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Oficina C

Green hydrogen as a fuel

Keys for its contribution to a decarbonised economy

Hydrogen produced using renewable energies is expected to play an essential role in the energy transition towards a decarbonised economy by 2050. Although its current main use is as a raw material in industry, hydrogen is a highly versatile fuel, which opens the door to a wide range of new applications. Its greatest appeal is as a replacement for fossil fuels. Spain is facing a series of challenges and opportunities in the deployment of this sector.

In the context of net-zero emissions, hydrogen has great potential as another component of the energy mix that will co-exist alongside other technologies.

Green hydrogen allows renewable energy to reach sectors in which direct electrification is difficult.

The current main use of hydrogen is as a raw material in industry, and it is produced from fossil sources without any measures to mitigate emissions. Experts indicate that its replacement by low-carbon hydrogen, principally green hydrogen, is a priority.

One of the great challenges is to reduce the production costs of green hydrogen and make it competitive.

Current European legislation does not cover new uses of hydrogen as an energetic material, which constitutes an obstacle for its entry to the market.

Hydrogen's value chain, including its production from renewable energies, is at an incipient phase for both national and global implementation.

Production method

Reports C are brief documents on subjects chosen by the Bureau of the Congress of Deputies that contextualise and summarise the available scientific evidence on the analysed subject. They also inform about areas of agreement, disagreement, unknowns, and ongoing discussions. The reports are drafted based on an in-depth review of the literature, supplemented by interviews with experts on the subject.

To produce this report Oficina C referenced 205 documents and consulted 27 experts in the subject. Of this multi-disciplinary group, 55% belong to the field of physics and engineering sciences (materials science, applied physics, aeronautical engineering, environmental engineering, industrial engineering, mechanical engineering, chemical engineering and energy systems engineering); 26% come from life sciences (biology and chemistry) and 19% from social sciences and humanities (law, business management, economics, philosophy and psychology); 74% work in Spanish institutions or centres, whereas 26 % have affiliations abroad.

Oficina C is responsible for the publication of this report.

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Green hydrogen as fuel

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Introducción

Green hydrogen technology has arisen in response to the search for alternatives to fossil fuel energies, and the need to meet the challenge of climate neutrality by 2050 and achieve Paris Agreement goals[-3].

Current production and consumption of energy in all economic sectors represents over 75% of greenhouse gas in the European Union (EU)[4].

Electrification: the process of substituting fossil fuels for electricity in the end uses of energy.

Energy mix: the combination of different energy sources to cover energy supply in a country.

Carácter intermitente de las energías renovables: interrupciones y/o exceso de producción de energía eléctrica debido a variaciones en el recurso renovable: horas de oscuridad en la energía solar, falta de viento en energía eólica, etc.

To achieve decarbonisation, the EU is committed to developing an electricity system based on renewable sources and the direct electrification of all possible end uses[3]. This will involve new challenges. On the one hand, increasing the penetration of renewable energies in the energy mix and developing solutions to manage their variability (storing renewable energies when and where there is excess production for use when and where production does not satisfy demand). On the other, seeking renewable energy alternatives for sectors that are difficult to electrify (industrial processes that consume high-temperature heat, use in mobility for maritime, aviation and heavy land transport, domestic use, etc.)

Hydrogen enters the energy mix as a support tool to solve these challenges. This element can be directly used for applications that are currently difficult to electrify, can help in managing the variability of renewables when stored as hydrogen and, in addition, opens the way to the possibility of reconverting hydrogen into electrical energy and delivering it to the grid[5-7].

It is also a very abundant element that is not naturally found in appreciable quantities in a free state, which means it must be produced by means of an energetic contribution[8]. Traditionally, hydrogen is generated from fossil fuels without measures to mitigate emissions, in processes which give off CO2. Its main use is in industry, as a raw material. The novel aspect of current energy transition is the production of low-carbon hydrogen, mainly from renewable energy sources. This is why hydrogen produced without carbon emissions is known as “green”.

Electrolysis of water: the decomposition of the water molecule into oxygen and hydrogen using electricity.

As there is no universal definition of green hydrogen[7,9-11], for the purposes of this report, green hydrogen is defined as production of the element using electrolysis of water with electricity from renewable energy sources. The process consists of decomposing the water molecule into oxygen and hydrogen using electricity[12]. This reaction, performed by a system called an electrolyser, does not generate CO2 emissions[12].

Although the use of green hydrogen as a raw material and fuel has great potential, its production, storage, transport and new uses are at an incipient stage of development.

Hydrogen is one of the technological means that can contribute to a decarbonisation of the world economy by 2050 [13-15]. With this goal, the European Strategy for Hydrogen plans to produce up to 10 million tonnes of this gas per year by 2030[3]. However, after the Russian invasion of Ukraine, the European Commission proposed an increase in its production and imports, to reach 20 million tonnes/year by 2030[16,17]. The Renewable Hydrogen Roadmap for Spain expects to meet 10% of the EU objective in the national production capacity of green hydrogen[18]. Spain has a great capacity to generate renewable energies at low cost, which favours its positioning as one of the European countries with greatest potential for the production and export of green hydrogen[18].

The hydrogen value chain

Energy carrier: a substance that needs an energy supply for its production and can be used to store energy until required for use.

The role of green hydrogen in energy transition is based on its production and use as a raw material and energy carrier for sectors where there are no (or extremely limited) other clean, efficient energy solutions[8,19-21]. Its value chain includes the whole range of necessary activities for the production, storage, transport and end use of green hydrogen[22]. This element's versatility enables it to be processed in different ways (pure in gaseous or liquid state or transforming it into other chemical substances) and used by such widely differing sectors as industry, mobility, electricity production or domestic use[6].

Its contribution to the energy sector explains why it can be directly consumed (as a raw material or a fuel) or function as an energy reservoir, helping manage the variability of renewable energies[23]. It also requires an infrastructure to transport it to the point of use and, as a gas, can be injected into the gas grid[24]. All of which highlight the versatility of the hydrogen ecosystem.

Production of green hydrogen

The production of green hydrogen, based on decomposing water into its oxygen and hydrogen molecules, requires an energy supply based on renewable energy sources[12], which may be wind, hydroelectric or tidal power, solar or geothermal energy[25,26]. In this context, Spain has an added value thanks to its potential to generate wind power and solar energy[7]. In 2021, renewable technologies produced 47% of the electricity generated in Spain and the two main sources of electricity generation were the wind and the sun[28]. The Comprehensive National Plan for Energy and Climate 2021-2030 (PNIEC), the Long-term Decarbonisation Strategy 2050 and the Renewable Hydrogen Roadmap necessarily link the deployment of green hydrogen to an increase in the generation of renewable energies[2,10,18,29,30].

Electrolysers are the equipment needed to produce hydrogen. There are four main electrolyser technologies. The differences between them are the degree of energy efficiency they achieve, the medium in which the water molecule split is produced, the working temperature, their materials and components, and their technology readiness levels (**Key Point 1**)[7]. Other low-emission processes to obtain hydrogen exist that could be used to supplement green hydrogen production during energy transition (**Key Point 2**).

Key point 1. Types of electrolysers for green hydrogen production.

These commercially available technologies exist but still require research to improve them:

- **Alkaline water electrolyser:** This type of electrolyser works in alkaline conditions at low temperature. It is the most mature of the technologies in use, and currently the cheapest[31]. However, the equipment is large, its operation is not flexible, and the hydrogen produced requires conditioning before it can be used[32].
- **Polymer electrolyte membrane (PEM) electrolyser:** This uses a proton exchange membrane as the electrolyte and works in acidic conditions at low temperature. They are compact, produce very pure hydrogen and operate more quickly and flexibly than their alkaline equivalent[32,33]. This technology requires precious metals, which increases its cost[34].

The following technologies are incipient and at the research and development stage:

- **Solid oxide electrolyser cell (SOEC):** The electrolyte is formed of low-cost, ceramic materials. This equipment can operate reversibly to produce hydrogen or electricity. It differs from the other technologies in its use of high working temperatures (700-850 °C) and can reach a high degree of energy efficiency[7,35]. Its main disadvantage is its association with high temperatures, which compromise the durability and stability of the materials[32,36].
- **Anion exchange membrane (AEM):** uses an anion exchange membrane as its electrolyte. It does not contain any precious metals, which means it has a low cost[37,38]. This technology combines the advantages of alkaline water and polymer membrane electrolysers, and the main challenges are to improve its efficiency, stability, conductivity and cost[39].

The consumption of hydrogen in Spain was around 500,000 tonnes in 2019, and it was used as a raw material for industrial processes[18,29]. The hydrogen generated to cover current demand mainly comes from natural gas and is known as "grey hydrogen" as its production emits CO_2. A further step is "blue hydrogen", the name given when the CO2 generated during grey hydrogen production is captured and stored[40].

Blue hydrogen is contemplated in the short term as a solution and incentive to increase demand for hydrogen and promote escalation of the technology in countries with reserves of natural gas and subterranean CO_2 storage capacity[7,41,42]. Since there is a degree of social rejection within Spain to the geological storage of CO_2[43], the Renewable Hydrogen Roadmap, in addition to subsidies under the Strategic Project for Recovery and Transformation (PERTE) for Renewable Energies, Renewable Hydrogen and Storage, directly focus on the promotion and introduction of green hydrogen as their main strategy[18,44].

Key point 2. Other ways of producing low-emission hydrogen

- **Hydrogen from fossil fuels with CO_2 capture (blue hydrogen):** although the production of hydrogen from fossil fuels generates CO_2 emissions, the possibility exists of minimising them by means of CO_2 capture techniques[27]. However, the hydrogen produced using this technology can only be considered low emission when extremely high percentages of CO_2 are captured and applied to all flows of the process that contain CO_2, ensuring that the captured CO_2 is permanently stored[27]. Minimising fugitive emissions of methane in the supply of fossil fuel is also essential as this constitutes a significant part of the emissions generated in fossil-fuel hydrogen production[45–47].
- **Biomass hydrogen:** this refers to the production of hydrogen from the waste materials of agricultural crops, forest waste, the organic part of solid urban waste, animal waste, etc[48]. Unlike fossil fuels, biomass CO_2 emissions come from carbon previously absorbed from the atmosphere by growing plants. For this reason, biomass may be zero-carbon emission when it is produced in compliance with strict sustainability criteria[21]. Biomass hydrogen can be produced using thermochemical processes like gasification[49,50], or biological processes based on micro-organism fermentation[51].
- **Hydrogen from splitting water molecules:** in addition to electrolysis, the other production technologies that decompose water are still at an incipient stage of development but have great potential for the final phases of the energy transition[41]. In these cases, splitting the water molecule is achieved using direct sunlight (photolysis), thermal energy (thermal decomposition) or using micro-organisms (biophotolysis)[21,52–54].

Storage and transport

These are essential stages in the management of worldwide demand for hydrogen. Nevertheless, they contribute to increasing the cost, energy consumption and CO^2 emissions in the value chain[55].

The versatility of hydrogen enables the design of optimum combinations of storage and transport, taking into account factors like the distance between the points of production and consumption, storage time, amount and final use[18].

The hydrogen produced can be compressed and stored in a gaseous state or liquefied to obtain liquid hydrogen[56]. Another option is to combine and transform it into different chemical substances[57,58]. These may be presented in gaseous (synthetic methane), liquid (ammonia, liquid organic hydrogen carriers and synthetic liquid fuels) or solid (hydrides) states[55,59].

Small-scale storage for short-term use usually employs high-pressure tanks (gaseous hydrogen) or solid materials[8]. Liquid storage is suitable on a large-scale in the short term[56]. For the long-term, however, the tendency is to opt for geological storage such as salt caverns, aquifers and exhausted natural gas or oil deposits (gaseous hydrogen), although these options are still at the development stage[60]. In Spain, the scientific community has identified the hydrographic basins of the Duero, Ebro and Guadalquivir as the areas with greatest potential for subterranean hydrogen storage[61–63].

On the other hand, transporting hydrogen implies the use of lorries, trains, boats and pipelines[64]. For short distances and small amounts, gaseous hydrogen can be transported to its final destination in tanks[18]. For longer distances and larger amounts, it is recommended to use pipelines[18]. The use of the existing network of gas pipelines would require technical adaptation of both materials and components since hydrogen may accelerate degradation[65]. In cases where technical adaptation is not possible and/or the demand for natural gas continues, new hydrogen pipelines can be built[65,66]. It is currently permitted to inject up to 5% hydrogen into the Spanish gas network, so the mix of hydrogen and natural gas can be directly consumed at end use[18,67]. However, the combination of gases implies a loss of the intrinsic value of green hydrogen in the mix, because no mature technology exists to separate the two gasses at the point of use[18].

For long distances, recommendations are to use sea transportation, in which hydrogen is transported as a liquid, ammonia or liquid organic carriers[27]. Spain has the potential to export hydrogen as it has access to both the Mediterranean Sea and Atlantic Ocean[18] and is connected with the rest of Europe via the Pyrenees[66].

Traditional and potential uses

Worldwide demand for hydrogen in 2020 reached 94 million tonnes, almost exclusively destined for industrial use[68], and generated 900 million tonnes of CO_2 emissions[265]. In this context, green hydrogen could start to replace the fossil-fuel hydrogen currently employed in industry and be used as a fuel for new uses:

Biofuel: fuel that is produced from organic waste and biomass.

- **Green hydrogen as a raw material:** it is employed for the traditional industrial consumption of hydrogen (oil refining[69], as a chemical to produce ammonia and methanol[70,71], etc). In these applications, the novel aspect resides in substituting the currently used grey hydrogen with green hydrogen. An emerging use is as a substitute for coal in the iron and steel industry[72]. Another novel application promotes its application as a raw material to generate synthetic fuels that do not come from fossil fuel carbons such as methanol or methane ammonia, **biofuels**[73] and other liquid hydrocarbons[7,74]

- **Green hydrogen as a fuel:** it has the potential for use in obtaining energy (1) in industrial processes that require high temperatures[68] (iron and steel industry[75,76] cement[77], glass[78], etc.), (2) in the mobility sector, particularly in maritime transport[79], aviation and heavy goods transport, (3) as an energy storage system for the electric grid when renewable energy production does not meet demand[6] and (4) for domestic use in boilers by inclusion of hydrogen in the gas system[80]. For certain industrial applications, the combined use of hydrogen as a raw material and as a fuel is being considered (iron and steel industry[81]).

Challenges of green hydrogen

Energy efficiency: a jigsaw puzzle of options

In the context of net-zero emissions, hydrogen has great potential as another component of the energy mix[15,82]. Energy transition requires an efficient management of energy[10] that involves a collective reduction of energy consumption, an increase in use of renewables, diversification of the energy mix (including other low-carbon technologies) and direct electrification of as many uses as possible. In line with this, the objective is to use green hydrogen with a double function: as a tool to decarbonise the uses that currently cannot be directly electrified due to technical and/or economic reasons, and as an energy reservoir for renewables[2,15,29,82-85].

One important area is the identification of the priority applications for green hydrogen in each country[27,86,87], because its indiscriminate use could slow down the energy transition and dilute decarbonisation efforts[27]. Although, technically speaking, hydrogen can be employed in different sectors, we should not lose sight of the fact that its production, transport and conversion involve the use of energy[7,88]. In particular, the production of green hydrogen requires renewable energies that could be directly, and therefore more efficiently, employed for other end uses[68]. This is why experts advise consideration of the following general factors to prioritise its use: the technological maturity of the applications, potential volume of the hydrogen demand and capacity to reduce greenhouse gases[68].

As for its application in Spain, the community of experts indicate that its use in industry – the main demand for hydrogen[16,18] – has high priority, given the current lack of clean alternatives for decarbonisation[68]. Another priority is its introduction in land transport, particularly for heavy goods, as this is one of the sectors that consumes most energy (38% of the total national energy consumption in 2019) and produces most CO_2 emissions[29,89]. In the case of the Balearic and Canary Islands, the introduction of green hydrogen could contribute to their transition to a 100% renewable energy sources economy (**Key Point 3**).

Key point 3. Island territories with 100% renewable energies

Experts indicate that green hydrogen-based solutions offer an opportunity for the territories of the Canaries and the Balearic Islands to achieve energy independence[90,91]. Given the physical restrictions and access to energy in these territories, green hydrogen has a significant role to play in the temporary storage of electricity[18].

The island of Majorca is currently a European reference point in transformation to a decarbonised economy thanks to the GREEN HYSLAND project, which aims to make it the first H_2 hub in the south-west of Europe. With this objective, the necessary infrastructure is being developed to produce green hydrogen from solar energy and distribute it to the island's tourism, transport, industrial and energy sectors, including injection into the gas network to generate green energy and heat at the end point of use[92]. The latest report of the Spanish Technological Platform for Hydrogen provides a full list of the green hydrogen projects in which Spain participates[93].

The Long-Term Decarbonisation Strategy 2050 and the Comprehensive National Plan for Energy and Climate 2021-2030 propose uncoupling economic growth from energy consumption[2,10]. Among the decarbonisation objectives for 2050 are the use of 100% renewable energies in the electric mix and 97% in the whole energy system[2,29]. It has been suggested that this increase in renewable energies is essential for direct electrification of end uses, and for the generation and application of green hydrogen in cases where electrification is difficult[3]. Increasing the use of renewable energies implies managing a higher amount of excess energy production at given moments of the day and times of the year[94]. In this context, green hydrogen can support the management of the variability of renewable energies by serving as storage for use at times of peak demand for electricity[62,94-97].

With this in mind, the integration of green hydrogen requires intelligent implementation to increase the system's global efficiency (**Key Point 4**)[56]. Setting up a value chain for each project calls for individual studies because there are different types of green hydrogen production technologies, end uses, infrastructure, etc.[98]. The Hydrogen Strategy of the Netherlands aims to conduct a study of its territory to achieve an optimum roll-out of hydrogen infrastructure, taking into account the location of its industrial fabric[99].

Key point 4. A change of paradigm: smart networks

The traditional energy system is experiencing a change in paradigm, with a move towards a more electrified system based on renewables, managed digitally via smart networks[100].

The goal is to optimise the production and distribution of electricity and achieve a better balance between producers and consumers[100]. In the traditional energy system, the flow of energy is one way, from the point of production to the point of consumption[101]. In the new system, the flow of energy and information is two-way, between energy consumers and producers, and it is managed by a central control system[101,102]. Consumers also take an active role as energy producers (with solar panels on buildings, among others)[103]. The Citizens' Climate Assembly of Spain (Asamblea Ciudadana para el Clima) has published a series of recommendations to promote the active role of consumers in generating energy and taking a responsible role in its use, for instance, with self-consumption of electricity[104].

For all of these reasons, the system's degree of complexity and flexibility increases in the attempt to achieve an efficient use of electrical energy for use in transport, industry, buildings and to produce other energies[100,205]. Hydrogen is an element that brings even greater flexibility to the system thanks to its capacity to store energy and manage the variability of renewable energies 56. Finally, the change of paradigm is heavily connected with digitalisation, which makes it necessary to increase the cybersecurity of smart networks to avoid shortfalls in supply and the threat of cyberattacks[106-110].

Towards an economy of scale and a global economy

One of the great challenges of energy transition is to reduce the production costs of green hydrogen and make it competitive[7]. In 2021 worldwide, green hydrogen was between two and five times more expensive than blue hydrogen[65,111]. Projections made prior to the Russian invasion of Ukraine indicated that in Spain green could become cheaper than blue hydrogen by 2026[27]. However, with the high prices of gas seen in 2022, green hydrogen is close to becoming the cheapest option for producing hydrogen in many regions of the world, as long as production capacities are available[65].

In any case, since the price of natural gas could decrease again in the long term, experts indicate that it is necessary to reduce the costs of generating renewable energies, which are responsible for most of green hydrogen's production costs[65,96,112-114]. In addition, they note that a commitment to research and innovation would allow diversification of hydrogen technologies, meaning they could reach commercial maturity and, together with a reduction in the costs of renewables, the technology could be deployed on a large scale[18,115]. These measures could cut green hydrogen production costs by 85%[7].

Alongside production costs, it is also important to bear in mind the costs of transporting hydrogen. These may increase with the large-scale, centralised production of hydrogen (which would lower production costs) far away from the point of end use[18]. Conversely, the small-scale, decentralised production of hydrogen implies higher production costs, but reduces transport costs as it is closer to the points of consumption[98]. So, the location of the hydrogen value chain infrastructure is an important consideration for cost optimisation[98].

This situation is similar from a worldwide perspective[86]. Green hydrogen can be produced more economically in places with abundant renewable resources, space for solar and wind power plants, and access to water[27]. Its development and introduction will therefore have an effect on the geopolitical energy trade, in which Spain has the potential to become energetically self-sufficient and an exporter of hydrogen[18,27].

Dependence on critical materials

Energy transition is conditioned by the availability of critical raw materials, which could mean that dependence on fossil fuels becomes a dependence on minerals[106]. Minerals are essential components of the technologies that generate and store renewable energies and hydrogen. Electric batteries require lithium, nickel, cobalt, manganese and graphite; turbines need rare earths; electricity facilities use copper and aluminium, and electrolysers and fuel cells employ platinum, iridium, nickel and zirconium [116,117]. The majority of these raw materials are considered critical because of their economic importance and supply risk[118,119]. It is also predicted that the current demand for them will quadruple in order to achieve the 2050 decarbonisation goals[116].

In this context, dependence on minerals implies the creation of a new international collaboration network to guarantee global supply, since deposits are a limited resource and concentrated in extremely specific geographical areas[106,118]. The scientific community is therefore researching how to diversify the types of materials used and searching for others that are cheaper and more plentiful[120-125]. There are also proposals to reduce the amount of materials in equipment[126,127], increase their stability and durability[128] and foster recycling[129]. All of these measures are part of the ecodesign strategy, an essential component within the circular economy framework to guarantee the system's sustainability[129,130].

Integration and living with technology

It is predicted that the integration of green hydrogen technology will occur progressively within the current ecosystem and will live alongside other technologies in multiple sectors, such as the:

Gas system: In Spain, it is currently permitted to inject up to 5% of hydrogen into gas pipelines[18]. Higher amounts would require modification of the natural gas network's materials, definition of new technical and safety limits, adaptation of end-consumer equipment (boilers and turbines for domestic and industrial use) and harmonisation of regulatory management of the system at national and European levels[131,132].

In certain cases, a point may be reached at which surpassing a given percentage of hydrogen concentrations is not viable for technical or economic reasons[131].

Hydrogen refuelling station: a filling station where hydrogen is stored, distributed and dispensed for use in vehicles. Hydrogen may or may not be generated at the filling station itself.

One possible solution is the creation of hydrogen pipelines for the exclusive distribution of hydrogen. Globally, 90% of operational hydrogen pipelines are in Europe and the United States[133]. The future of decarbonising the gas network therefore contemplates the co-existence of gas pipelines to transport other renewable gases, such as biomethane, alongside hydrogen pipelines (adapted from the existing gas network or newly built) to serve the needs of each region[9,86,134–138].

Mobility: For light vehicle land transport the co-existence of various technologies is expected: vehicles with internal combustion engines that use renewable fuels, battery electric vehicles and electric vehicles with green hydrogen fuel cells[139,140]. The last two are the most advanced forms of decarbonisation in the sector, and both require the deployment of an infrastructure of charging points as well as **hydrogen refuelling stations** to supply energy[139,141,142].

There are pros and cons associated with each technology; electric vehicles that use hydrogen fuel cells have greater autonomy than those with electric batteries and require less time to refuel[143]. Currently the principal disadvantage is the high cost of producing green hydrogen[141], and a lower efficiency of the whole process compared to storing energy in batteries[141]. On the other hand, electric vehicles with a battery, that directly use electricity, clearly have a more advanced position on the market, both for vehicles and in infrastructure of charging points[144]. However, although great advances have been made in batteries, their autonomy is lower, and their charging times are longer[141]. Despite the debate on whether they compete with or are complementary to each other[141,144–146], both battery electric vehicles and green hydrogen fuel cell electric vehicles are considered suitable options for decarbonisation, which means that the choice of one or the other will depend on the context and needs of each consumer[143,146].

Environmental impact

Experts indicate that the transition towards green hydrogen implies a saving in CO_2 emissions[85] since in most applications its use only generates water[147], avoiding direct emissions of contaminant gases[148]. However, the current low-carbon-emission technologies are not automatically green[149]. Uses that require the combustion of hydrogen, such as the combustion of fossil fuels, can also generate nitrogen oxides, which are greenhouse gases[150].

In the same line, a full analysis of its value chain shows that there is a carbon footprint associated with the CO_2 emissions generated during the extraction of materials, the functioning of renewable energy power plants and the equipment involved in the production and storage of hydrogen, transport to the point of consumption etc.[151–153]. Even so, comparison of the full value chain of the different hydrogen technologies shows that green hydrogen has a much lower carbon footprint and much lower total consumption of energy than grey hydrogen, or than the fossil fuels it replaces in different applications[154–157].

Another important point is prevention of hydrogen leaks into the atmosphere during its production, storage, transport and use. This consists of avoiding potential atmospheric changes that might affect air quality (variations in concentrations of methane, ozone, water vapour, etc)[150,158–160]. Although uncertainty exists on atmospheric impact, recent scientific studies show that a global warming impact exists, though it is quite limited[160].

In terms of global water consumption, it is estimated that the transition to a hydrogen economy would require a lower volume than what is currently required in the production and use of fossil fuels[161,162]. Nevertheless, on a local scale, the areas with the greatest production potential for green hydrogen are also regions with high water stress, as occurs in Spain[27,163]. To avoid consuming fresh water in these regions, the production of green hydrogen from desalinated water is under consideration[164]. Another option is the direct use of sea water, which is at a developmental stage and faces numerous hurdles[165–170]. All things considered, the implementation of local projects requires detailed case studies to achieve a sustainable development that covers water consumption related to the energy and food production sectors.

Social and economic opportunities

The European interest in hydrogen technologies has undergone exponential growth in recent years[82]. Since the launch of the European Strategy for Hydrogen in 2020[3] various member states have published their national strategies in the field[18,82,99,172,173]. Although the EU considers electrolysis a strategic opportunity for the export of technology[82] and actively participates in the publication of patents and scientific papers on hydrogen technologies, major competitors like China, Japan, South Korea or the United States are currently leading the field[174].

Meanwhile, the Renewable Hydrogen Roadmap indicates that green hydrogen represents an opportunity to foster the creation of qualified work, stimulate the economy, modernise industry, promote competitiveness, improve energy security and support research and innovation in Spain[18]. National interest in the sector is already evident from the growth of R&D&i organisations and companies that conduct activities in this element's value chain[175,176]. Due to the fact that the green hydrogen is still at an initial phase, it would be recommendable to train experts and users in hydrogen technologies to foster the optimum deployment of the sector[177,178].

On the other hand, its development opens the doors to a geopolitical market with new participants[179] among whom Spain has the potential to achieve energy independence and become an energy exporter for countries in the north of Europe[27,172]. In this context, improving electricity interconnection and the creation of a hydrogen infrastructure interconnection with the continent are two key factors to enable energy transactions[29].

Likewise, in order to make the energy transition towards a green hydrogen economy sustainable, in addition to environmental questions, the technological, economic and social dimensions must be taken into account[154, 180 181]. Attention to these matters is relevant to minimise or avoid current inequalities and avoid their transference alongside the new energy transition[182]. Inequalities may be related to demography (gender, race, age, socio-economic class), space (urban or rural areas) or time (between generations or for future generations) and may affect the natural environment[149,183-185]. Various indicators exist to analyse the social impact of energy projects worldwide[186]. In the case of green hydrogen, this depends on the actors involved in the production, transport and end use of hydrogen (including the origin of the materials and energy, technological production platforms, intermediaries, industrial applications and and use), as well as contributions from promoting institutional, financial and economic actors[139,187-189].

Regulation in a social and technological transition

Guarantee of origin system: the system that enables provision of evidence to the end client that a determined amount of energy has been produced from renewable sources.

One of the main regulatory bottlenecks is the lack of a universal definition of green hydrogen[82]. Although Spain has the goal of becoming a hydrogen exporter[18], European projections indicate that on the whole, Europe will be a net importer[27.86.143]. This means that it will be necessary to have a universal definition of green hydrogen to make transactions on the international market possible[139,190]. Likewise, work is under way on creating a **guarantee of origin system** to ensure clean origin throughout the value chain[18,64,82].

New uses of hydrogen as an energetic material are not covered by current European legislation, which is an obstacle for the entry of this product to the market[74]. In addition, experts indicate that regulations, codes and international standards need to be harmonised for the sector to take off[74]. Today's international standards cover the current uses of hydrogen[191-194]. In order to ensure the safety of new uses, it will be necessary to undertake further studies and widen the scope of standards[55,191,195,196]. In the case of Spain, various studies show that the applicable safety and environmental impact controls are restrictive and appropriate for industrial activity projects, regardless of the hydrogen production method (with or without CO_2 emissions), the scale of production (small scale or industrial) its end use (industry, mobility or integration with other energy sectors)[197,198]. All of which slow down the deployment of small-scale projects or new applications, such as hydrogen refuelling stations with *in situ* hydrogen production[197]. The Renewable Hydrogen Roadmap identifies these obstacles and proposes a series of lines of action to simplify administrative procedures and eliminate regulatory hurdles to production of the gas[18].

In conclusion, energy transition depends on the expectations, acceptance and behaviour related with hydrogen technologies of all actors involved (the political community, market agents and society)[189,199,200]. In order to foster a social and technological transition that welcomes the uses and infrastructures related with this resource and generates a cultural change, general recommendations are to involve the population[201,202]. The attitude to hydrogen in Spain is positive, although this could easily change given that familiarity with the technology is still low[203]. So, information and involvement campaigns would be a suitable tool for the current initial stage of hydrogen technologies[203]. In this context, scientists highlight the importance of dealing with society's perceptions and related feelings of its risk, costs and benefits to promote confidence in this technology[204,205]. These factors influence the path to the introduction of green hydrogen within a common, sustainable technological framework for the environment that is economically viable and socially responsible.

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