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1. Objective

This position paper comprises initial ideas, research questions and thought-provoking input to promote European competitiveness with regard to transport infrastructure for green hydrogen. It was developed by the designated expert group for Transport and Infrastructure of the agenda process on green hydrogen on the basis of a seed paper. Following a public consultation carried out in August and September 2021, the paper was further developed and refined in a thematic workshop on 7/8 October 2021 in Berlin. Key aspects of this final position paper have been incorporated into a joint strategic research and innovation agenda (SRIA), the main out-come of the agenda process on green hydrogen.

2. Catalogue of country-specific information

Definition of scope

Starting conditions for green Hydrogen in Europe may vary on the national or regional level. This concerns in particular the availability and readiness of transport infrastructures. In order to respect country specifics in the agenda process, the different initial situations need to be considered in terms of hydrogen strategies, transport capacities, R&I projects and hydrogen initiatives. In the following, some countries are described by way of example demonstrating the variety and complexity of the issue. As hydrogen projects currently have taken on significant momentum and the European energy system experiences quick changes, it is important to stress that these depictions reflect the situation as of September 2021.

2.1 Belgium

The federal government recognises the relevance of hydrogen for the country's energy transition and plans to establish an appropriate framework for innovative pilot projects and the development of a hydrogen backbone, using the existing gas grid as much as possible. Green hydrogen is also included in Belgium's recovery plans. Hydrogen should help to decarbonise transportation (cars, buses, trucks, rail, aviation, fluvial navigation), the residential sector and buildings, and industry (steel, cement, chemical industry). For the Walloon region, a hydrogen strategy is in preparation and will be published by mid-2021. The Walloon region aims to increase the share of renewable energies. Hydrogen from decentralised production is to be stored centrally in the long-term. A hydrogen strategy for the Flemish region was published in December 2020 and contributes to the Flemish and Belgian Energy and Climate Plan. A national hydrogen strategy has been published in October 2021. Inland green electricity for the production of green hydrogen will be used to a limited extent since currently only 8% of the total electricity consumption in Wallonia comes from renewable energy, in the Flemish region about 14%. Therefore, Belgium also foresees the import of green hydrogen. In line with the European Hydrogen Strategy, the Flemish region also sees a role for low carbon hydrogen in the transition phase (especially for decarbonising energy-intensive sectors) but will stimulate at the same time green hydrogen production.

Belgium is part of the Green Octopus project (designed by WaterstofNet as a contribution to the IPCEI Hydrogen Technologies & Systems). The project aims at developing a green and low carbon hydrogen economy along a cross-

border hydrogen backbone connecting the Sea Ports in Belgium and the Netherlands. Green Octopus is also looking for further cooperation with Germany and France. Fluxys, the Belgian gas infrastructure group, has commissioned a study on the conversion of gas infrastructure to hydrogen infrastructure. A recent study of the "Hydrogen Import Coalition", a strategic collaboration between DEME, ENGIE, Exmar, Fluxys, Port of Antwerp, Port of Zeebrugge and WaterstofNet, investigated the import of hydrogen (or synthetic fuels). The transport of green hydrogen bound to carrier molecules (LOHC) to Europe could be economically and technically feasible by 2030. These carriers could also serve as feedstock for the Belgian chemical industry. The report also emphasises the importance of an EU-wide Guarantee of Origin scheme and public-private funding. Belgium has an extensive private hydrogen network in place that is crucial for the hydrogen supply to important industrial clusters.

2.2 Romania

The Romanian energy system is currently highly dependent on fossil fuels, being in serious need of overhaul in order to sustain the upcoming energy transition. According to the latest information from the national regulatory authority, Romania has an installed power of 20,655 MW, with approximately 4,700 MW in coal power plants and 3,200 MW in gas-fired power plants. A substantial contribution of 6,100 MW comes from hydroelectric power. With just 2 MW of battery storage installed, the flexibility of the energy system currently relies on hydroelectric power plants and conventional generation based on coal and natural gas. Romania has a significant technical potential for energy production from renewable sources. It is several times higher

than the current total electricity consumption, but it is difficult to be integrated into the national energy system due to the intermittent nature of production and energy system safety reasons. Hydrogen will be essential for overcoming these issues.

According to National Energy and Climate Plan (NECP) estimates, the share of renewable sources in the gross final consumption of electricity is expected to increase to 49.4% (compared to 44% in 2020) by 2030, and in the field of transport to 14.2% (compared to 10% in 2020) in the context of additional measures and future policies. By increasing the RES capacities until 2030, it can be expected that there is a development potential for hydrogen production and use in many sectors. It is recognised that hydrogen, as an energy carrier, can support Romanian long-term energy security and clean energy production as well as the decarbonisation of industry processes, heating and transport sectors, but no concrete targets related to hydrogen are mentioned. Current Romanian legislation does not include sufficient details on future-proof systems and technologies.

An energy strategy and a hydrogen strategy for Romania are under development. Research, innovation and development of hydrogen-based technologies and fuel cells have received attention. Actions are carried out mainly in academia, in research centres affiliated to universities and in independent research centres. Industry has access to almost all the hydrogen production technologies currently in place worldwide, all of which are connected with functional industrial units with a purpose strictly related to the main industrial production. Among the projects developed or possible to be implemented under Horizon Europe by Romanian entities related to the

hydrogen transport and infrastructure are: HyUnder for assessment of large-scale underground storage of hydrogen, HyTeach for skills development in the hydrogen and fuel cell area, Green Hydrogen@Blue Danube for development of hydrogen production and transport using LOHC, Zero Urban Delivery @ Rainbow Unphycorm with applicability in the field of ecological hydrogen transport.

2.3 Czech Republic

The hydrogen strategy of the Czech Republic was officially published in July 2021 and reiterates Czech ambition to take part in an evolving hydrogen economy. The main focus is put on low-carbon hydrogen production (from renewables, steam methane reforming with CCS/CCU, municipal waste pyrolysis, and hydrogen from energy generated in nuclear plants) as one of the key elements to unlocking an emission-free future. According to the strategy, the Czech Republic will never become a self-sufficient country in hydrogen production, therefore an emphasis is put on hydrogen imports and hydrogen technologies, which could serve as an excellent export product with higher added value for Czech companies.

Today, the amount of hydrogen production and consumption (a little more than 100,000 tons per year) is mostly comprised of petrochemical and chemical industry. Main producers of hydrogen in the Czech Republic are located in the Ústí region (the first hydrogen valley initiative member from the Czech Republic). The predominant production methods so far are partial oxidation (POX), steam methane reforming (SMR) and electrolysis. The prognosis of consumption of low-carbon hydrogen is set to be around 100,000 t/a in 2030. The overall consumption

of low-carbon hydrogen is set to peak at around 1,700,000 tons of hydrogen in 2050. The Ministry of Industry and Trade believes that until 2030 the main sectors where low-carbon hydrogen will be used are the chemical industry and transportation sector. The Czech hydrogen strategy ponders the pros and cons of hydrogen production from renewables in the Czech Republic, where a relatively low number of sunny and windy days is prevalent. In order to ramp up production, the Czech Republic will try not to hinder any possible solutions in terms of alternative sources (organic waste incineration, fossil fuel reforming with CCS). Imports will therefore be crucial for the Czech Republic in the future to meet its demands. There are currently no hydrogen production targets for individual technologies such as electrolyser capacities or other low-carbon hydrogen technologies. The Czech National Action Plan for Clean Mobility from 2020 has set a non-binding target of 80 hydrogen refuelling stations (HRS) available in 2030. No other binding or non-binding targets for hydrogen are currently in place.

There is significant production of grey hydrogen corresponding to the demand from the national petrochemical and chemical industry. However, at this point there is no hydrogen infrastructure in terms of pipelines and HRS (2 expected to be opened later 2021 for public). There are currently no import terminals for hydrogen in place, nor are there any planned. Infrastructure in the Czech Republic is part of the European Hydrogen Backbone initiative. Private and governmental stakeholders are cooperating closely together mostly in terms of enabling crucial investments needed via public funds. At the moment, hydrogen is formally included in Czech legislation only as a fuel for transport and not

defined as gas in the Energy Act. However, this situation should change very soon.

The Czech natural gas infrastructure is reliable and well-connected at the domestic and European levels. Hydrogen is not a new topic for the Czech gas industry. More than 100 years ago, gas companies launched pipeline systems for the transmission and distribution of coke oven gas / municipal gas containing 50-60% of hydrogen. Technical modifications necessary for hydrogen transport in the existing gas system are possible. Although it will be necessary to make some modifications to the network, the requirements for investments in so-called repurposing (modification of infrastructure to pure hydrogen) and retrofitting (modification of infrastructure to a mixture of hydrogen and natural gas) are significantly lower compared to the newly built hydrogen infrastructure. Consequently, the main aim is to maximise the future potential in repurposing/retrofitting the current natural gas infrastructure for hydrogen since the Czech Republic is one of the transitional countries for natural gas nowadays and intends to keep its role in the future.

The Czech Republic will presumably never be at a forefront of green hydrogen production in Europe due to its environmental and geographical conditions. The overall target for production of low-carbon hydrogen and best cost-effective approach compliant with EU-wide rules should be studied further in order to ramp up hydrogen production. The Czech Republic is a heavily industrialised country and committed to reducing greenhouse gas emissions. The emission limits imposed by the European Green Deal could impact the competitiveness of these industries by putting a price on carbon. The challenge of transforming the all industries towards a more

sustainable approach of producing goods is therefore pricy especially in countries such as the Czech Republic. Industries affected by carbon pricing need to rethink their processes and start to use new low-carbon technologies which may ultimately lead to job loss due to restructuring. The peculiarities of each region, especially in terms of producing and importing low-cost low-carbon hydrogen should be considered as a prerequisite for limiting some types of hydrogen production on the EU-wide level.

2.4 Germany

Currently Germany is the largest producer of grey hydrogen in Europe, which is mainly produced via steam methane reforming, as a by-product from chlorine production and petro-chemical processes. The produced hydrogen is used on a large scale in refineries, ammonia production, and other chemical industries. Two large hydrogen transport networks in Western and Central Germany, amounting to a total of 370 km, are operated by the industrial gas companies Air Liquide and Linde to deliver hydrogen to the main industry customers. Another hydrogen pipeline with a length of 30 km is located in the North of Germany, owned by the refinery company Raffinerie Heide. Germany's leading role in hydrogen is also depicted by its number of hydrogen refuelling stations, which is currently 92, and therefore the highest number of HRS in Europe. Thanks to its pronounced chemical sector, German industry has already gained expertise with hydrogen infrastructures and has established local hydrogen and HRS networks.

In June 2020, the German government presented the national hydrogen strategy and set the framework for a German green

hydrogen economy, driving global hydrogen markets and hereby contributing to global climate protection. Due to its geographical location, Germany will become a transit country for European hydrogen transport, and partnerships with neighbour countries will be crucial. Furthermore, Germany has the highest share of bedded salt deposits and salt domes in Europe, which offer optimal conditions for the storage of hydrogen in salt caverns.

National hydrogen production, imports as well as transits, require a sufficiently connected hydrogen transmission and distribution network. The target is to use parts of the well-established natural gas network and connected storage systems and rededicate it to hydrogen. Additionally, new hydrogen pipelines will be built. In addition to the national hydrogen strategy, German transmission system operators designed a visionary hydrogen network of 5.900 km pipeline length across Germany in the network development plan in July 2020, consisting of 90% rededicated natural gas pipelines. This network plan represents a starting point to connect industrial demand and production centres of green hydrogen until 2030 and will be continuously extended.

According to the national hydrogen strategy, this German transformation process should aim at greenhouse gas neutrality in 2045. Regulations, as well as internationally accepted technical norms and standards, are important infrastructure requirements and have to be implemented or adjusted to establish a high level of infrastructure security and raise technology acceptance of hydrogen. A transitional regulation for hydrogen networks has already been implemented through an amendment of the German Energy

Industry Act (EnWG). It applies until there is a pan-European regulation.

Since the announcement of the national hydrogen strategy, a significant number of projects has already been realised or is under implementation. In the short term, an injection of green hydrogen into natural gas pipelines is carried out in order to understand blending effects on pipelines and slowly increase the hydrogen ratio. Currently, an injection of up to 10vol-% hydrogen into the natural gas (distribution) networks is allowed according to German regulations. As of 2021, there are at least ten implemented green hydrogen projects that feature blending in Germany, the earliest started around 2013. Recently, the number of pilot projects for hydrogen pipelines has been increasing, both for the rededication of existing natural gas pipelines as well as for new-builds. Foremost among these is the project Get H2 Nukleus which plans the first dedicated 130 km hydrogen network with non-discriminatory access in Germany by 2023. "Reallabore der Energiewende", an ideas competition organised by the Federal Ministry for Economic Affairs and Energy, includes several hydrogen projects with pipeline construction, such as Westküste100, H2Stahl, or the Energiepark Bad Lauchstädt project. Overall, at least twelve hydrogen pipeline projects have been announced in Germany until mid of 2021, the overall pipeline length amounts to over 280 km. The country's storage potential in salt deposits is being explored in EWE's HyCAVmobil project in Rüdersdorf in Berlin, whereas the conversion of natural gas storages into hydrogen storage is investigated by VNG in the realm of the HYPOS project cluster. Germany is also a center of LOHC research. LOHC – liquid organic hydrogen carriers – such as dibenzyltoluene, are a chemical storage option for hydrogen.

Currently, there are at least eleven LOHC research projects in Germany, among those AquaVenutus, TransHyDE/H2Mare, Get H2 and HECTOR.

2.5 Netherlands

In March 2020, the Dutch government released its hydrogen strategy, emphasising the importance of hydrogen for the energy transition and realisation of a climate neutral economy. The strategy takes up the target defined in the National Climate Agreement to scale up electrolysis capacity to 500 MW by 2025 and 3-4 GW by 2030. However, future green hydrogen demand of the country and the north-western European region cannot be met by offshore wind farms alone and thus requires import from overseas. Against this background, the Port of Rotterdam follows the vision of becoming an international hydrogen hub with an estimated annual throughput of 20 million tons of liquid, or chemically bonded (NH₃, MeOH, LOHC) hydrogen in 2050. By 2030, the port also plans to produce 1.2 million tons of climate-neutral hydrogen per year on own premises in a combined approach (electrolysers, CCS).

Timely development of a hydrogen infrastructure that can support the matching of supply and demand is an important element of the hydrogen strategy. At the moment, there are already various hydrogen transport pipelines operational in the Netherlands. Air Products, operates a private hydrogen network in the Rotterdam industrial area. This network delivers hydrogen to local industry through some 140 km of pipelines. Also, Air Liquide operates a private hydrogen pipeline network in the Netherlands. This network is part of a larger transboundary network that connects various production facilities and

large-scale hydrogen customers from the Port of Rotterdam to northern France. These pipelines are dedicated hydrogen pipelines and have a much smaller diameter (and thus capacity) than high-pressure natural gas pipelines in the Netherlands and elsewhere. In the Dutch province of Zeeland, a 12 km pipeline links up chemical companies Dow Chemical and Yara. Initially used for natural gas, this stretch of transmission pipeline has been used successfully for transport of around 400,000 tons of hydrogen annually since late 2018. Various projects have demonstrated that, with modest alterations, both existing transmission and distribution infrastructure can be used for hydrogen.

Currently a plan for a national hydrogen backbone is being developed. The plan provides for a phased realisation of a core network, which may already consist of 1,400 km of pipeline by 2030. The development will initially focus on connecting the five large industrial clusters in the Netherlands where large-scale hydrogen consumers are located. In addition, storage facilities in the network to be provided in the form of salt caverns and branches to neighbouring countries, in particular Germany and Belgium, are already being taken into account. 85% of the backbone is expected to consist of reused gas infrastructure. In addition, plans exist for a direct hydrogen pipeline routing from the Port of Rotterdam to the industrial hubs of Western Germany. This routing is part of the so-called 'delta corridor' project which would use existing pipeline right of ways and consist of a multi-core, multi-use concept enabling transport of LPG, propane as well as CO₂ along with bulk Hydrogen transportation.

Next to transport and distribution pipelines also hydrogen refuelling stations can be considered part of the hydrogen infrastructure (distribution of hydrogen for vehicles). The National Climate Agreement set the target of 50 refuelling stations, 15,000 fuel cell vehicles and 3,000 heavy-duty vehicles by 2025.

2.6 Spain

The Spanish Hydrogen Roadmap, published in October 2020, outlines some production and demand targets for 2030. With regard to production, 4 GW of installed capacity of electrolyzers is scheduled, which accounts for 10% of the European strategy target for 2030, estimating that there could be an installed capacity of 300-600 MW by 2024. As for the demand side, the set targets are: 1) a green hydrogen penetration in 25% of the industry's hydrogen consumption, currently estimated at some 500,000 t/a, 2) 100-150 public access hydrogen stations, 150-200 FCEV buses and 5000-7000 FCEV light and heavy goods vehicles, 3) two commercial lines of hydrogen-powered trains, 4) reduction of emissions by 4.6 million t CO₂eq. It is estimated that public/private investments of 8,900 million EUR will be necessary in order to achieve the objectives set out in the Roadmap. The Recovery, Transformation and Resilience Plan presented by the Spanish Government in April 2021 and approved by the European Commission in June 2021, estimates investments of 1,555 million EUR for the Renewable Hydrogen Roadmap.

The hydrogen transmission network in Spain can act as an enabler for the decarbonisation of Spanish industry by making the sustainable gas of the future accessible, offering flexibility and security of supply, which are indispensable for the continuity of industrial processes. The

use of current infrastructures in the short term will allow for the generation of demand and scaling up of green hydrogen production by injecting it directly into the natural gas grid (blending) as a temporary measure. The first sections of dedicated hydrogen pipelines to cover mainly industrial demand are expected to come into place from 2025.

The export potential of green hydrogen produced with enormous wind and solar resources in Spain supports the rationale for the development of a hydrogen gas corridor from North Africa and Spain, through France and up to Germany. The extensive gas network throughout Spain, connected to Morocco and Algeria, allows for the repurposing of numerous natural gas pipelines to be used with hydrogen, so that the renewable energy can be captured where it is produced. Enagás, together with other European TSOs, has promoted the European Hydrogen Backbone project, which comprehends an "initial vision" of the future European backbone network. Outlined in the 2035 "vision" of the European Hydrogen Backbone is a first international connection for green hydrogen through the west of the Pyrenees (Larrau) to the south and east of France, where there are geological cavities, which can store this sustainable gas. The adaptation and new ad hoc developments on the eastern axis of the gas network in France connect with the hydrogen network in Germany. This initial international connection will be reinforced and completed in 2040 with a connection through the Basque Country (Irun) and with the development of a third interconnection through Catalonia.

3. List of research questions

The following list contains questions and thoughts on transformation requirements for infrastructure and research priorities. It addresses not only the problem of where and how to start the transformation in the description of research priorities, but also respects the complexity of the transformation and the importance of integrating the system as a whole when establishing a transport infrastructure for green hydrogen.

I. Strategic elements of the transformation towards a hydrogen infrastructure

Hydrogen is not new to people and industry, it has a rich history as an energy carrier (coal-based town gas) and feedstock in (petro-) chemical industry (ammonia syntheses, plastics production, fuel production). Minor applications are in metallurgy, as fat hardening reactant, as coolant or as a protective gas. Despite of more than 100 years hydrogen-handling experience, hydrogen is commonly best known for its oxyhydrogen-reaction and for being a historical lifting gas in airships.

Hydrogen production

- 1) How much hydrogen can be expected from national and European sources and what fraction has to be imported globally in the time horizons 2030, 2040 and 2050?
- 2) How should hydrogen be certified for the carbon footprint of its production process?
- 3) What is the potential for the production of low carbon hydrogen from alternative sources (pyrolysis of

natural gas with CCSU, pyrolysis or plasma gasification of waste, nuclear power plants) in Europe?

Infrastructure options

- 4) Should the integration of green hydrogen be based on a European hydrogen backbone infrastructure from the beginning or will national hydrogen infrastructures be sufficient and more adequate for the initial period until 2030? What will be the long-term perspective for a European hydrogen backbone? How could the two systems best complement each other? What is the desired balance between privately owned infrastructure along with open-access systems?
- 5) What will be the role of container-based transport of hydrogen and hydrogen derivatives versus the transport via hydrogen pipelines in a diverse European context in the transition period until 2030 and in the long term?
- 6) What are the most viable storage options for green hydrogen (physical vs. chemical)?

Planning and regulation

- 7) Should electrolyzers be located close to the centres of renewable energy supply and storage options centrally in the grid or both rather in the vicinity of demand? Do we need a European coordination for the infrastructure planning or an integrated decision process for infrastructural development in order to integrated H2 efficiently (from

technological and cost perspective)
into the energy system?

- 8) Should we plan infrastructures for hydrogen and electricity in an integrated framework or independently?
- 9) How can the decision processes for hydrogen network planning account for the uncertain demand, production sites and import routes, while also accounting for the vital mid- and long-term role for decarbonisation?
- 10) What are the requirements for institutional changes for regulating infrastructures (institutional resources, new regulatory arrangements)?
- 11) What are requirements to change the commodity for existing pipelines (e.g. new approval, dependent on H₂ concentration)?
- 12) How to adapt current long-term contracts for the transmission of natural gas in case of the transformation to hydrogen transmission?
- 13) How to engage with citizens to have their support for large-scale new H₂ infrastructure?

II. Research, development and transformation needs towards a hydrogen infrastructure

- 14) What is the state of H₂-readiness level (i.e. 100% H₂-readiness as well as readiness for H₂ blending) of established technologies? What is the economic feasibility of hydrogen technologies (e.g. cost of

electrolysers) in the respective countries?

- 15) What are the main challenges to be addressed by research, development and innovation in the field of safety of hydrogen infrastructures in particular regarding material development and sensor technologies?
- 16) What are the main challenges to be addressed by research, development and innovation in the field of transport options based on hydrogen-derivates like ammonia and LOHC?
- 17) What are the main challenges to be addressed by research, development and innovation in the field of liquid hydrogen transport?
- 18) How important is the discovery of new pathways for production and use of hydrogen and how relevant is the related fundamental science?
- 19) How could regulation, standardisation and certification of new infrastructure components and systems enable the diffusion of green hydrogen in Europe?
- 20) What analytical tools and methods are needed to provide decision support for building-up a new hydrogen infrastructure?

4. Expected impacts

Depending on the particular research question and the specific field to which it relates, various scientific, societal and/or political impacts are possible. Some general impacts are listed exemplarily below. They are further examined in the SRIA.

- Support regulatory bodies and decision making
- Inform broader society
- Demonstrate feasible option and learning experience through demo projects
- Prevent or limit adverse side effects when developing H2 infrastructure
- Prioritisation of industrial and public R&D activities
- H2 planning guidelines and standardisation
- Ensure technology leadership