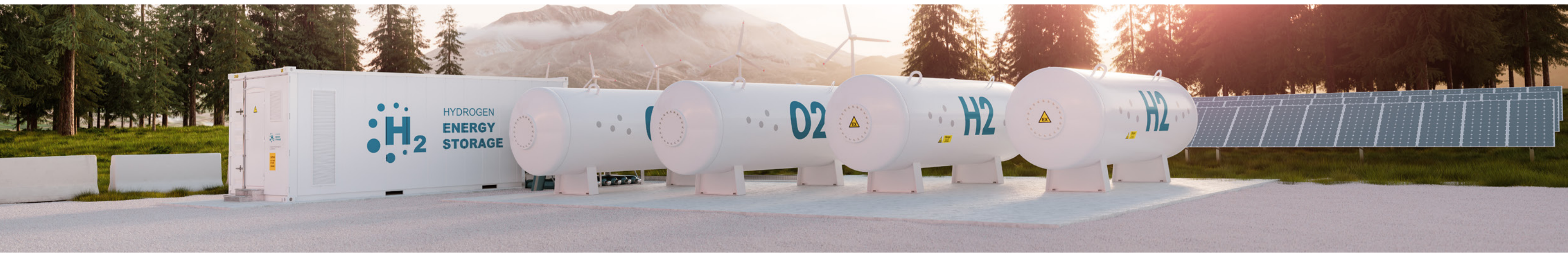

Hydrogen: From Star of Oil Refining to Sustainable Fuel of the Future

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Hydrogen, while still being an essential reactant in oil refining to produce clean hydrocarbon fuels, will play a fundamental role as sustainable fuel to reach global decarbonisation in 2050. National and international, institutional and private collaboration and initiatives must and are facilitating the transition. Physical and chemical properties of hydrogen are very different from today's fuels, requiring special safety measures and equipment materials and designs for its production, storage, distribution, and use. Not all hydrogen is sustainable. It depends on how it is produced. Production cost is still high but new processes are being developed to reduce it. Hydrogen will power transport directly as a fuel, or by means of a hydrogen fuel cell were the use of sustainable electric power is more challenging or expensive.The transition will cause the loss of jobs but will create many new ones..

KEYWORDS: Hydrogen, Initiatives, Properties, Production, Sustainability, Applications, Fuel cell.

El hidrógeno, si bien sigue siendo un reactivo esencial en la refinación del petróleo para producir combustibles de hidrocarburos limpios, jugará un papel fundamental como combustible sostenible para alcanzar la descarbonización global en 2050. La colaboración e iniciativas nacionales e internacionales, institucionales y privadas deben y están facilitando la transición. Las propiedades físicas y químicas del hidrógeno son muy diferentes a las de los combustibles actuales, lo que requiere medidas de seguridad y materiales y diseños de equipos especiales para su producción, almacenamiento, distribución y uso. No todo el hidrógeno es sostenible; depende de cómo se produzca. El costo de producción sigue siendo alto, pero se están desarrollando nuevos procesos para reducirlo. El hidrógeno impulsará el transporte directamente como combustible, o por medio de una pila de combustible de hidrógeno donde el uso de energía eléctrica sostenible es más desafiante o costoso. La transición provocará la pérdida de puestos de trabajo, pero creará muchos nuevos.

PALABRAS CLAVE: Hidrógeno, Iniciativas, Propiedades, Producción, Sostenibilidad, Aplicaciones, Pila de combustible.

INTRODUCTION

The evidence of human influence on climate change has become very clear according to the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) of more than 900 scientists and 195 governments and released in August 2021 [1].

Sustainable hydrogen will play an essential role in fighting climate change in sectors where electrification is technologically very challenging or too expensive. The organizers of the Achema 2022 Congress acknowledge the importance of the development of a hydrogen economy dedicating a special session to it saying that *"Hydrogen will play a central role, especially within the process industries, the transportation sector and the energy systems in general"*.

Industries with no alternative to the consumption of fossil fuels will have to apply CO_2 capture and storage (CCS) to become carbon neutral. (Already in 2007 the European Commission set CCS as an objective for 2020!).

Besides hydrogen, also sustainable are "drop-in fuels", i.e. synthetic substitutes of petroleum-derived hydrocarbon fuels, produced by a solar-driven thermochemical synthesis process from H_2O and CO_2 captured directly from ambient air. The evolution towards hydrogen will be progressive passing through a transition phase of coexistence with biofuels and synthetic hydrocarbon fuels [2, 3].

The physical and chemical properties of hydrogen are very different from today's hydrocarbon type fuels requiring special safety measures, equipment designs and materials for its production, storage, distribution and use as transportation fuel. Not all hydrogen is equally sustainable. It depends on how it is produced. The *"UN High Level Climate Action Champions"* (a "bridge" between the presidency and national governments, businesses, investors, cities and other sub national governments, and civil society) have launched guidelines to help to streamline the production and use of clean hydrogen. Some estimates predict that more than 50 % of the global renewable electricity capacity could finally go to hydrogen production. According to the Hydrogen Council, a global CEO-led initiative of leading companies, global demand for renewable and low-carbon hydrogen could grow by 50 % by 2030 if a significant scaling up of production, infrastructure and end users takes place. International collaboration of governments, policy makers, funders, businesses and research institutions is necessary to accelerate the development of a Hydrogen economy on a world scale [4-6].

» Some estimates predict that more than 50 % of the global renewable electricity capacity could finally go to hydrogen production

DISCUSSION

MILESTONES OF PUBLIC AND PRIVATE HYDROGEN INITIATIVES

In September 2018 an EU Hydrogen Initiative was launched by the Council of the European Union with the aim to maximize the great potentials of sustainable hydrogen technology for the decarbonisation of the energy system in multiple sectors of the industry, transport, and mobility. The Initiative was supported by 26 Member States, 2 EFTA states, the European Commission and approximately one hundred European companies, organizations, and institutions. (Including Spain and its National Hydrogen Centre at Puertollano).

On December 12th 2018, at the COP24 in Vienna, an Expert Group Meeting took place, organized by the United Nations Industrial Development Organization (UNIDO). 169 States are members of UNIDO including Spain. The experts considered that the decarbonisation of the global energy system might be hard to achieve without widespread application of hydrogen technologies. UNIDO experts fixed the target prices of hydrogen at $3/kg by 2030 and $2/kg by 2050 [7].

On July 8th 2020 the European Commission announced the European Clean Hydrogen Alliance (ECH2A) as part of its Hydrogen Strategy for a Climate Neutral Europe, including industry, public institutions, the research and innovation community, and civil society, with the aim at an ambitious deployment of hydrogen technologies by 2030. 997 Projects were elected in June 2021 [8].

Three months later, on October 6th 2020, the Spanish Council of Ministers approved a "Hydrogen Roadmap", a commitment to renewable hydrogen with a 100 % renewable electricity system not later than 2050 [9].

In April 2021 the Energy Transitions Commission, a coalition of more than 45 leaders from global energy industries, financial institutions and environmental advocates, released a report analyzing the feasibility of achieving a net zero greenhouse gas emissions (GHG) economy by 2050 and the actions it required. They foresee that sustainable electrification will be at the heart of this transformation enabled by the rapidly falling costs of renewable energy, with a complementary role for clean hydrogen technology in sectors that are difficult, impossible or too expensive to electrify [10].

On July 14th 2021 the European Commission announced the "European Green Deal", by which all 27 EU Member States committed to turn Europe into the first climate neutral continent by 2050 and to promote hydrogen in industry and transport. The commitment was converted into a European Climate Law [11].

From November 29th to December 3rd 2021 a "European Hydrogen Week" took place which brought together the European industry, policy makers, government representatives as well as the research community to discuss and steer the potential and opportunities for clean hydrogen in the upcoming years in the different sectors of the economy. A "Clean Hydrogen Partnership" was launched by the European Commission, Hydrogen Europe and Hydrogen Europe Research, representing more than 300 companies, and 30 national associations, and including over 750 projects. A panel discussion with industry and research representatives assessed the key actions that need to happen for clean hydrogen to make the road to 2050 a success. "*Clean hydrogen is the energy of the next generation*" said President Ursula von der Leyden in her opening speech, and that more than 200 new hydrogen projects had been announced globally, 55 per cent of them in Europe. The EU will support Clean Hydrogen with one billion euros for the period 2021-2027, complemented by at least an equivalent amount of private investment by the private members of the partnership (on 18 May 2022 the EC announced a "REPowerEU Plan" of an additional investment of € 200 million available for the Clean Hydrogen Partnership through the Horizon Europe Programme. The funds will help double the number of Hydrogen Valleys in Europe. (REPowerEU is the EU's plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition). RePowerEU announced also future measures to develop the skills for the hydrogen economy through Erasmus +.

On December 15th 2021, the European Commission issued new proposals to decarbonize gas markets, promote hydrogen and reduce methane emissions. One of the aims is to establish market rules which will be applied in two phases, before and after 2030, and notably cover access to hydrogen infrastructures, hydrogen production and transport activities, and tariff setting. A European Network of Network Operators for Hydrogen (ENNOH) would be created to promote a dedicated hydrogen infrastructure, cross-border coordination and interconnector network construction, and elaborate specific technical rules.

This year 2022 high level Hydrogen events have taken place: in May a World Hydrogen Summit & Exhibition in Rotterdam, dedicated to hydrogen industry's advancement, and a European Hydrogen Energy Conference in Madrid about hydrogen and fuel cell science and technology; and in June a Hydrogen Summit "Accelerating the Energy Transition" has taken place in London.

HYDROGEN PROPERTIES

Hydrogen is the simplest of all elements but is complicated to handle. At normal conditions it is lighter than air. It is odorless, colorless, tasteless, and not toxic. It has the lowest boiling and melting points of all substances second only to helium, and the highest heat conductivity and diffusion coefficient of all gases. It can explode when put in contact with oxygen at about 500 °C or in contact with a catalyst, a spark, or a flame. When burned hydrogen produces only water vapor. Hydrogen has a much higher specific energy than any hydrocarbon fuel.

The Table 1 shows some hydrogen properties compared with those of

TABLE 1.

SOME PROPERTIES OF HYDROGEN COMPARED TO OIL DERIVED TRANSPORTATION FUELS

	Hydrogen	Jet Fuel – Jet A1 (Kerosene type)	Diesel oil
Physical State at 20ºC	Gas	Liquid	Liquid
Molecular Weight, g/mol	2	170 approx.	250 max. approx.
Liquid Density	0,0708 at -253ºC and 1 atm.	0,775-0,830 at 15ºC approx.	0,850 at 15ºC approx.
Vapour Density	0,08376 kg/m3 at 20 ºC, 1 atm.	-	-
Melting/Freezing Point, ºC	-259,24	-51max.	-12 approx. (gel)
Boiling Point (or range), ºC	-252,78	150-288	150-370 approx
Heat of Combustion, MJ/kg	120	42,8 minimum spec.	42-46
Liquid Energy Density, MKJ/m3 (*)	-8,491	-38,346	-37,184

(*)The values given are negative as they represent the energy lost by the fuel. Ref: [12-16]

kerosene type jet fuel and diesel oil which it will substitute.

The small molecules of hydrogen gas diffuse through many materials, such as nickel and palladium, which can be used to purify hydrogen. This property makes hydrogen more difficult to contain than other gases. Hydrogen leaks pose a potential hazard. A fire or explosion occurs when a spark is provided to a mixture of hydrogen and oxygen releasing a substantial amount of heat.

Hydrogen has the highest energy per mass among all fuels, but its low density at ambient temperature results in a low energy per unit volume. For example, liquid hydrogen needs about four times the volume for the same amount of energy as kerosene based jet-fuel. But the amount of energy liberated during the combustion of hydrogen, on a mass basis, is up to three times the heat of combustion of common hydrocarbon fuels, and the energy of a hydrogen gas explosion is about 2.5 times that of such hydrocarbon fuels.

Hydrogen is flammable and explosive over a very wide range of concentrations in air (4–75 % and 15–59 %) at standard atmospheric temperature. But in many respects, hydrogen fires are less dangerous than gasoline fires. Hydrogen gas rises quickly, and consequently hydrogen fires are vertical and highly localized. Also, hydrogen burns more vigorously than gasoline, but for a shorter time. Hydrogen emits non-toxic combustion products when burned in contrast with gasoline fires that generate toxic smoke.

Hydrogen has low electro-conductivity, the flow or agitation of hydrogen gas or liquid may generate electrostatic charges that result in sparks. For this reason, all hydrogen conveying equipment must be thoroughly grounded. Hydrogen's high energy density and its extremely high combustion temperatures (up to 2,800 °C) make it suitable for steel, aluminum and cement production industries. Hydrogen does not exist in its molecular form on earth. Hence it must be produced from compounds such as water or hydrocarbons [17].

The minimum quality characteristics of hydrogen fuel for utilization in vehicular and stationary applications are specified by the International Standards Organization in standard ISO 14687:2019: *"Hydrogen fuel quality - Product specification"*.

HYDROGEN PRODUCTION AND SUSTAINABILITY - THE "COLOURS" OF HYDROGEN

Hydrogen is labeled with different "colours" depending on the sustainability of the prime material and the production process. Until now, world production of hydrogen has been responsible for emissions of hundreds of million tons of CO_2 per year, because it is mostly produced in oil refining by catalytic reforming of naphtha and steam reforming of refinery fuel gas or light naphtha. This hydrogen is not sustainable it is called **"Grey Hydrogen"**. Today however this hydrogen is still an essential element of oil refining, because it has a very important positive environmental and health effect by removing sulfur and nitrogen compounds from heating and transportation fuels, and producing smokeless jet fuel as well as healthier solvents eliminating aromatic hydrocarbons by catalytic hydrotreating. [18]

Hydrogen is also produced by steam reforming and partial oxidation of natural gas, which contains about 95 % of methane (CH_4), a strong greenhouse gas which, according to the United Nations Environmental Program, UNEP, has caused about 30 per cent of global warming since pre-industrial times. Typically, 0.299 kg of hydrogen is produced per kg of natural gas. This hydrogen is also called "Grey Hydrogen". However if the CO_2 by-product is captured efficiently and fixed in a sustainable way, then this hydrogen is sustainable and is called "Blue Hydrogen". The competitiveness of blue hydrogen depends on the development of viable technologies for CO_2 capture, storage, and use.

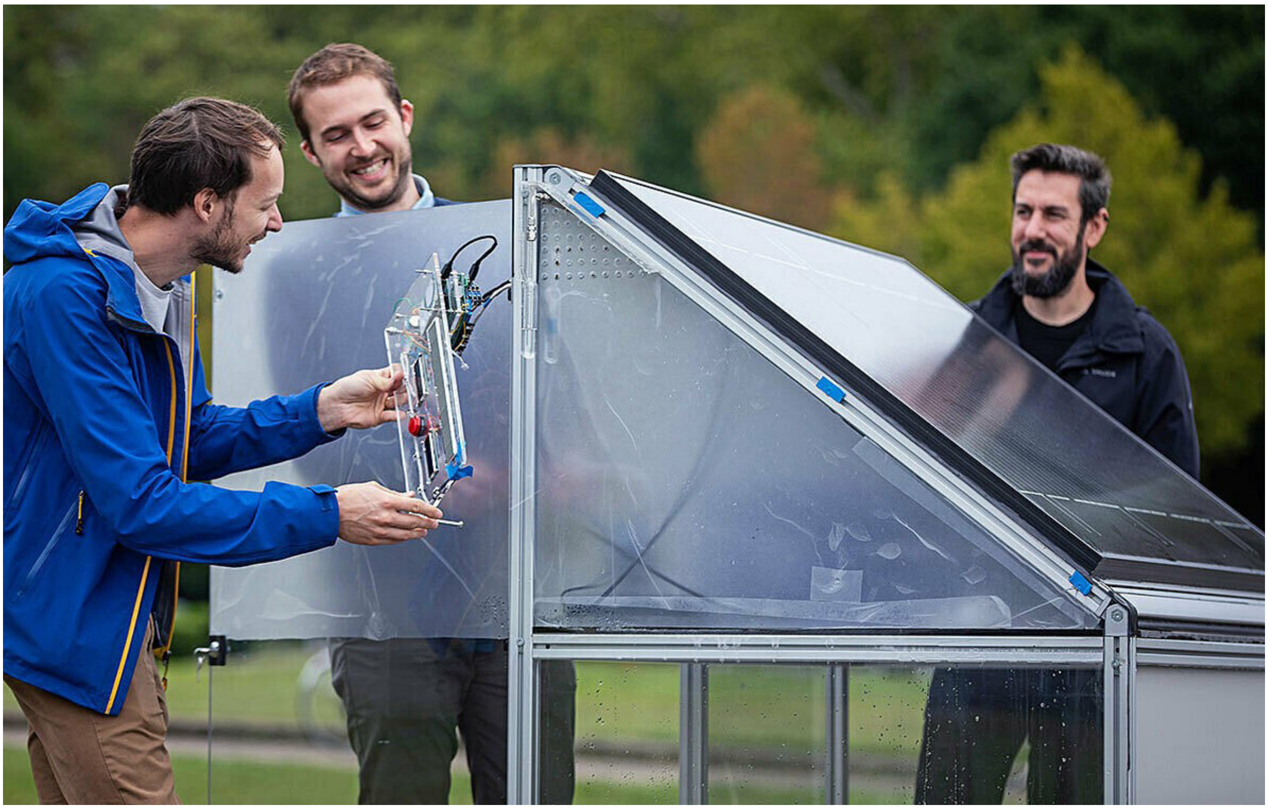
"Turquoise Hydrogen" is produced by pyrolysis of methane from natural gas using renewable energy, converting it into hydrogen and solid carbon. It is sustainable if the natural gas is extracted and processed without emissions and if the carbon produced is not combusted but fixed or storaged.

"Green Hydrogen", is obtained by electrolysis of water using electricity from a sustainable energy source (wind, solar, hydro) with zero emission of CO_2. Also nuclear energy may supply the electricity to produce sustainable hydrogen, which in this case is called **"Pink Hydrogen"**.

Hydrogen produced from biogas, a mixture of 55-65 % methane, CH_4, and CO_2, using a multistep process, including mainly biogas reforming, water-gas-shift reaction, and hydrogen separation, may also be considered as "Green Hydrogen". Repsol has produced for the first time renewable hydrogen from biomethane obtained from solid urban waste. The European Commission adopted on 15 December 2021 a "Methane Strategy" of the European Union with proposals to reduce methane emissions in the energy sector in Europe [19, 20].

To reach the maximum 2 °C increase target of the Sustainable Development Goals, the production of several hundreds of millions of tons of green hydrogen would be necessary representing between 10 and 20 percent of world energy consumption. This will not be easy because it will require a strong increase of

FIGURE 1. Solar hydrogen panel, Solhyd project - courtesy of university KU Leuven



renewable electricity production and storage. (The European Union aims to increase renewable electricity by 6 GW of capacity in 2024 and to 40 GW by 2030. In 2020 Spain's renewable energy production reached already 44 % of the total. The Spanish company Iberdrola is a world leader of sustainable electric power production and increased its capacity in 2021 by 9.2 % reaching more than 38 000 MW, and plans to reach 60 GW in 2025 investing 14 300 millions of Euros. Of the new installations 76 % are photovoltaic) [21-23].

REDUCING HYDROGEN PRODUCTION COSTS

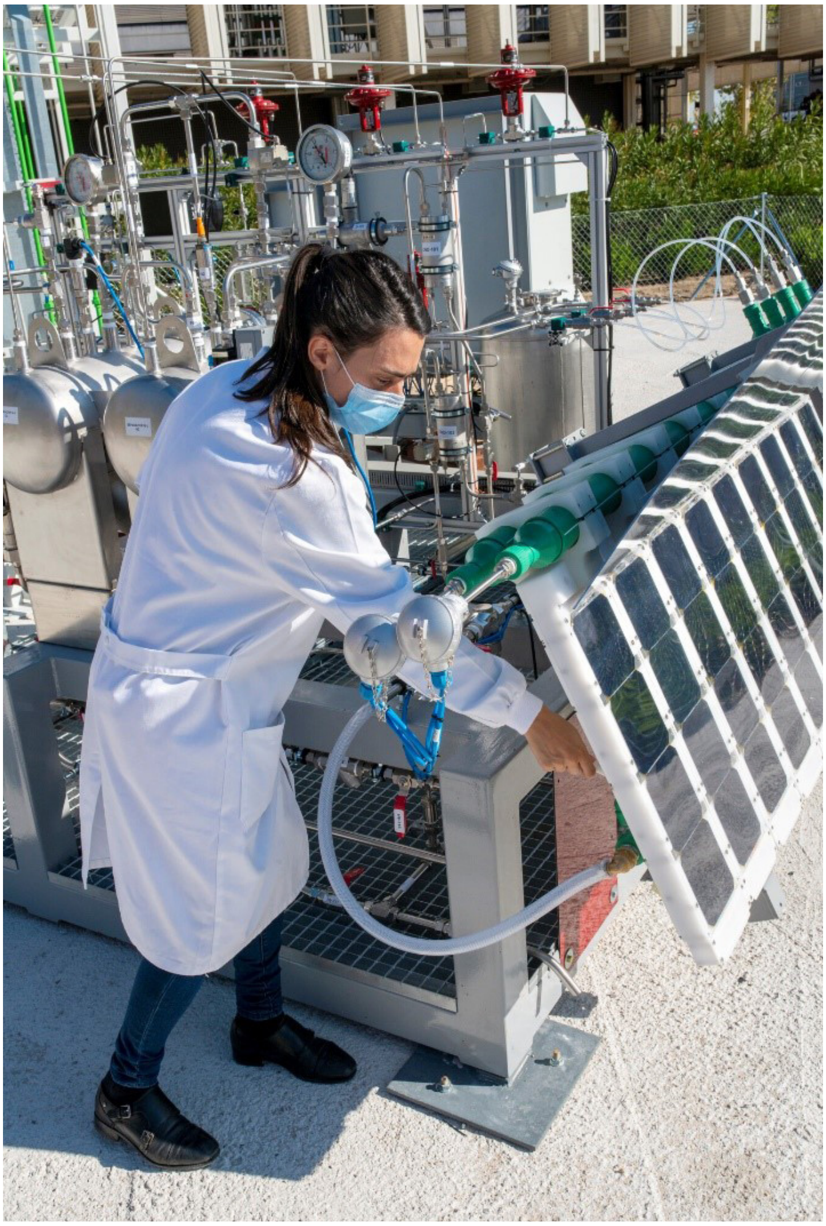
The cost of green hydrogen produced from renewable electricity is still high, because the electrolysis process is very energy-intensive, and varies with the geographic location. It is several times more expensive than grey hydrogen, but costs are falling because electrolyser manufacturing technology is improving and solar and wind energy costs are declining. Capital costs will come down with the massive scaling up of electrolyser capacity and the appearance of new technologies (more than 300 patents have been filed during the last 20 years). Electrolyser costs are expected to halve in 2030, also because of economies of scale. The price of solar energy has fallen 85 % since 2010, while wind power is half as expensive. Estimates indicate that the cost to produce green hydrogen could be reduced by 64 % by 2040.The EU plans to invest $430 billion in green hydrogen by 2030, installing at least 6 Gigawatt of renewable hydrogen electrolysers by 2024 producing up to one million tons of renewable hydrogen, and installing at least 40 Gigawatt of electrolysers by 2030 producing up to ten million tons of renewable hydrogen [24-28].

The following are two examples of new green hydrogen production processes that are being developed:

1- Scientists of the Centre for Surface Chemistry and Catalysis of the Belgian university KU Leuven, lead by Professor Johan Martens, have developed, as part of the Solhyd project, a "solar hydrogen panel" that converts moisture in the air directly into green hydrogen and oxygen (Figure 1). The cost to produce hydrogen via the panel is claimed to be much lower than generating electricity with solar panels followed by production of hydrogen by electrolysis. The panel is being field-tested before its commercialization this year. (Note: KU Leuven is first on the Reuters ranking of innovative universities in Europe) [29].

2- Another new one step green hydrogen production process is being developed by Sunrgyze, a company constituted in 2021 and owned by Repsol and Enagas, with the collaboration of several Spanish research centers. The process, called "photoelectrocatalysis", uses a device that receives directly solar radiation and a photoactive material generates the electrical charges that cause the

FIGURE 2. Photoelectrocatalysis pilot unit of Repsol and Enagas - courtesy of Repsol



splitting of water into hydrogen and oxygen. A pilot unit has been assembled and tested for more than 4,000 hours at the Repsol Technology Lab in Mostoles near Madrid (Figure 2). A demo plant will start up in 2024 in Puertollano with a daily production of 100 kg of green hydrogen. Commercial maturity of the process is foreseen before 2030 [30].

SPANISH GREEN HYDROGEN PRODUCERS.

Presently the leaders of green hydrogen production in Spain are Repsol (and its Basque subsidiary Petronor), and the electric power company Iberdrola.

Repsol and Petronor will undergo a profound and progressive transformation from oil companies into sustainable energy companies. Since 2021 the development of the hydrogen value chain for Repsol is lead by its Hydrogen Director and President of Shyne, Tomás Malango. As the transition to a hydrogen economy will also require new skills, Repsol and Petronor have launched in 2021 an interuniversity master's degree in Hydrogen Technologies in collaboration with various Spanish universities.

In October 2021 Repsol announced its intention to install in the Iberian Peninsula a renewable hydrogen capacity of 552 MW in 2025 and 1.9 GW until 2030.This will require to increase 200 times the production of electrolysers and to meet the objectives established in the European Hydrogen Strategy (40 GW in 2030), with a total investment of 2549 millions of Euros [31, 32].

On 8 November 2021, at the Guggenheim Museum in Bilbao, Petronor and Repsol launched the Basque Hydrogen Corridor, BH2C, a project with the participation of 78 organizations (8 institutions, 12 knowledge centres and business associations and 58 companies). The project aims to advance with the decarbonisation of strategic sectors such as energy, mobility, industry, and services. The project is part of the Hydrogen Roadmap of Spain. On May 27 of this year work was started on a Decarbonisation Hub in the Port of Bilbao with an investment of 103 million euros intended for the production of synthetic fuels with water and CO_2 removed from the atmosphere. This plant will be powered by renewable hydrogen produced by a 10 MW electrolyser [33].

In January 2022, Repsol launched Shyne (Spanish Hydrogen Network), a project of a consortium of official institutions and companies from the energy, industrial and transport sectors with the collaboration of technological centres and universities, to lead the development of renewable hydrogen in 10 autonomous communities of Spain. Total investments amount 3230 million euro, and many new enterprises and more than 13000 employments requiring new skills will be created. The goal is to install 500 Megawatt (MW) in 2025 and two Gigawatt (GW) in 2030 to produce green hydrogen, the largest in Spain for this purpose [34].

Repsol has already signed collaborating agreements with Talgo and Alsa to promote the decarbonisation of rail and bus transport. The Official College of Industrial Engineers of Madrid has awarded its honourable mention to the "*most innovative company*" to the Repsol-Talgo alliance for its promotion of the development of the hydrogen train [35].

Iberdrola is part of an international initiative of industry leaders called the "Green Hydrogen Catapult", targeting the deployment of 25 Gigawatt of renewable-based hydrogen production by 2026. It has the intention to invest 3000 million Euros for the production of green hydrogen in more than 60 projects in eight countries, and has already started up a plant in Puertollano, the largest for industrial use in Europe with an investment of 150 million Euros. The plant is made up of a 100 MW photovoltaic solar plant and one of the largest hydrogen production systems through electrolysis in the world (20 MW). It can produce up to 3,000 tons of renewable hydrogen per year to be used in the local ammonia factory of Fertiberia and will allow the manufacture of fertilizers without using fossil fuels [36].

Apart from the above companies, a joint venture of ArcelorMittal, Enagas, Fertiberia Group and DH2 Energy, called HyDeal Ambition, was launched in February 2021with the participation of 30 European companies. The project includes the production of green hydrogen generated by solar-driven electrolysis in the Iberian Peninsula with the ambition to achieve 95GW of solar and 67GW of electrolysis capacity by 2030 to deliver 3.6 million tons of green hydrogen per year to users in the energy, industry, and mobility sectors at €1.5/kg before 2030 [37].

HYDROGEN STORAGE, TRANSPORTATION, AND USE

Because the chemical and physical properties of hydrogen are very different from today's liquid fuels, current equipments, designs and materials cannot be used. Hence storage, pipelines, container equipment, burners, heaters, etc. need to be specifically designed or adapted for hydrogen. Hydrogen can be stored physically, chemically, and geologically. It can also be used to storage excess renewable electric energy. The International Organization for Standardization has created hydrogen technology standards, ISO/TC 197, in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen for manufacturers, sellers, buyers, customers, trade associations, users or regulators. They cover different management areas such as quality, environment, health, safety, energy, etc.

Physical storage is as a high-pressure gas (200 - 700 bars) in special metal or composite cylinders, bottles or tanks. Mechanical strength of these materials is important. Hydrogen can also be stored as a cryogenic liquid in strongly insulated low pressure vessels at -253°C and max. 5 bars. Until recently, storing hydrogen in the liquid form was reserved for certain special applications in high-tech areas such as space travel, for example the European rocket Arianne 5. Where available, geologic storage such as salt or rock caverns can be used for significant quantities of hydrogen.

Chemical storage can be done in nano-structured materials which encapsulate hydrogen in the form of metal hydrides at ambient temperature and pressure. An example is to form solid metallic hydrides through the reaction of hydrogen with certain metal alloys. The most promising materials are composed of magnesium and alanates (Alanates are composed of a "complex anion" [AlH4]– or [AlH6]3– and respective cation). But the drawback of this technology is that only a low weight of hydrogen can be stored in these materials. To maintain the energy equivalence of hydrogen with diesel oil, 4.5 kg of metal hydride are required to replace one kilogram of diesel [38-46].

Transportation. Compressed gaseous hydrogen is most transported by tube trailers with several high-pressure and refrigerated steel cylinders varying in length from about 6 meters for small tubes to about16 meter on jumbo tube trailers. Each cylinder typically contains about 5-8 Nm^3 of hydrogen at pressures ranging between 150–300 bar.

Hydrogen will be used in the transport sector, especially in cars, heavy-duty and long-distance trucks, buses, airplanes, and ships. (Many test units are circulating already). Advantages of hydrogen in the transport sector are, for example, that hydrogen trains can travel up to 1000 kms with one hydrogen charge and at a maximum speed of 140 kilometres per hour. Each refuelling process takes about 15 minutes, about the same as of a diesel train.

> » Chemical storage can be done in nano-structured materials which encapsulate hydrogen in the form of metal hydrides at ambient temperature and pressure

Hydrogen is suited for the direct propulsion of aircraft. Big long-range airplanes could burn hydrogen in modified turbines. Only 9 tons of hydrogen would be needed to obtain the same energy as 23 tons of kerosene on board of an Airbus A320. Airbus is working on the design of liquid hydrogen cylinder type storage tanks at -253°C made with a multilayer material that reduces losses by radiation. The tank is also made up of two envelopes separated by an empty space, such as the cryogenic tanks that are already used in the aerospace industry (for example the already cited Arianne rocket). According to the Iata, by 2040 a hydrogen aircraft for short-haul flights (100-150 seats, 45-120 min flights) would become available. For shorter distances and less seats electric airplanes may be more advantageous. Refilling the hydrogen tank of a car takes still less time than recharging the battery of an electric car, although the time of the latter is being reduced.

Existing natural gas pipelines may be used when a low concentration of hydrogen is injected. Nortegas, the second natural gas distributor in Spain, has launched H2SAREA, a research project for the safe injection of hydrogen into the natural gas network. To transport large hydrogen quantities repurposing existing pipelines is required. In Spain eight companies from the energy sector and six research centers coordinated by Enagas, have united in May of this year in a consortium called GreenH2Pipes, with the intention to promote the generation, injection and future transportation of hydrogen through the existing natural gas network as well as its storage [47-50].

Where direct use of hydrogen combustion or electric power is difficult and/or more expensive, a hydrogen fuel cell is used. A hydrogen fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as by-products. A hydrogen fuel cell produces zero harmful emissions. A typical example of a hydrogen fuel cell is the Proton Exchange Membrane Fuel Cell. In this fuel cell, the anode and the cathode are separated by a porous electrolyte membrane. At the anode, hydrogen reacts with a catalyst, creating a positively charged ion and a negatively charged electron. The proton passes through the electrolyte membrane, while the electron moves through a circuit, creating an electric current. At the cathode, the protons, electrons, and oxygen combine forming water and heat. In recent years, Proton Exchange Membrane Fuel Cell technology has shown a remarkable progress. A car equipped with high pressure hydrogen storage and using a hydrogen fuel cell may cover up to between 500 and 600 km between fill-ups [51-53].

CONCLUSIONS

Bearing in mind the profound differences between today's petroleum fuels and hydrogen, the move to a hydrogen economy is a worldwide revolution that must take place in an orderly manner with the participation and coordination of national and international institutions, private-public collaborative associations, industrial companies, SME's, and research centres. Electrolysis of water using renewable power is until now the main producer of sustainable hydrogen, hence the production of wind and solar energy must increase strongly and electrolyser production cost must and is being reduced. In order to phase-out Russian fossil fuel imports, the EU will speed up the deployment of renewable energy, as Charles Michel, President of the European Council, said at the European Parliament. An important step forward is the development of new revolutionary hydrogen production technologies which do not depend on the electric power network.

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