU2.

According to this SRIA, in the period 2020-2030, the main sectors of maturity are those related to sustainable mobility, industrial applications in the chemical and steel sectors and applications for the production of heat and electricity in the industry. Applications of electrolysers for grid balancing, power-to-gas, injection of H_2 into the gas grid (blending with natural gas) and accumulation of surplus renewable energy on a daily and seasonal basis are addressed. Other important fields pertain to the use of fuel cells in CHP and Micro CHP (combined heat and power) systems and the production of hydrogen from the gasification of municipal solid waste (circular hydrogen). From the point of view of the research objectives, in the Horizon Europe framework programme (2021-2027), the priorities regarding hydrogen production have been identified and are essentially the electrolysis and other modes of green hydrogen production. Specifically, producing clean hydrogen at low cost and enabling higher integration of renewable within the overall energy system.

Other hydrogen initiatives

At the same time the European Hydrogen Strategy has been published, the EC has established the **European Clean Hydrogen Alliance** (ECH2A). It aims at an ambitious deployment of hydrogen technologies by 2030, bringing together renewable and low-carbon hydrogen production, demand in industry, mobility and other sectors, and hydrogen transmission and distribution. With the alliance, the EU wants to build its global leadership in this domain, to support the EU's commitment to reach carbon neutrality by 2050. By bringing together industry, public authorities and civil society, the alliance will play a crucial role in facilitating the implementation of the European Hydrogen Strategy vision. It will maximize the impact by engaging all stakeholders in the hydrogen value chain and by mobilising resources to develop an investment agenda to stimulate the roll out of production and use of renewable and low-carbon hydrogen, and to build a concrete pipeline of projects. This will create the base for a sustainable and competitive industrial hydrogen ecosystem in the EU.

In the framework of **MISSION INNOVATION** (world-wide initiative), the challenge Clean hydrogen has the potential to contribute in decarbonising hard to abate sectors, such as industry and heat, which are responsible for two thirds of global emissions and can help unlock the full potential of renewable energy. The goal of this Challenge is to increase the cost-competitiveness of clean hydrogen by reducing end-to-end costs to USD 2 per kilogram by 2030. The aim of the Mission is to catalyse cost reductions by increasing research and development in hydrogen technologies and industrial processes and delivering an increase of hydrogen valleys covering production, storage and end-use worldwide by 2030, to unleash a global clean hydrogen economy.

Other initiatives include the **ten-year plan for the development of the European gas infrastructure**. This initiative stresses the importance of the transition and decarbonisation of gas by increasing both production of renewable energy and biomethane obtained from CO_2 (power-to-gas), with hydrogen seen in the long term (2050) as an energy vector.

The **European backbone of the hydrogen distribution network** was prepared by the main European operators of gas transport and storage networks. The document outlines the development strategy proposal for the transport of the new energy vector, which in 2030 will extend for 6800 km, connecting the European hydrogen valleys.

There are other relevant initiatives like the **Hydrogen Council** that aims to promote collaboration on hydrogen among different countries within and outside the EU.

An important topic, which is participating in an invisible way in all strategic documents, concerning hydrogen, is public acceptance. It is a central factor for the accelerated deployment of hydrogen technologies, starting with hydrogen production from renewables. However, those strategic documents cannot reach the public, even the policy makers in many EU countries. The documents have to be adapted for fast public acceptance in a new, more expressive way. For the moment, the most powerful is the voice of journalists. However, more collaborative algorithm is needed, combining actively science, industry and society which is one of the goals of this Agenda process on green hydrogen. It should be noted, that Hydrogen is more popular and accepted in the transport sector. This should be used and extended to all economic niches so that we could have real objectives for hydrogen economy deployment.

2. Target setting of the Agenda Process Initiative

The aim of the Agenda Process Initiative in the field of Green Hydrogen Production is to fill missing parts (gaps) in the other EU initiatives applying a bottom up approach at EU level with wide participation of the stakeholders through the whole value chain by:

- Joining Science, Industry and Society in the Agenda Process initiative
- Addressing more in-depth society needs
- Applying a holistic approach for hydrogen production.

With regard to the R&D objectives included in the Agenda Process, the following definitions are used:

- **Hydrogen Production focus is on "Green hydrogen**", i.e. hydrogen produced from renewable energy sources (RES); thus, all fossil resources are excluded.
- **Short-term objectives:** these refer to the needs of further research, development and demonstration for production technologies which are ready for scaling up and have been already developed at medium-high TRL (TRL 6-8, time framework for application 1-3 years)
- **Medium-term objectives**: these refer to further development of technologies and processes that have been validated at laboratory level (TRL 4-6, time framework for application 3-10 years)
- **Long-term objectives**: these refer to breakthrough research (TRL 1-4, time framework for application >10 years)

In all cases, the general aim is that all these research efforts on short, medium and long-term objectives should be carried out in parallel to make green hydrogen a wide-scale energy vector at 2030.

Besides focusing on production technologies other relevant aspects of the Agenda Process Initiative are:

- ✓ To integrate hydrogen production in the energy system, thus ensuring effective sector coupling, taking advantage of hydrogen being an energy vector.
- ✓ To Increase the hydrogen role in a circular economy context.
- ✓ Deployment of legislation issues (including regulations, codes and standards - RCS) unified on EU level
- ✓ Foster company- and technology competition in order to decrease costs of electrolysis (€ net per kW) due to:
    - Increased performance
    - Generated scale effects
- ✓ Creation of Hydrogen Business Cases:
    - OPEX based and CAPEX funded business cases
    - Direct use of electricity for electrolysis (power plant integration): long term projects with low electricity prices --> great potential with PV
    - Additional electrolysis exemption from net fees (grid cost)
- ✓ Increasing resilience of energy system by creating decentralized Green Hydrogen Economies based on Hydrogen Hubs with 10 to 15 MW (and more)
- ✓ To promote early stage research to force breakthroughs for overcoming scientific and technological challenges in hydrogen production for the different technologies.
- ✓ To foster collaboration between research and industry applying both breakthrough and underpinning approaches at low and high TRLs.

3. Needs assessment

The aim of the Agenda Process Initiative is to bring the attention, through a public consultation with policy makers, society and other stakeholders, on hydrogen production topics which are not sufficiently addressed by other initiatives or that require, in a holistic context, specific priorities. These are shortly summarised below. It is pointed out that this is not an exhaustive list and will be implemented through the public consultation.

- ✓ More fundamental research is required, e.g. research needs at low TRLs to address the present gaps. These regard new technologies based on the use of non-critical raw materials characterised by high performance, efficiency and durability. Breakthrough research is needed to reduce the hydrogen cost to make this energy vector economically competitive at world level.
- ✓ Developmental activities, research efforts and strategies to reduce the CAPEX, OPEX of the present technologies; overall objective is to reduce the cost of hydrogen produced (€ per kg)

✓ Demonstration activities to favour the rapid creation of a distributed green hydrogen infrastructure in Europe.

✓ Addressing a common **Terminology** at EU level (e.g. JRC Report 'EU harmonised terminology for hydrogen generated by electrolysis' published - Ares(2021)4778451)

✓ Addressing a common certification of origin to guarantee sourcing of hydrogen from green sources.

✓ Promoting programs addressing traceability, deployment mechanisms and market diffusion for green hydrogen production

✓ Companies demands (bridging industry with science); fostering technology transfer

✓ Addressing effective exploitation of results from research projects

✓ Business cases driven R&D (OPEX based Business Cases; CAPEX will decrease later due to company- and technology competition with scale effects and increased performance).

✓ Joined research and industrial efforts on technological development of recycling of materials and components

✓ Joined efforts of science, industry and active society for wide public information about the importance of hydrogen production from renewables and its utilization for fast and efficient global decarbonization.

4. Development of research questions

4.1 Identification of main R&D topics

➢ General presentation (for all topics)

The new Agenda Process Initiative on Green Hydrogen research and development should operate in synergy with the European strategy "A hydrogen strategy for a climate-neutral Europe", the activities relating to the European Green Deal, the activities of the Recovery Plan, the planned activities in Horizon Europe (HE) and, in particular, the partnership of Clean Hydrogen for Europe. The aim of the Agenda Process Initiative is to further promote activities on hydrogen while being complementary to the already existing EU programs. The general approach is to consider the role of the society, the specificities of the EU countries and the different opportunities, taking into account the various existing gaps. In particular, scientific-technological development should promote the creation of synergies, interdisciplinary interactions and an increase in critical mass through the creation of networks of laboratories and research infrastructures with wide access to the EU researchers. The final aim is to enhance the competitiveness of EU industries and research entities, establish synergies among the EU countries, and stimulate initiatives of cooperation between research, industry and policy makers.

Short-term requirements:

Short-term requirements should include further development of the technologies that have already reached maturity, further scaling up of processes and plants e.g. from multiMW level electrolyser to 100 MW-class electrolysers while pursuing the following objectives:

- ✓ Demonstration of high-power (multi-MW and 100MW-class) electrolysis technologies that meet cost, performance, duration, dynamics and use of hydrogen in end usage targets (eg. HRS, P2G, industry etc.);
- ✓ Scale up of medium scale highly efficient electrolysers
- ✓ Development of production automation and quality control processes;
- ✓ Demonstration of electrolysis plants directly powered by RES and for grid balancing.
- ✓ Demonstration of biomass derived hydrogen production processes on a wide scale
- ✓ Demonstration of plants for the gasification of waste and biomass for the production of hydrogen and their integration with electrolyser and into production systems;
- ✓ Demonstration of plants with production of hydrogen from biogas;
- ✓ Demonstration of a full-size biological reactor for the production of hydrogen from residues;

Medium-term requirements:

On the medium term, further development of industrial products based on already validated technologies and processes is required. In this context, research activities aimed at pursuing diversified objectives are required:

- ✓ Increase efficiency, durability and reliability of the electrolyser stack, photoelectrolysis, modules, biochemical reactors;
- ✓ Simplification of the BoP to make the hydrogen production systems more economical and more easily interfaced with the electricity grid in the case of electrolysers;
- ✓ Scaling up of stacks and production systems, development of processing technologies suitable for the realisation of high-power electrolysers;
- ✓ Development of innovative components to optimise and reduce losses and costs;
- ✓ Development of tools for monitoring, diagnostics and control of electrolysers;
- ✓ Development of high-pressure electrolysis stacks in order to reduce/avoid the subsequent compression phase;
- ✓ Development of reversible systems (electrolysis/fuel cell) and co-electrolysis (syngas);
- ✓ Scale up of the most promising technologies for gasification of biomass and waste including the development of hybrid systems and solar gasification;
- ✓ Development of photo (electro) chemical systems consisting of large area modules with efficiency > 10%; scale up of the most promising technologies to 1-100 kW capacity;
- ✓ Integration of solar driven electrochemical hydrogen compression with photovoltaic + electrochemical (PV+EC) and photoelectrochemical systems
- ✓ Integration of chemical looping cycles in solar-CSP concentration plants and in traditional power plants or in oxy-combustion processes;
- ✓ Integration into other production schemes, e.g. (bio)refineries.
- ✓ Develop advanced in operando monitoring techniques of both processes and relevant catalytic and electronic mechanistic steps to identify avenues to overcome the current performance (conversion efficiency, stability) limitations
- ✓ Electrolysers in "co-generation mode" e.g. for exploitation of generated heat, synthetic fuel production etc.
- ✓ Development of innovative solutions for exploitation of the generated O_2
- ✓ Demonstration of mid-size plants for the production of hydrogen from direct sunlight.

Long-term requirements:

- ✓ Significant reduction of costs and increase efficiency (step-change required).
- ✓ Overcome kinetic limitations in hydrogen production reactions
- ✓ Develop technologies for high pressure (>150 bar) hydrogen production for > 100 kW capacity

- ✓ Development and use of new materials, new technologies, new designs and new processes, avoiding critical raw materials
- ✓ Study of processes for recycling of components at the end of their life as priority actions to reduce the impact, costs and increase the useful life of all hydrogen production technologies.
- ✓ Develop optimal dynamic behaviour for the electrolysis systems being this essential for grid balancing service.

4.2 Electrolysis technologies for green hydrogen production

➢ Research questions/topics

- Which electrolysis technologies need stronger support on the short-, medium- and long-term?

The large-scale diffusion of green H_2 is strongly related to decrease of both the cost of electricity and the cost of electrolysis systems while increasing the uptime hours. Moreover, it is important to improve the conversion efficiency. One of the main requirements is the availability of electrical power from renewable power sources at a competitive cost and in appropriate amounts. In this context, hydrogen can promote the rapid penetration of renewables in the energy system.

Distributed and centralised H_2 production, improvement of the durability and reliability of electrolysers and reduction of operating and investment costs can ensure the achievement of the European objectives with regard to high purity green hydrogen (5N) production at a cost lower than 2-3 €/kg. This can make green hydrogen competitive with hydrogen from fossil fuels especially if proper carbon taxes will be applied in EU countries. Regarding the sector coupling, an effective and direct integration of electrochemical systems with renewable energy sources and enhanced interface with the grid are relevant aspects. Hydrogen can provide grid-balancing service, store the surplus of renewable energy, allow seasonal energy storage and can be converted into liquid H_2 vectors (e.g. NH_3) in an integrated way. This can be realised in different geographical areas and at different time-scales. In this regard, it would be important improving the electrolysis technology to make use of waste and sea water.

Current commercial technologies (alkaline, PEM) require to upgrade, upscale, reach a higher manufacturing capacity, and deploy large amounts of (sustainable and affordable) hydrogen for the market to take off. This needs strengthening the value chain. For the necessary cost reduction and efficiency improvement (directly affecting to CAPEX and OPEX figures), new technologies that can drive into that direction are also developed (SOEC, AEM, etc.), and minimization of critical materials usage is fostered. Production capacity requirement remains quite huge, so new routes other than water electrolysis, that can offer volume, are to be explored and further developed (biomass, photo, etc.).

With regard to **PEM electrolysis**, it will be necessary for the next years to reduce the content of precious metals (Ir, Ru, Pt) in the catalysts/electrodes and on the long term to develop critical materials-free components including hydrocarbon membranes to replace fluorinated membranes. This gap is presently addressed by another similar but competitive technology i.e. anion exchange membrane electrolysis; however, it is still unclear if AEM electrolysis can reach the same level of performance of PEM electrolysis. Moreover, in the case of AEM electrolysis it is necessary to develop new/advanced membranes and electrocatalysts. For conventional PEM systems, it will be appropriate, on the long term, to replace the titanium-based bipolar plates (recently included in the EU 2020 list of critical raw materials) with less expensive and more easily machinable metals or develop innovative coatings that maintaining the same corrosion resistance characteristics can also provide optimal interface resistance.

With regard to **alkaline electrolysis**, although this is a consolidated technology, it will be important to develop a more compact stack design, improve efficiency, achieve high current density with low ohmic losses, facilitate the management of concentrated caustic solutions and improve the purity of the hydrogen produced and in general the dynamic behaviour of the alkaline electrolysis system.

For **solid oxide electrolysers**, it will be necessary on the long term to develop new ceramic electrolytes operating at lower temperatures and nanostructured catalysts: this should include intermediate temperature ceramic proton conducting electrolytes. Other relevant requirements are the search for efficient and stable systems operating at high pressure, decrease costs through the reduction of critical materials, in particular rare earths, Co etc. It is fundamental to reduce the operating temperatures from the current 750-800°C to 600°C, to improve corrosion resistance, durability and the use of low-cost ferritic steels. It is substantial for the next generation SOECs to improve the dynamic behaviour, and in particular the stability to redox and thermal cycles, as well as to produce compressed hydrogen; to develop reversible cells for polygeneration (high quality fuel, electricity and heat) and for power-to-X-to-power applications; to develop thermal and mass flow management in co-electrolysis systems for syngas production and subsequent conversion. Effective direction is coupling with chemical/electrochemical reactors for production of ammonia or e-chemicals.

Recycling, re-use and substitution of critical materials are emphasized. There is a need to develop a full end of life (EoL) strategy in order to reduce cost through the use of sustainable products and innovation and to ease the vulnerabilities in existing supply chains.

For all electrolyser technologies, there is a need on a fundamental scientific level, for research to overcome the slow kinetics of the oxygen evolution half-reaction, which contributes significantly to the limitation of the electricity to hydrogen conversion efficiency.

New electrolysis technologies

Among the other emerging technologies, research efforts for the next years should be addressed to develop **anion exchange polymer membrane electrolysis** (AEMEL) and **proton conduction ceramic electrolysis** (PCCEL).

Research and development targets for AEM electrolysers revolve around primary requirements of (a) Increasing durability of the MEA, (b) reducing / eliminating the use of PGM and CRM catalysts while maintaining high performance, and (c) reducing the concentration of, and possibly eliminating the use of alkaline electrolyte. Point (c) is a techno-economic choice rather than an absolute requirement, and the ability to advance in this direction is tied to advances in (a) and (b). Regarding durability, although the alkaline stability of modern ionomers is excellent when well hydrated, questions remain regarding their susceptibility to free-radical induced degradation mechanisms and also oxidative degradation at the anode side, which operates under high voltage, oxygen concentration, and preferably temperature. With regard to performance and CRM usage, while performance of alkaline membrane and ionomer is not of great concern with added alkaline electrolyte, when reduced concentration or elimination of electrolyte is desired, increasing the alkalinity of the alkaline functional groups becomes a critical need especially for the oxygen side where alkalinity is key to high performance. Finally, the mechanical integrity of alkaline MEA's remains a challenge with respect to durability, as well as to performance especially in low-concentration electrolytes. Since hydrocarbon AEM's and ionomers are not able to be fused by hot-pressing, this is a significant challenge that can be addressed both from the mechano-chemical properties of the ionomer, as well as production/engineering advances.

To address the problem of hydrogen compression, it will be important to develop polymeric hydrogen pumps for high efficiency electrochemical compression which may be combined with hydrogen production by proton conducting solid oxide electrolyzers which can produce dry and initially compressed (up to 50 bars) hydrogen.

For what concerns the sector coupling of electrolysers, the following relevant aspects should be prioritised:

- Direct coupling of electrolysis with renewables
- Application of electrolysers in grid balancing service
- Coupling of electrolysis with industrial processes (heat balance etc.)

Flexibility and reactivity to changes in the input conditions and loading effects need to be ascertained. The effects of transient operation on stack and system lifetime are not yet well quantified for large-scale electrolyser systems. Systematic data on the impact of operating parameters on durability is necessary and understanding of degradation mechanisms is crucial under dynamic operation

In general, a common virtual space for research database and other information for research groups working in similar topics for further collaboration is needed as well as a database for testing facilities.

4.3 Gasification and thermochemical processes of biomass and wastes from renewable sources

- Research questions/topics
    - Which biomass-based processes need to be considered as suitable for green hydrogen production?

Direct production of H_2 from intermittent renewable sources, such as wind and solar sources, using electrolysis is characterised by intermittent operation and limited operating times (uptime hours). For large-scale use, the hydrogen supply chain should be integrated with alternative production technologies for continuous use needs, particularly in the industrial field. Thus, the generation of green hydrogen from electrolysis can be complemented by gasification of biomass and/or solid renewable waste. On the long term, conversion of organic waste substances via microorganisms (biotechnologies), catalytic reforming of bio compounds in aqueous phase (APR), gasification in supercritical water (SCWG) are promising.

Thermochemical conversion of biomass such as gasification and pyrogasification are interesting technologies to convert biomass wastes and residues into hydrogen and syngas for fuel application. With regard to gasification of biomass and waste, research needs regard the development of innovative reactors, integrated processes combining syngas production and hydrogen upgrading, materials and processes that improve operational flexibility and conversion efficiency as well as new solutions for the treatment of synthetic gas. The design of catalysts as bed material to avoid TAR and to increase H_2/CO ratio are also challenges of the innovative gasification processes. Significant advantages can rise from the integration of biomass gasification with the electrolyser due to the possibilities to use the hydrogen to increase carbon conversion and the oxygen stream as oxidant.

New bioreactors with a high production rate for medium and large plants; development of microbial cells based on innovative processes, configurations, innovative materials and electrodes; development of integrated separation systems are other relevant areas of interest.

With regard to reforming of biomass and wastes and biogas, research is needed regarding the improvement of reactor design, to operate under isothermal conditions for maximizing hydrogen production. Main challenges stem from the exothermicity of the process, which limits heat transfer. Further on, development of novel catalysts, able to efficiently operate under isothermal conditions and in membrane reactors; multifunctional materials are envisaged.

Biogas/biomethane pyrolysis and thermocatalytic cracking with renewable carbon black capture can represent a sustainable energy breakthrough converting dispatchable renewable energy sources into clean energy vectors, including hydrogen, with negative CO_2 emissions. Further, the remaining renewable carbon can start a circular usage as precursor for steel production, cement industry, fuel cell production, batteries etc. Further research needs are on catalyst regeneration and the reduction/minimization of clogging of reactor due to carbon black. Metal catalysts are used to drive the process, although cheaper carbon materials can be also used. The technology is at TRL of 3-5, and research is needed mostly on adapting the catalysts/process to the characteristics of biogas (i.e., presence of impurities, hydrocarbons other than methane, etc.). The development of catalysts with high stability is also key.

The electrooxidation of aqueous solutions of biomass-derived organics (e.g., bioethanol, glycerol, sugars) is an interesting technology that can be used to produce high-purity hydrogen at voltages well below those required for water electrolysis, thereby significantly reducing the energy requirements of the process. Apart from hydrogen, this technology potentially allows the co-production of high-value chemicals in the anode chamber, thereby increasing the economic appeal of the process. This technology is currently at a low TRL (3-4), with improvements required mostly in electrocatalysts used as anodes. Thus, new materials with higher activity and stability while being able to catalyze C-C breaking processes are required before scaling up.

4.4 Photoelectrolysis & photocatalysis (direct solar hydrogen)

➢ Research questions/topics

- Which photo-based technology do you think is most promising?

In the view of long-term applications, the direct conversion of solar energy into hydrogen, by water electrolysis using energy from photons, is an area of growing interest where increasing solar-to-fuel conversion efficiency to values of commercial interest is paramount. In this context, it will be appropriate to develop tandem solar systems and innovative photoelectrolysis or photocatalytic materials and devices, based on non-critical materials. In the next 5 years, there is an urgent need for standardised benchmarking protocols (similar operating conditions illumination, device temperature, electrolyte/pH, pressure) for photoelectrolysis (photoelectrochemical photoelectrodes, PEC and photovoltaic integrated electrolysis, PV+EC,) and photocatalysis (PC) to compare the solar to hydrogen conversion efficiency as well as to accurately track progress in device performance. At the same time, there is need to develop new approaches and improve experimental techniques for synthesis, for spectroscopy, for microscopy and modelling of PEC and PC devices to overcome the current limitations of recombination losses, in efficient use of incident photons and limited lifetime in realistic operating conditions. Within the next 10 years, it shall be necessary to scale PEC and PC based technologies from laboratory-scale proof-of-concept systems to demonstrator or pilot level (> kgs- H_2/day) production. This should be accompanied by suitable reactor designs that allow reliable and safe operation for high rates of hydrogen production. In the longer term, there is need to develop the capability to design and prepare highly performing and durable photocatalytic and photoelectrochemical materials on a commercial scale.

4.5 Emerging technologies

- Research questions/topics
    - Which emerging technology do you think is most promising?

Electrolysis of sea and waste water is an emerging area of interest especially for developing countries. Pure water is produced from electrochemical hydrogen utilisation.

In this field, it will be also important to promote the development of new systems, research on advanced materials for thermochemical cycles (chemical looping) with high conversion kinetics; fluid-dynamic and thermal optimisation of the redox reactor by direct coupling with solar concentrators; reactor/solar collector integration.

These include concentrated sunlight (CSP) eventually combined with thermodynamic cycles, artificial leaves, water electrolysis through combined and mechanical stresses (ultrasounds) and solar radiation, water electrolysis through the combination of magnetism and electrocatalysis, biologic processes etc.

Innovative technologies such as the production of hydrogen through water sono-phono-catalysis (solar energy and mechanical ultrasound stress) have recently emerged and need to address specific attention and research efforts.

4.6 Overarching issues

- Research questions/topics: Which main overarching topic do you see as more important for green hydrogen production?

Relevant aspects deal with:

- Quality of Hydrogen and **Hydrogen guarantees of Origin:**

Hydrogen quality guarantee as a product for specific applications (e.g. MetroHyVe European Project for mobility sector). Develop automation and quality control processes for continuous production of large volumes of Hydrogen. Quality control is also important for product manufacturing; other relevant aspects are quality assurance, standardization of (performance) tests.

Guarantees of Origin (GOs) can provide transparency on the GHG footprint of the produced Hydrogen, the hydrogen production technology, temporal and geographical origin of the hydrogen volumes and other potentially relevant attributes. (Example: European CertifHy project). Develop a single, consistent and reliable set of objectives. A necessary step is the development of protocols for measurement of the green hydrogen environmental impact based accepted environmental metrics.

System integration: Utility scale production technologies and Energy communities (distributed generation via H_2 production)

Hydrogen is at the centre of energy system integration, bridging electricity, gas and fuel infrastructures to make the system more efficient and flexible. Better integration of TEN-E and TEN-T networks, synergies between energy and transport networks can facilitate the flow of Hydrogen from its production point to crucial parts of the European transport and logistics network and make green hydrogen using electrolysis more affordable by reducing investment costs and providing a sustainable business/economical case for the H_2 producers and end-users.

- **Administrative barriers:**

For the development of common hydrogen market, data base for the legislative frame in every EU country (such as Fuel Cells & Hydrogen Observatory) should be supported and analysed and based on the results from the analysis a common EU legislative frame should be developed. This approach can be very useful for countries with less experience in hydrogen deployment

- **Circular economy**

Establishment of a robust value chain including implementation of measures to avoid shortages and vulnerability to supply chain bottlenecks for critical parts and components such as catalysts and membranes by discouraging monopolies of supply. Research into innovations for efficient and low-cost recycling of precious metals and other materials within Europe while minimising environmental impact. Develop seeds for business cases and models based on recycling of electrolysers. Investigate avenues to alleviate possible competition for resources such as PGM (fuel cells), nickel (steel and batteries), iron (steel) and cobalt (batteries).

4.7 Safety, pre-normative research

➢ Research questions/topics

- Which normative and pre-normative barriers need to be overcome for the diffusion of green hydrogen production?

Although considerable progress has been made recently at European and national level on regulation, the authorisation difficulties that all demonstration projects for green hydrogen production have encountered show that improvements are needed, remaining to be an issue at local, regional and national levels. Joint efforts are necessary to harmonise the regulatory framework for all applications, in order not to limit deployment on any region in Europe. This means that specific initiatives should be addressed in this regard involving policy, makers, stakeholders, experts and society. Specific programs should be addressed to the development of safety provisions for hydrogen production and usage, high-pressure storage tanks and towers, for high voltage components of electrolysers and fuel cells; safety for tunnels in the case of trains, airports and ports safety, safety problems associated with hydrogen/natural gas mixtures for the gas network, etc.

Standards and regulations: It is necessary to strengthen the standardisation work and insist on harmonization of hydrogen production standards, to support the development of the hydrogen energy industry and give full play to the supporting and leading role of the standard to the industrial development.

4.8 Raising public awareness, social acceptance and skills

➢ Research questions/topics

- What are the main points to consider in order to increase social acceptance?

When scientific results and innovative technologies are introduced into society, their social acceptance depends mainly on their reliability; the introduction of Hydrogen is not an exception. Hydrogen has characteristics that are different from existing energy technologies, as well as some historical prejudices associating the technology to the "hydrogen bomb" or even to the "Hindenburg disaster", and this makes it necessary to make an extra effort to ensure solid and fail-safe technology and to promote its social recognition and acceptance of the technology, in order to achieve its widespread use.

Also the fact that hydrogen has recently raised as some kind of "wave", "touching everything", is causing fear to general public: as occurred in the past with biofuels, accused on conflicting with food, now electrolysis is conflicting as regards water availability (even when water consumption is not so relevant).

Specific concerns of the society regard the cost of hydrogen and availability of water. Regarding water, to produce 1 kg of hydrogen, corresponding to a theoretical 39.4 kWh of energy based on the HHV, a minimum of 9 kg of water are required. Costs of hydrogen production are expected to decrease in the next years by effect of new policies, decrease of renewable energy cost, decrease of capital costs and scaling up of production plants. The aim is to achieve 2-3 Euro/kg H_2 target cost by 2030. Moreover, regarding the **Hydrogen Economy Cost,** there are still significant misunderstandings in society's cognition of hydrogen energy systems. New technology innovations lead to shorter product lifecycles and consumers often face the dilemma of choosing between keeping the existing product and upgrading to a recent version. They deal with stress and uncertainty. Some strategies include refusal, delay and extended decision-making.

Hydrogen production processes and technologies need experts with specific skills required but who also have an overall view of hydrogen-related supply chains. Training of dedicated personnel is essential, especially in the engineering sector, and it is necessary to retrain already trained personnel through technological updating and learning initiatives. A specific moment is the coupling of specialists from renewables and hydrogen production, and the building of new expertise. In addition, it is necessary to train the staff of the authorities in charge of control, safety, maintenance and authorisation as well as enhance school and university education in the field.

Important aspects to be addressed are:

Jobs creation and skills improvement: There is people's concern with fast-changing technologies-afraid to find a new job because they will not want to look like an incompetent employee. People think they lack the skills to succeed elsewhere in a new hydrogen economy. Even where jobs do disappear, people must have the training to lead to other job opportunities. In this context, it is necessary to establish the basis for educational and training strategies to ensure specialist's skills and knowledge is acquired in a time manner for industry needs, in order to provide requalification and define new certified qualifications, roles and related capabilities

In respect to public awareness, new forms of communication for knowledge and information enhancement are needed – more illustrative with higher impact, because consumers will govern the market. In this process hydrogen production as both energy carrier and important raw material for industrial processes which opens new jobs, has to find its place.

Common communication platform of the Agenda Process (common for the 3 main topics)

- Data base for research groups/research topics for future partnership
- Industrial platfom for industrial needs
- Civil society space

Educational materials for schools and universities have also been developed, as well as training programmes in areas such as safety. These aspects need to be further extended and rolled out in more languages to strengthen the public's access to such material.

5. Conclusions and main questions

A new approach is required for strategic programs on hydrogen production. It is necessary to create an integrated programme for the hydrogen supply chain, with sub-projects that are able to support the possibility of ensuring synergies, collaboration and critical mass in an interdisciplinary way addressing a wide TRL range (from 1 to 8).

The European Hydrogen Strategy foresees a huge demand of renewable hydrogen in Europe. It setting requires moving towards sustainability, cost effectiveness and capability to deploy. Tools are to be reinforced to foster knowledge translation into products and services, further developing the value chain.

A common standardisation and regulation framework should be in place, capable to generate and stand trust, to allow the necessary large investments.

Concerns and uncertainties from the society are to be faced. This transition needs to be properly managed.

The new programs should better focus on overcoming the specific challenges of the hydrogen production sector and the gaps related to hydrogen technologies. Workplans including indicators and specific objectives should be agreed through a broad participation of national bodies and by the systemisation of research activities in the sector. It is necessary to facilitate the creation of joint laboratories between academic organisations and industries while promoting the creation of spin-offs and start-ups. In general, it will be important creating a network of laboratories, able to systematise the existing resources in terms of both capacity and instrumentation. Facilities should be established in centres that already have a high level of specialisation by promoting broad accessibility on the basis of shared programs.

The most important advantage of a new European Partnership is its ability to coordinate otherwise fragmented stakeholder landscapes and act in a concerted manner across research, innovation, deployment point, as well as in horizontal and societal aspects without which impacts will fail to materialise or will be severely delayed. The public's acceptance of hydrogen energy needs active popularisation and education, in which the efforts of the government and scientific research institutions are needed. Relevant aspects are evaluation of social acceptance of H_2 technologies at the different levels of the value chain and looking at the different components of community acceptance, market acceptance and socio-political acceptance. Specific activities and demonstrative events to raise public awareness sufficiently according to the benefits of hydrogen technologies are required. Other aspects deal with development of educational targets, including service and specific events, e.g. summer and winter schools.

Since hydrogen technologies are emerging on the market, innovative approaches with demonstration accent should be developed for increase of the public awareness and acceptance, for manifestation the positive social impact of new jobs, of improved quality of air etc.