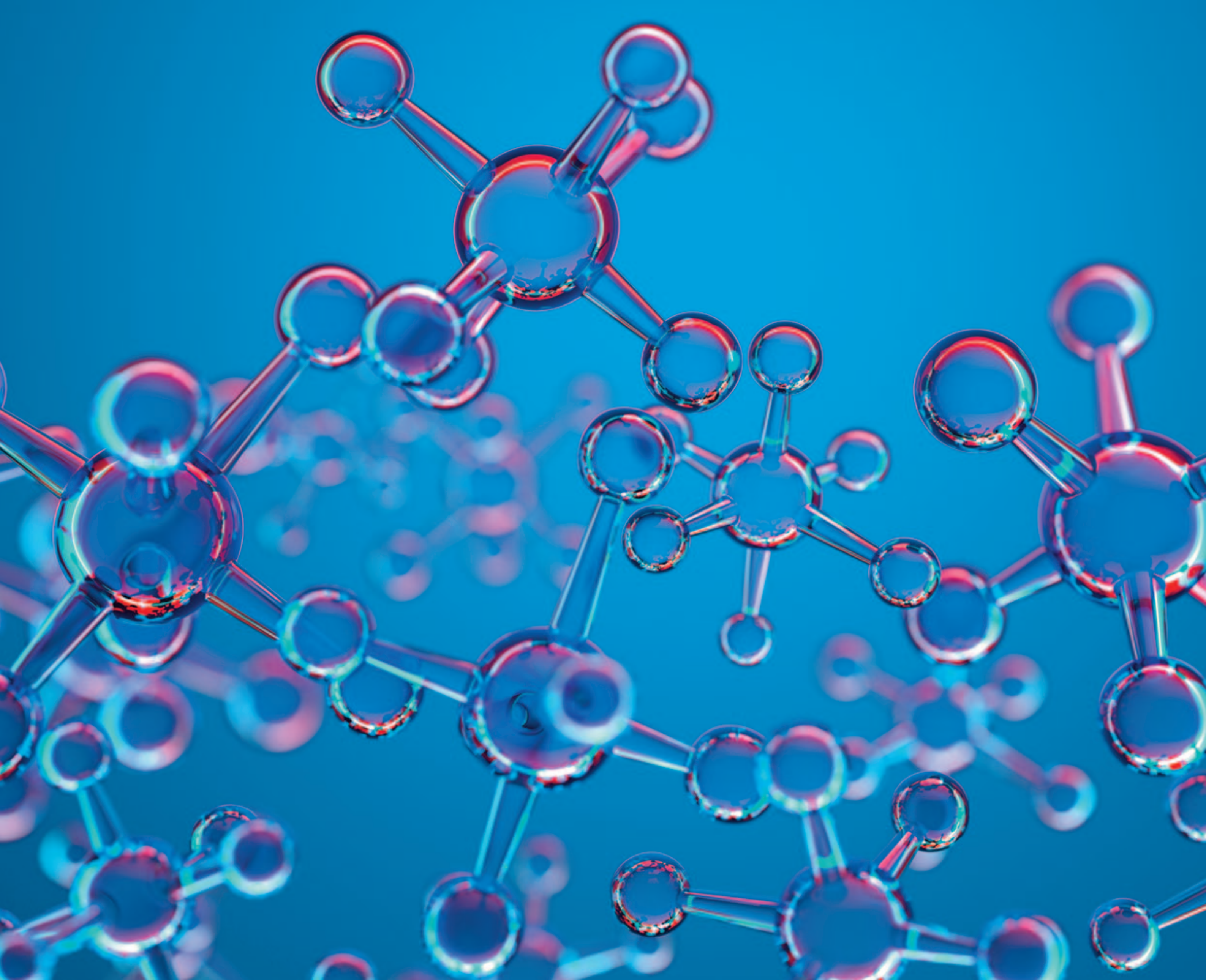
Hydrogen
An essential energy vector in evolving towards a decarbonized economy



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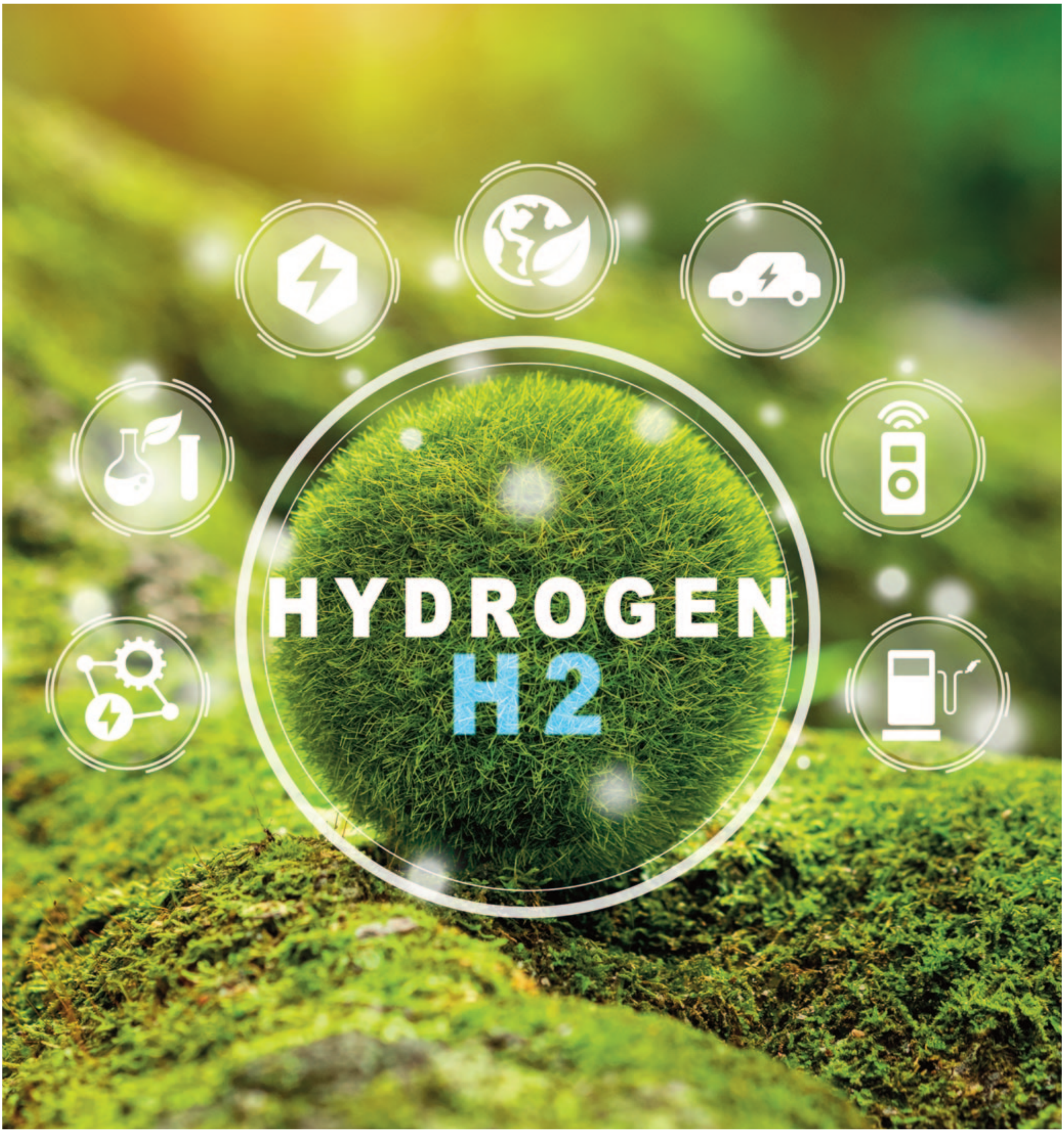
Index

Introduction

"Energy is essential for development, and sustainable energy is essential for sustainable development"

Tim Wirth[1]



In recent decades, the world's population has grown dramatically. By mid-November 2022, the world's population had reached eight billion, more than three times the number of people in the middle of the 20th century, and a quarter of this increase has taken place in the last 25 years (in the last decade alone this increase was 11.3%)[2]. This demographic growth has been accompanied by a growth in economic development which has been spurred by increased industrialization. Both elements have significantly intensified the demand for energy. Specifically, in the last 25 years, total consumption[3] of primary energy[4] grew by 57.8% (in the last decade, the increase amounted to 14.4%, with around 80%[5] of total global demand being met by fossil fuels: coal, oil and natural gas).

This increase in energy consumption presents a set of challenges that need to be addressed, including global concern about the impact that energy production and consumption can have on climate change. According to the United Nations[6], fossil fuels, such as coal, oil and gas, are by far the biggest contributors to global warming, generating more than 75% of total global greenhouse gas emissions and nearly 90% of all carbon dioxide emissions. Another important challenge to be addressed is the impact of energy production and consumption on the environment due to air and water pollution processes, land use, the need for large areas for the installation and operation of power plants, or waste management, among other reasons[7]. Renewable energies, which contribute decisively to mitigating this impact on climate, are not exempt from producing potentially adverse environmental impacts (potential extensive use of land, impacts on flora and fauna, etc.).

In addition, they present challenges in terms of the accumulation and storage of the energy produced, due to the variability of generation. Finally, the current energy mix poses a geopolitical challenge for countries dependent on fossil fuel energy that do not have such natural resources, which could jeopardize energy security[8].

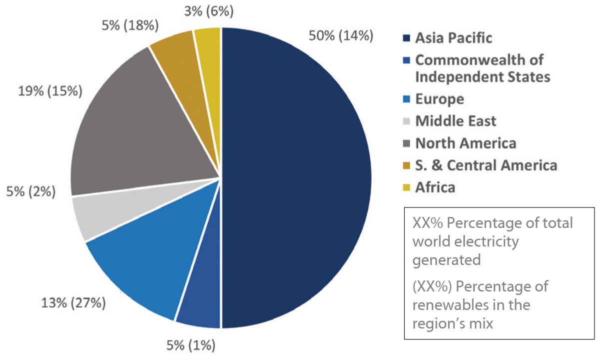
As a result of the aforementioned circumstances, the need to identify additional energy sources to transform the energy mix has grown, with the intended effect being the mitigation of the adverse consequences stemming from the production, transportation and use of energy. In this sense, renewable energies (excluding hydroelectric generation) are the ones that have had the greatest growth in electricity generation. Electricity production through renewable energies has increased more than 18-fold since the beginning of the 21st century, and although not all geographical areas have seen the same growth (see Figure 1), globally, renewable energies accounted for 14% of electricity production in 2022, surpassing nuclear energy, which accounted for 9%. However, coal and gas still remain the largest energy sources, accounting for 35% and 23% of production, respectively[9].

In this context, hydrogen, a commonly consumed gas in industrial processes, is becoming very important because of its ability to act as a decisive energy carrier (as it can be used to store and transport energy for later release). Recent studies[10] indicate that 60% of emission reductions could come from renewable generation combined with green hydrogen[11]. Therefore, there is a consensus on the key role that green hydrogen can play in accompanying this energy transition, enhancing the integration of renewable energies themselves or even acting as a decarbonization solution in some sectors (transport, industrial processes, etc.). The development of green hydrogen is an accelerator for the hydrogen sector in general and is not incompatible with the future incorporation of other types of hydrogen, such as white hydrogen. The creation and expansion of transport infrastructure, market development, industry transformation, and adaptation of consumption patterns around green hydrogen are not only perfectly compatible with white hydrogen, but could also converge synergistically.

This publication aims to provide an understanding of hydrogen by explaining its different types as well as its value chain and key challenges, and by analyzing a case study that illustrates in a practical way how analytical tools can be leveraged to address some of the challenges involved in its adoption process, such as the selection of optimal sites for developing new projects.

[1] Timothy Endicott Wirth, a Harvard graduate with a PhD from Stanford, he served in the U.S. House of Representatives and the U.S. Senate. He was Secretary of State for Global Affairs during the Clinton administration. From 1998 to 2013, he was president of the United Nations Foundation, and currently serves on its board of directors.
[2] Source: United Nations "2022 Revision of World Population Prospects".
[3] Energy Institute: Statistical review of world energy 2022.
[4] Primary energy: energy from renewable and non-renewable sources that has not undergone any conversion or transformation process (RAE).
[5] Source: U.S. EIA "International Energy Outlook 2021 (IEO2021)."
[6] Source: United Nations. Renewable energies: energies for a more secure future. Retrieved from https://www.un.org/es/climatechange/raising-ambition/renewable-energy.
[7] IPCC, "Special Report on global warming of 1.5°C" (2019).
[8] According to the International Energy Agency, energy security is defined as the uninterrupted availability of energy sources at an affordable price.
[9] Energy Institute: "Statistical Review of World Energy".
[10] B.E. Lebrouhi: "Global hydrogen development - A technological and geopolitical overview" (2022).
[11] It is hydrogen generated by electrolysis of water, using electricity from renewable sources.

Figure 1. Total electricity generation by geographic area and percentage of renewable sources in the mix of each region in 2022.



Commonwealth of Independent States (CIS). Member countries are: Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova (participation suspended),Russia, Tajikistan, Turkmenistan and Uzbekistan.
Source: Energy Institute.

Executive summary

"Science is man's progressive approach to reality"
Max Planck[12]

Hydrogen is the lightest and most abundant chemical element in the universe and is an energy carrier, as it can be used to store and transport energy for later release. It has a high calorific value (although its energy density per volume is much lower than that of other fuels), it is inexhaustible, and it can be combined with other elements to form multiple derivative products.

This gas can be produced from various energy sources and by different methods, giving rise to different designations. These include green hydrogen (produced mainly by electrolysis of water and renewable energy sources), pink hydrogen (obtained by electrolysis with the energy source being nuclear), blue hydrogen (generated from hydrocarbons while capturing and storing the pollutant emissions produced), yellow hydrogen (produced by electrolysis while using non-renewable electricity as a source), turquoise hydrogen (obtained by pyrolysis of natural gas in a molten metal reactor), white hydrogen (present in nature) or black, gray and brown hydrogen (generated from hydrocarbons).

Among them all, green hydrogen is receiving increased attention (including from regulators), as the absence of greenhouse gas emissions during its production, its ability to balance the variability of renewables, the role it can play in the decarbonization of some sectors and its multiple applications make it the main catalyst in the process of energy transition to a carbon-neutral economy. Also, the extraction of white hydrogen from large natural deposits is recently being assessed and studied, which could contribute to the development of the sector and position hydrogen as an energy source in addition to its capabilities as an energy carrier.

The vast majority of the hydrogen consumed is produced from fossil fuels, mainly natural gas, coal and reformed naphtha. These forms of production are responsible for carbon dioxide emissions and contribute to global warming; therefore, there is consensus on the need to generate hydrogen using methods that do not release greenhouse gases in the process, such as electrolysis of water from electricity produced by renewable energies (only 0.1% of hydrogen was produced in this way in 2022).

Once generated, hydrogen must be stored and transported to its final consumption site, which is a challenge in itself. Hydrogen can be transported by ship, truck or pipeline depending on the distance between the producer and the consumer, in a gaseous, liquid or solid state, or in liquid organic carriers. (e.g., methanol, ammonia).

On the demand side, hydrogen has a wide variety of applications, with industrial and metallurgical processes such as oil refining, chemical production or steel reduction being at the forefront (e.g., ammonia or methanol) or steel reduction. In transportation, hydrogen is used in fuel cell vehicles, especially those for commercial purposes and buses, although its application to private cars is expected to grow in the next decade. It is also used for in the production of e-fuels (synthetic fuels). In addition, research is being carried out into applications in other sectors, such as energy and construction, as an alternative to fossil fuels.

Despite the progress and growing interest in green hydrogen, there are significant challenges on the road to its widespread and sustainable adoption. These challenges can be grouped into several areas:

[12]Max Planck, German theoretical physicist, considered the founder of quantum theory. In 1901, Planck published the law of the blackbody spectrum. He was awarded the Nobel Prize in Physics in 1918 for his work in quantum theory.

- **Hydrogen production:** one of the main challenges is to reduce its production cost to make it competitive with other energy sources. The main component of this cost is energy consumption. Therefore, the cost reduction effort will involve improving electrolyzation technology and developing economies of scale, among other measures.

- **Demand creation:** Another challenge is to generate sufficient demand for green hydrogen in different sectors, such as industry, transportation and power generation, to justify investments in production and distribution. This implies the need to improve production and storage technologies.

- **Hydrogen market:** unlike other energy resources, hydrogen is currently predominantly an industrial gas produced and consumed on-site, making it difficult to form a market with benchmark price indexes. However, as the sector develops, the creation of hydrogen markets can be expected, which is essential to encourage investment and competition.

- **Transport infrastructure:** the development of an adequate infrastructure for hydrogen transport, whether by road, pipeline or other means, is crucial for its efficient and safe distribution. This requires addressing technical issues such as the management of hydrogen being misaligned with network or safety requirements.

- **Regulation:** the main challenges at the regulatory level include the creation of specific frameworks for green hydrogen, the technical defining what can be considered green or renewable hydrogen, the development of the necessary financial and non-financial incentives, the creation of guarantee of origin systems, the development of specific regulations that encourage transportation with emission-free vehicles together with the use of hydrogen as a fuel in maritime transportation and the evolution of pipeline gas transportation regulations.

Organizations are facing these challenges by defining strategies, selecting new projects based on an appropriate investment analysis, managing the associated risks (e.g., by carrying out an internal reorganization, if necessary, or transforming their operations to implement new processes), adapting to regulations, and meeting sustainability objectives. Transitioning companies to the hydrogen market requires a holistic approach that spans from strategy to operations, and an understanding not only of its economic viability, but also commitment to sustainability and compliance with evolving regulations. Similarly, investment in advanced technologies and collaboration with partners and suppliers are essential for success in this market.

To solve some of these challenges, it is necessary to rely on specific tools to improve decision-making. An example of this is the application developed by the Chair of Hydrogen Studies at Comillas Pontifical University, of which Management Solutions is a patron, and which relies on Geographic Information Systems (GIS) to identify optimal locations for the construction of renewable hydrogen production projects. The model calculates a hydrogen compatibility index that categorizes the different variables analyzed at each site (land compatibility for the installation of renewables and water availability; existing electricity, gas and road infrastructure; possible off-takers[13]; etc.) and determines the best alternative according to the chosen criteria.

Green or renewable hydrogen is emerging as an essential pillar in the transition to a sustainable economy, but only through collaborative efforts, investment in technology and regulatory support will it be possible to overcome current challenges and unleash its full potential as a transformational energy carrier.

[13]Stakeholders or potential consumers,

Global context

"Renewable energy is the only credible way forward if the world is to avoid climate catastrophe"
António Guterres[14]

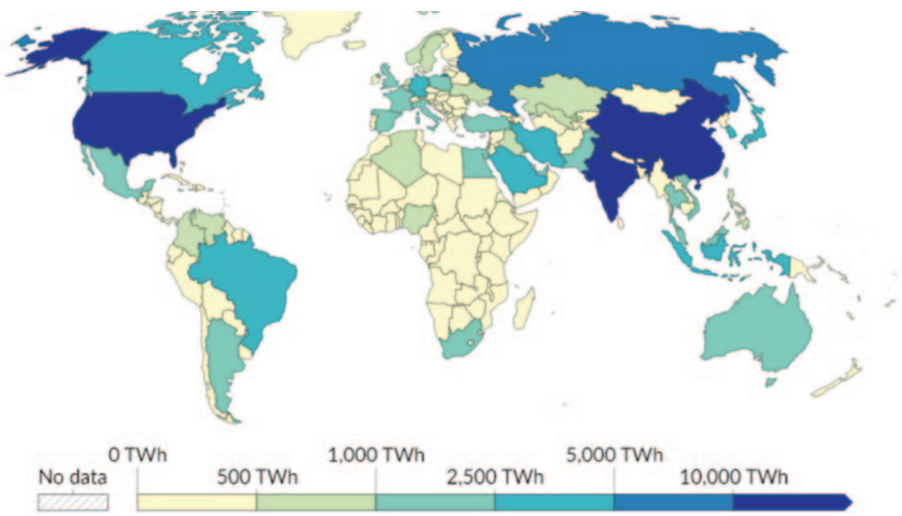
In recent decades, global energy consumption has been on a steady upward trajectory, driven by population growth, industrialization and rising living standards, especially in developing countries. As a result, global energy consumption varies significantly between countries, influenced in turn by their levels of industrialization and urbanization (see Figure 2).

From 2012 to 2022, total primary energy consumption[15] increased by 14.4%. Recently, consumption has increased to 442 EJ, and around 80%[16] of the world's primary energy demand, required for industries, transportation and households, is met by fossil fuels (coal, oil and natural gas). In 2022, coal accounted for about 27% of the world's primary energy mix, oil, the most widely used energy source, accounted for 32%, and natural gas, prized for its cleaner combustion properties relative to coal and oil, accounted for about 23%[17] (see Figure 3).

As for electric power, data in 2022 shows that coal contributed about 35% of its generation, gas generation remained at 23% which is close to its ten year average[18], and renewables experienced the largest growth, reaching 14% of total power and surpassing nuclear power, which accounts for 5% of the total.

[14] António Guterres is the current Secretary-General of the United Nations, where he has been an influential voice on global issues, including climate change, human rights and sustainable development.
[15] Primary energy: energy from renewable and non-renewable sources that has not undergone any conversion or transformation process (RAE).
[16] Source: U.S. EIA "International Energy Outlook 2021 (IEO2021)."
[17] Energy Institute: "Statistical Review of World Energy".
[18] Íbid.

Figure 2. World primary energy consumption in 2022.



Source: Our world in data, "Energy production and consumption" 2022.

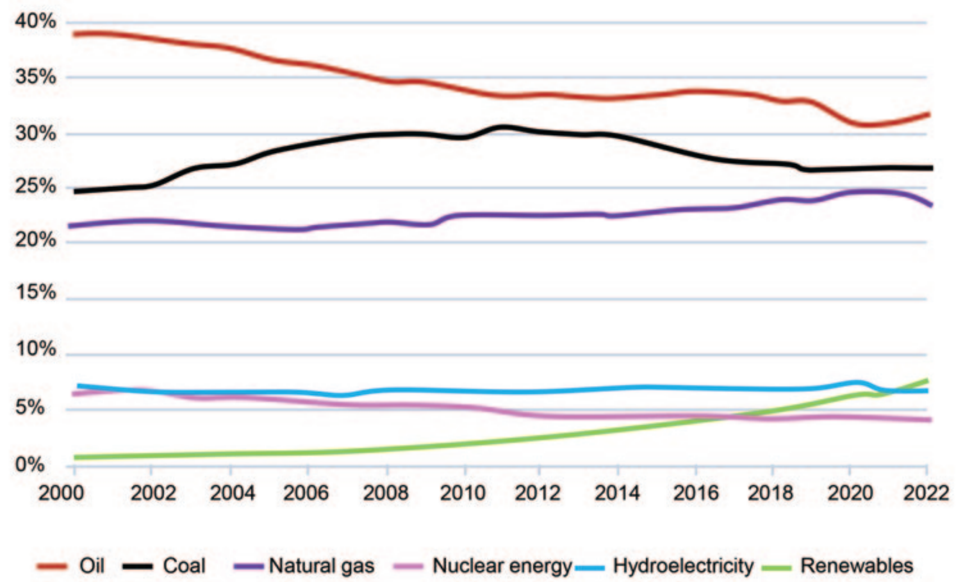
The fight against climate change requires reducing dependence on fossil fuels in order to achieve a carbon neutral society based on sustainable energy sources. Globally, there is a commitment to renewable energies as a means to achieve this neutrality, as they do not emit greenhouse gases during electriciy generation.

However, these energy sources have drawbacks, as they have environmental impacts (potential extensive land use, impacts on flora and fauna, etc.) and present challenges in terms of accumulation and storage of the energy produced, due to variability in generation.

In this context, hydrogen can play an essential role in accelerating the transition to a carbon-neutral energy system. It can be produced from renewable energy sources, stored efficiently, used to balance their variability and contribute to increasing their share in the global energy mix

In addition, this element could also play a relevant role in energy distribution due to the possibilities it offers for its transportation and for transforming potential in those sectors where electrification presents more inconveniences and limitations.

Figure 3. World primary energy consumption.



Source: Energy Institute. "Statistical Review of World Energy 2023.


H2
HYDROGEN

Overview of hydrogen

"We recognize that low-carbon and renewable hydrogen [...] should be developed and deployed where it can have an impact as an effective emissions reduction tool to drive decarbonization across all sectors and industries"
Declaración G7 2023[19]

What is H2?

Hydrogen (H2) is the lightest chemical element and the most abundant substance in the universe (75% is H_2)[20]. It has the properties of an energy vector, i.e. it can be used to store and transport energy for later release. Moreover, in the case of hydrogen, this energy release is carried out without emitting greenhouse gases into the atmosphere, unlike fossil fuels. This property, together with the fact that its use can be extended to a multitude of industrial and commercial applications, makes it an essential player in the energy transition to a more sustainable ecosystem.

The most outstanding properties that would allow hydrogen to spearhead the transformation of the current energy model are the following:

- **High calorific value and low energy density per volume.** Hydrogen has a high calorific value (the energy of 1 kilogram of hydrogen gas is approximately the same as that of 2.8 kilograms of gasoline), but because it is a light gas and occupies a large volume in its natural form, it has a much lower energy density per volume than other fuels (see LH_2 and CH_2 in Figure 4). This means that, depending on the application, it is not necessarily the most energy-efficient option[21]. Although an electric motor powered by a hydrogen fuel cell is two to three times more efficient than a gasoline internal combustion engine[22], when considering the upstream transformations necessary to produce the hydrogen (e.g. electrolysis process with an efficiency of around 60%) or compared to electric mobility, which has efficiencies of around 90% for cars with batteries, its efficiency is not a decisive factor.

- **Inexhaustible.** Since it is stored in water, hydrocarbons, and other organic matter, a priori hydrogen can be considered inexhaustible.

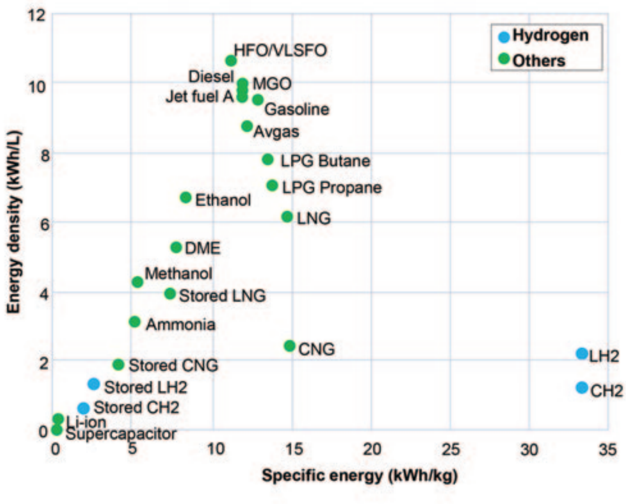
- **Storable.** Unlike other forms of energy, it can be stored and transported in multiple ways (transport by hydroproduct, sea, land, etc.).

- **Production flexibility.** It can be produced from different sources and in different parts of the world depending on the availability of renewable energy in each region.

- **Versatility of conversion to derivatives.** It can be combined with other elements to form multiple derivative products (such as hydrocarbons, ammonia, methanol and synthetic fuels, etc.), with higher density per unit volume than gas and greater efficiency for transportation purposes.

[19] G7 Ministers meeting on Climate, Energy and Environment in Sapporo, Japan April 15, 2023.
[20] IPNA - CSIC: "The origin of the first chemical elements".
[21] National Renewable Energy Laboratory. "National Renewable Energy Laboratory (2020).
[22] US Department of Energy, "Hydrogen Basics" (2022).
[23] IRENA: International Renewable Energy Agency

Figure 4. Energy density and specific energy of various fuels and energy storage systems.



Notes: Avgas = aviation gasolina; CH2 = hydrogen compressed at 70 Mpa; CNG = natural gas compressed at 25 Mpa; DME = dimethyl ether; HFO/VLSFO = heavy fuel oil/very low sulphur fuel oil; LH2 = liquefied hydrogen; Li-ion= lithium-ion Battery; LNG = liquefied natural gal; LPG = liquefied petroleum gas; Stored CNG = Type IV tank at 250 bar; Stored CH2 = best available CH2 tanks at 70 Mpa; Stored H2 = current small-scale LH2 on-board tanks; Stored LNG = small-scale Storage at cryogenic conditions; MGO = maritime gasoil. Numbers are exptessed on a lower heating value (LHV) basis. Weight of the storage equipment is included.

Source: IRENA[23]. "Hydrogen Overview" (2022).

In addition to the above properties, if hydrogen is produced without emitting greenhouse gases, it is considered a clean fuel. This occurs, for example, in the case of water electrolysis production from renewable sources, with oxygen being emitted as a by-product of the process followed by water vapor during combustion. It should be noted that hydrogen produced from other non-renewable energy sources is also considered clean hydrogen but only if the emission of CO2 in the production process is controlled and does not exceed established limits, which will depend on the country and its legislation.

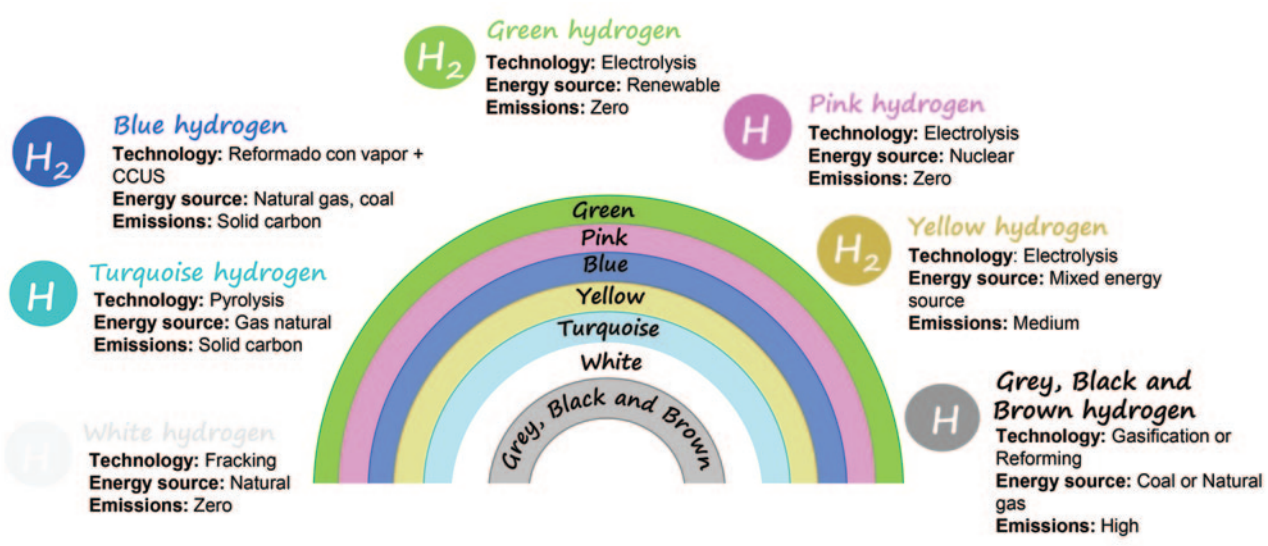
What types of H2 are there?

On the planet, hydrogen is found combined with other elements, such as carbon in the formation of organic compounds, or oxygen in the formation of water molecules. To separate hydrogen from the element that accompanies it, it is necessary to subject the compounds to specific processes. Depending on the process and the energy used in the process, hydrogen is called by different names (see Figure 5):

- **Green.** This is hydrogen generated by water electrolysis which uses electricity from renewable sources. Other examples of green sources of hydrogen include those produced through natural gas reforming which is the process by which hydrogen is replaced with biomethane or through photocatalysis and photoelectrocatalysis, whereby the energy source is renewable and no CO2 is emitted.
- **Pink.** Hydrogen is called pink when it is obtained by electrolysis, but the energy source used to produce electricity is nuclear energy. It is considered clean due to the low carbon emissions in its production.
- **Blue.** This hydrogen is also obtained from hydrocarbons, but in this case the polluting emissions are captured and stored using CCUS technologies[24]. This makes it possible to produce low-carbon hydrogen that is considered clean hydrogen.
- **Yellow.** In this case, the hydrogen production method is also electrolysis, but the electricity source used is mixed (not completely renewable).
- **Turquoise.** Hydrogen is generated through the pyrolysis of a molten metal by passing natural gas through it, releasing hydrogen and carbon in a solid state.
- **White.** Hydrogen found in nature, usually in subway deposits, is called white[25].
- **Black, gray and brown.** This is obtained from hydrocarbons by steam reforming, partial oxidation and autothermal reforming techniques or gasification of the fossil fuel which separates the carbon and hydrogen bond.

[24]Carbon capture, utilization and storage (CCUS).
[25]Earth-Science Reviews, "The occurrence and geoscience of natural hydrogen: A comprehensive review." (2020)

Figure 5. Types of hydrogen by production method, energy source and emissions.



Source: Técnicas Reunidas "Present and future of hydrogen".

Among all forms of hydrogen production, it is green hydrogen that is receiving the greatest regulatory impetus, as the absence of greenhouse gas emissions during its production makes it the main catalyst in the process of energy transition to a carbon-neutral economy.

When is hydrogen considered renewable?

In order to boost the role of hydrogen, the different regulatory bodies are defining the premises under which hydrogen can be considered as green or renewable[1]. By way of example, the European Union considers hydrogen renewable if it meets the following characteristics:

- Liquid and gaseous fuels of non-biological origin that are produced from electricity are considered renewable only when the electricity used in their generation comes from renewable sources.
- This renewable electricity can be supplied in two ways: (i) direct connection to a renewable production plant (wind, photovoltaic, etc.), or (ii) electricity taken from the grid as fully renewable.

(i.a) "The renewable electricity generating facilities must have been in operation for a period of less than 36 months prior to the start-up of the plant for the generation of liquid and gaseous fuels of non-biological origin".

(i.b) "If the installation producing renewable electricity is connected to the grid, apart from the plant generating liquid and gaseous fuels of non-biological origin, it must be demonstrated that no electricity from the grid is used by means of a smart metering system".

(ii.a) "Electricity shall be considered as fully renewable if the facility producing the liquid and gaseous fuel of non-biological origin is located in an auction area where the average production of renewable electricity is above 90% in the previous calendar year and the production of liquid and gaseous fuel of non-biological origin does not exceed a maximum number of hours in relation to the production of renewable electricity in the auction area".

(ii.b) "In auction zones where the average production of renewable electricity represents the dominant percentage, but less than 90%, the electricity used shall be considered as fully renewable as long as the hours of production of liquid and gaseous fuel of non-biological origin do not exceed the share of renewable electricity generated in the auction zone".

(ii.c) "If the above conditions are not met, the electricity shall be considered as fully renewable if it originates from an auction area where the emission intensity is less than 18 g CO_2 eq./MJ provided that the following condition is met:

There are one or more renewable power purchase agreements justified by a PPA (Power Purchase Agreement)[2] in one or more renewable generation facilities for an amount of electricity equivalent to that declared as fully renewable in the production of liquid and gaseous fuel of non-biological origin".

In addition, the European Commission's hydrogen strategy defines renewable hydrogen as hydrogen produced by electrolysis of water driven by electricity from renewable sources or also through biogas reforming or biochemical conversion of biomass. In EU legislation, renewable hydrogen and hydrogen-derived fuels produced without the use of biomass are referred to as renewable fuels of non-biological origin (RFNBO).

[1] European Commission. "Delegated regulation on Union methodology for RFNBOs" (2023).

[2] PPA: long-term clean energy purchase and sale agreement from a specific asset and at a pre-fixed price between a renewable developer and a consumer.

Value chain

"If you can't describe what you are doing as a process, you don't know what you are doing"
W. Edwards Deming[26]

The hydrogen value chain involves a large number of actors along its three stages (Production, Transport and Storage, and Consumption), although some of them may be vertically integrated in various parts of the chain. Figure 6 summarizes the main stages of this chain.

Production

Hydrogen can be extracted from water or fossil fuels. The latter are used in 95% of current hydrogen production27 and are responsible for CO2 emissions in the process. As described in the previous section, there are different origins according to their mode of production.

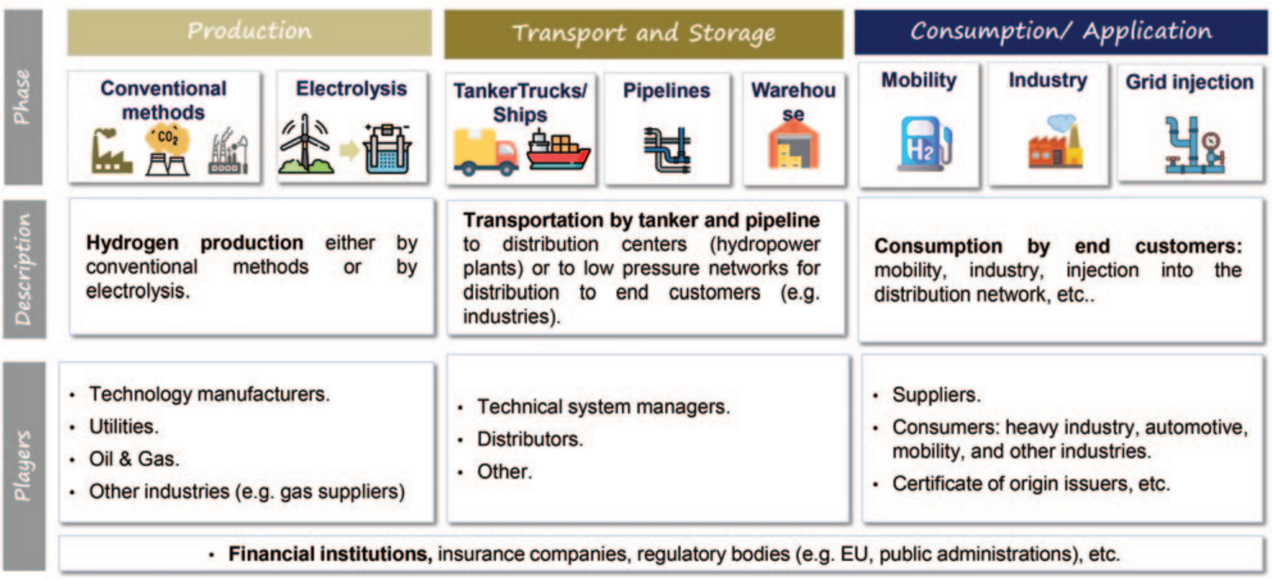
a) Hydrogen from fossil fuels.

Hydrogen obtained from fossil fuels comes mainly from natural gas, followed by oil and coal. The most common thermochemical production routes are reforming (steam reforming, partial oxidation and autothermal reforming) and gasification, the method by which gray hydrogen is obtained, which can become blue if carbon emissions are captured in the process (CCUS).

[26] W. Edwards Deming was an American statistician who revolutionised the manufacturing industry. He is famous for his 14 points of management and the PDCA (Plan, Do, Check, Act) Cycle, which focused on continuous process improvement to increase quality and reduce costs.

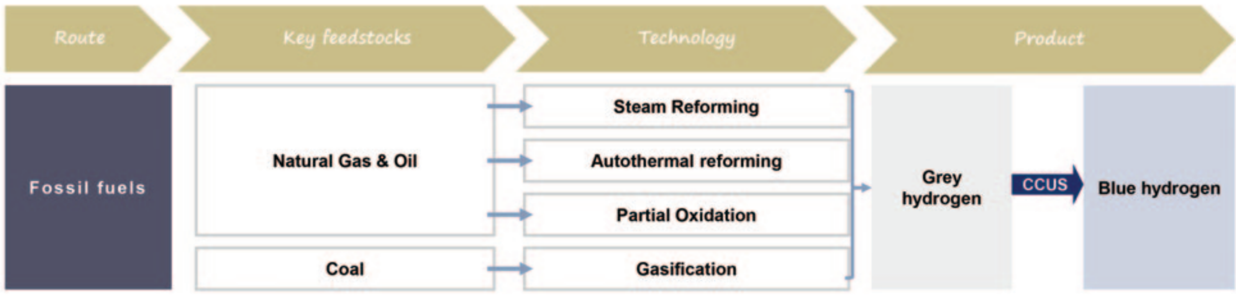
[27] IRENA, "Geopolitics of the Energy Transformation: The Hydrogen Factor" (2022).

Figure 6. Hydrogen value chain differentiated into three stages: production, transportation and storage, and consumption/application.



Source: Own elaboration.

Figure 7. Hydrogen production pathways from fossil fuels.



Source: Own elaboration.

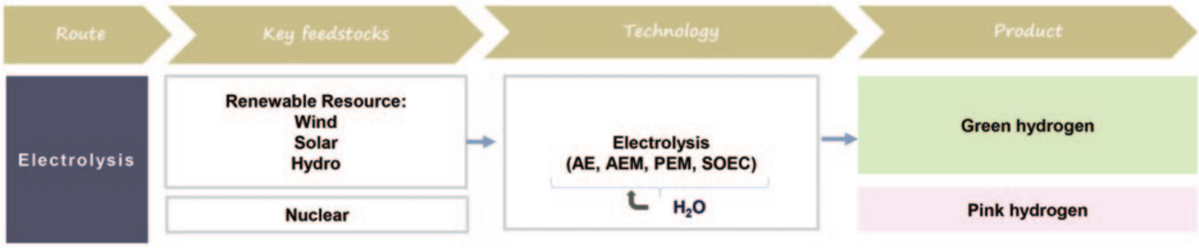
b) Hydrogen from renewable sources.

Electrolytic hydrogen.

The other main hydrogen production route is water electrolysis, an electrochemical technology consisting of the decomposition of water into its constituent elements, hydrogen and oxygen, by passing an electric current through water in an electrolyzer. This process can be carried out without emitting greenhouse gases as long as it can be integrated with renewable sources that provide the energy needed to split the water molecule. However, hydrogen production by electrolysis is much more expensive technologically and economically than producing the same hydrogen using thermochemical processes based on fossil fuels, although there is room for improvement to make current water electrolysis technologies more efficient and hence less expensive. The most widely used electrolyzer technologies to date are:

- Alkaline electrolysis (Alkaline Electrolysis, AE). An alkaline solution is used as the electrolyte.
- Polymer Membrane Electrolysis (Proton Exchange Membrane, PEM). A polymeric membrane is used to separate hydrogen and oxygen ions during electrolysis.
- Solid Oxide Electrolysis Cell (SOEC). A solid ceramic electrolyte is used for electrolysis, with a high temperature input.

Figure 8. Hydrogen production pathways from renewable resources.



Source: Own elaboration.

Hydrogen from biomass

Conversion of biomass into hydrogen can be achieved through two basic techniques: hydrogen production by thermochemical processes (pyrolysis and gasification) and/or by biological conversion (fermentation and biophotolysis).

- Thermochemical processes: One of the most common methods is pyrolysis, which produces pure hydrogen gas from biomass by heating it in the absence of air. On the other hand, hydrogen can also be produced by gasification of biomass through partial oxidation at high temperatures.
- Biochemical conversion: All processes under this umbrella are considered zero-emission; therefore, the final product is green hydrogen. Among the biological conversion techniques, the most relevant are biomass fermentation and biophotolysis.

In the production stage, the involvement of different stakeholders is of special relevance:

- Technology developers are engaged in researching and improving existing technology by lowering costs or improving performance through either research institutes or R&D departments.
- Technology manufacturers are leading developers of electrolyzers, components for wind farms and solar photovoltaic parks, compressor manufacturers, etc.
- Feedstock suppliers: In the short and medium term, feedstock suppliers are needed to provide the necessary resources for the manufacturing of hydrogen. In the long term, however, hydrogen is expected to be green, which will negate the need for feedstock suppliers.

Figure 9. Hydrogen electrolysis technologies.

	AE	PEM	SOEC
	Alkaline electrolysis is the most **mature**, the most **efficient** and has the **lowest CAPEX** of the existing electrolysis technologies, which makes it ideally suited for large and continuous demand for hydrogen. However, it has limited scope for improvement.	Membrane technology has **great development potential thanks to synergies with PEM fuel cells**. Its rapid response to load changes allows it to provide grid services and adapt to fluctuating renewable energy prices..	SOECs are the **most promising electrolysis technology** due to their **high energy efficiency** and ability to operate in reverse mode **like fuel cells**. Lifetime and high CAPEX are the main barriers to commercial scale-up of the technology.
Electrolyte	KOH or NaOH	Polymeric membrane	Metal oxide membrane
Electrode	Nickel-plated steel	Platinum or iridium	Níquel, LSM-YSZ
Temperature	70-90 °C	80-100 °C	650-1000°C
Useful life	60000 -90000 h	30000-90000h	10000-30000 h
Efficiency (%)	63-70 %	56-60 %	**74-81%**
CAPEX (€/kWe)	445 – 1190 €/kW$_e$	980 – 1600 €/kW$_e$	2500 – 5000 €/kW$_e$
Pros	• **Commercial scale.** • **High durability.** • **Low cost.**.	• Solid electrolyte. • Ability to function as a **fuel cell**.	• Solid electrolyte. • **High efficiency**. • Ability to function **as a fuel cell**.
Cons	• **Corrosive** electrolyte. • The hydrogen produced needs to be purified..	• **High costs** associated with the electrode and membrane. • High water requirements.	• **Need for high investment (CAPEX).** • **Short lifetime.**

Source: Own elaboration.

- Utilities and Oil & Gas companies are strategically positioning themselves in the hydrogen market in order to initiate their energy transitions more quickly.

Transportation and storage

Hydrogen transportation will represent a major challenge in the coming years, as the connection method between producer and consumer may vary depending on the transport distance and the intended end use. There are several transportation options, such as pipeline transport and transport in liquid or gaseous form via ships or tankers. The choice of the most appropriate option will depend on the specific circumstances of each case.

Hydrogen can be stored in different ways, including in gaseous or liquid form, in solid form, or in liquid organic carriers. Each of these forms of storage is discussed below.

Storage in gaseous or liquid state.

Hydrogen can be stored physically as either a gas or a liquid.In gaseous storage, given the low density of hydrogen, it must be compressed and stored in very high pressure tanks. If large volumes are to be stored, salt caverns, reconditioned natural gas fields or aquifers could be used. On the other hand, liquid storage requires the hydrogen to first undergo a liquefaction process at -253ºC.

Solid storage.

Another way to store hydrogen is through intermediate compounds, such as metal hydrides, by reversible chemical processes. In these processes, hydrogen is absorbed by a metal through heat input and then released by lowering the pressure of the metal hydride below the equilibrium pressure[28,29]. Solid storage offers higher density and lower risk of leakage, although it is still under development and requires additional chemical processing.

Storage in liquid organic carriers.

Finally, another way to store hydrogen temporarily is by means of liquid organic hydrogen carriers that are formed from hydrogen and another compound. Both generate a third substance that is stored and transported. Once the hydrogen is to be released, the chemical reaction is reversed, and both the hydrogen and the initial compound are recovered. This type of storage provides a solution to the instability of hydrogen and its transport but involves the need for chemical inversion to recover the hydrogen and may have a lower energy yield.

In the transport and storage phase, the involvement of different agents such as hydrogen distributors, transporters and technical managers is of particular relevance.

[28]Pressure at which the reaction rates of formation and decomposition of the compound are equal.
[29]NATURGY. "Hydrogen: Energy vector of a decarbonized economy" (2020).

Hydrogen transport mechanisms.

Pipeline

One of the most common forms of XX transportation is the use of the natural gas transmission network. Today, the transmission network has 1.2 million km installed worldwide, to which an additional 200,000 km under construction or in the bidding phase should be added[1]. In order to reuse these facilities, it would be necessary to reconfigure the existing pipeline system to adapt it to the new gas. The cost of this reconfiguration is estimated to be 50% to 80% less than the cost of installing a new hydrogen supply network[2]. In the short term, there is the option of blending as an alternative until pipelines are fully adapted. This method consists of introducing a low percentage of hydrogen into the gas network, together with natural gas. However, blending presents several challenges, such as the incompatibility of materials in the network, safety requirements (hydrogen is highly flammable and explosive), the need for hydrogen quality assurance systems and the different transport pressure of one and the other gas. In this context, some initiatives are working to upgrade gas transmission networks to allow their use for hydrogen, such as the HyReady initiative or the European Hydrogen Backbone (EHB).

One of the main problems with blending hydrogen and natural gas is that, due to its lower density, hydrogen requires a higher transport pressure. To achieve a proper mixing of both gases in the transport network it may be necessary to increase the pressure of the gas in the network or reduce the pressure of the hydrogen before blending. Typically, natural gas is transported at pressures between 5 and 100 bar, while higher pressures are used for hydrogen. This difference can cause, among other things, hydrogen pockets to appear during the injection process, not integrating properly with the natural gas.

Other alternatives could be the so-called repurposing (adapting the existing natural gas network to hydrogen conditions in order for natural gas to be replaced with hydrogen) or building greenfield hydroproducts in parallel to the existing network taking advantage of available land and rights-of-way (see section Hydrogen transport infrastructure).

Ship

This means of transport is intended for long distances, as it is more expensive than transport by hydro-ducts. The state in which hydrogen is transported will vary depending on the type of storage and the use to which it is to be put, and may be liquid, in the form of ammonia or as an organic carrier. The transport of liquid hydrogen is similar to the transport of liquefied natural gas, except that the boiling point of liquid hydrogen is considerably lower (-253°C for hydrogen compared to -162°C for natural gas). Therefore, in order to achieve the cooling of gaseous hydrogen at such low temperatures, a large amount of energy is required. The main advantage of transporting hydrogen in this state is that a higher purity of hydrogen is achieved for consumption, which is necessary for some applications.

With regard to ammonia transport, it would be possible to take advantage of the experience and infrastructures already in place for the manufacture of fertilizers, thus reducing the need for additional investment.

Finally, hydrogen could also be transported absorbed in organic components, called liquid organic hydrogen carriers (LOHC[3]). These substances do not require refrigeration and, due to their physical properties, could be stored in oil tankers.

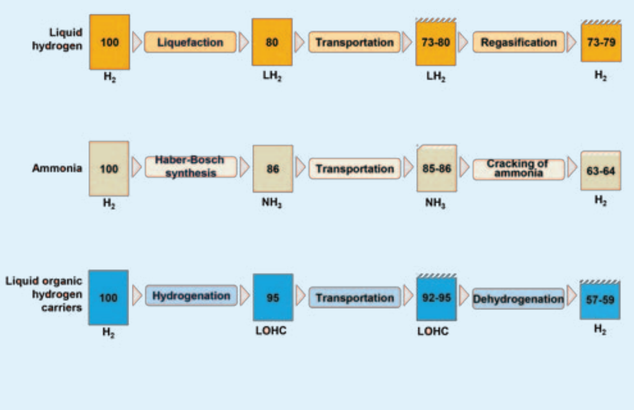
Figure 10 shows the numerical values representing the percentage amount of energy subtracted from hydrogen as a function of the transport used, along the supply chain, assuming that, at each stage of transport, the energy needs are covered with hydrogen itself or some fuel derived from it.

Truck

Due to their high cost, trucks are usually used for short distances and whenever there is no hydro-duct system. Compressed or liquid hydrogen is transported in special containers.

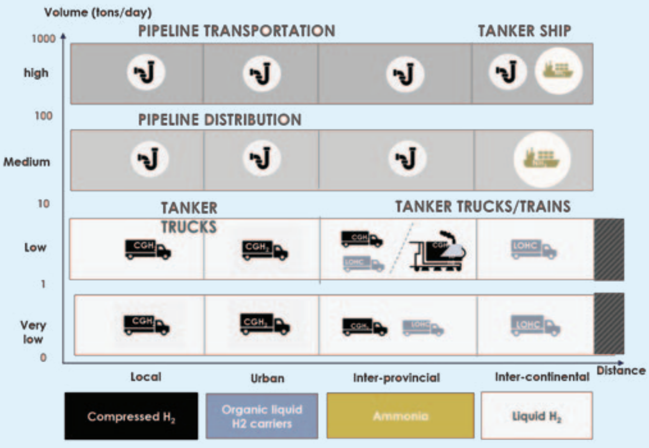
[1]IEA. "Global Hydrogen Review 2022" (2022).
[2]Íbid.
[3]LOHC: Liquid organic hydrogen carriers.

Figure 10. Energy available along the conversion and transport chain in hydrogen equivalent terms.



Source: IEA. "Global Hydrogen Review" (2022).

Figure 11. Comparison of different types of hydrogen transport according to volume and distance.



Source: BloombergNEF. "Hydrogen Economy Outlook" (2020).

Marketing (Consumption/Application)

Hydrogen has applications in four main areas:Industry, Transportation, Energy and Other fields.

Industrial application

Currently, the sector that consumes the most hydrogen is industry. The three main hydrogen consuming industries are petroleum refining, the chemical industry (particularly in the production of ammonia and methanol), and the metallurgical industry. Virtually all of this hydrogen is gray, although it could be replaced by green hydrogen from renewable resources. In addition, the use of hydrogen as a substitute for fossil fuels in high-temperature industrial applications is being evaluated.

Transport application

In transportation, there are two main lines of technological development for hydrogen: (i) direct use as a power source in fuel cell vehicles and (ii) e manufacture of renewable fuels (RFNBO - Renewable Fuel of Non-Biological Origin) or 'e-fuels' with zero net emissions, to replace ordinary gasoline or diesel.

Currently, road vehicles considered as heavy transport are the main source of hydrogen demand in transportation. Most of it is consumed in trucks and buses due to their high annual mileage, heavy weight and need for autonomy, compared to fuel cell electric cars. It is also presented as a solution for rail transport, as it allows the decarbonization of diesel lines when electrification is difficult and distances are too long to be covered by battery electric trains[30]. In addition, interest is growing in the use of hydrogen and hydrogen-derived synthetic fuels in the maritime and aviation sectors, although these are less mature technologies than those described above.

Application in Energy.

Renewable energies need s generation to maintain grid stability. Conventional generation assets such as gas turbine power plants are key in balancing supply and demand. While they are currently necessary, they are being considered for elimination in a future carbon-free energy system. This opens up an opportunity to include hydrogen and other low-carbon fuels in power generation, as they can be used to balance such variability[31]. This implies the possibility of producing and storing hydrogen during periods of surplus renewable energy production for later use during periods of high energy demand. However, it should be noted that the efficiency of this type of storage will depend directly on the electrolyzer technology. In this case, there will be two ways in which renewable variability can be balanced:

- Power to Power: the renewable surplus is used to produce H2 through electrolyzers, which is then stored and converted into electricity through hydrogen fuel cells.

- Power to Gas: the renewable surplus is used to produce H2 through electrolyzers, which is then stored and injected into the gas grid.

Application in construction and other fields.

The possibility of being able to use hydrogen in the domestic and tertiary sector, inside buildings, as a flexible, adapted and continuous energy supply is being studied. This use would be a possible alternative to fossil fuels for district heating, for example.

[30]IEA. "Future of Rail" (2019).
[31]Shell. "Shell Scenarios – Sky: Meeting the goals of the Paris Agreement" (2018).

However, the entry of new energies into these areas is complex, as it depends on multiple factors such as the type and location of buildings or general convenience, which reinforces the likelihood that, in the future, various energy sources and technologies will coexist in this sector.

Oxygen produced by electrolysis is also being used for rocket propulsion, as part of the oxidant in combustion.

In the consumption phase, end users include:

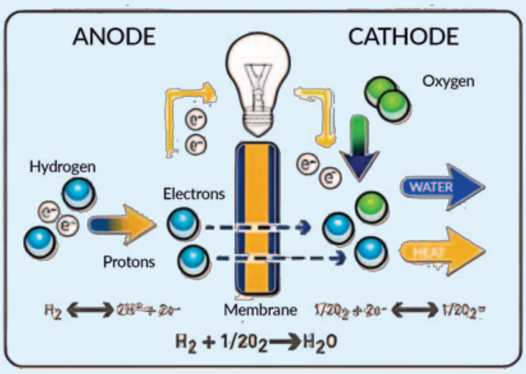
- Consumers: mainly industry, the transport sector (e.g. automotive sector), the energy sector (e.g. Oil & Gas companies), and other applications where its use will depend on the development of the sector.
- Hydrogen marketers: over the years, they will experience significant growth and consolidate their position as key players in the industry.
- Hydrogen plant managers: specialized in the design, construction, operation and maintenance of hydrogen refueling stations for fuel cell vehicles.

Hydrogen fuel cells

Hydrogen fuel cells (Fuel Cell) are devices in which a reverse process to that carried out by electrolyzers is performed: the chemical energy of hydrogen and oxygen is converted into electrical energy and water through an electrochemical reaction. As can be seen in Figure 12, hydrogen is introduced into the anode and separated into protons and electrons through the oxidation reaction. The electrons move to produce electrical energy (heat in Figure 12), while the protons move through the electrolyte to the cathode, where they combine with oxygen to form water.

Hydrogen fuel cells have certain advantages over battery electric cars, such as shorter recharge times and lower vehicle weight due to smaller batteries. In addition, hydrogen has a higher energy density than batteries and allows more autonomy and smaller vehicle footprint, especially at high pressures or liquefied. However, it is important to keep in mind that the energy efficiency of hydrogen fuel cells is lower than that of battery electric cars, and that the production and distribution of hydrogen requires an energy input.

Figura 12. Proceso químico por el cual funciona una pila de combustible de hidrógeno.



Source: Biodisol. "Clean energy potential of fuel cells".

RFNBO

"RFNBO" means renewable liquid and gaseous fuels of non-biological origin. It is a product group of renewable fuels defined in the Renewable Energy Directive (Art. 2.36). These fuels are produced from renewable energy sources other than biomass. Therefore, gaseous renewable hydrogen produced by feeding electricity based on renewable energy through electrolysis is considered a RFNBO. At the same time, liquid fuels, such as ammonia, methanol or e-fuels (synthetic fuels), are considered RFNBOs when produced from renewable hydrogen[1].

Renewable hydrogen that is produced from biomass sources (such as biogas) is not considered an RFNBO, but is covered by the Renewable Energy Directive under the definition of 'biomass fuels'. RFNBOs will only count towards the EU's renewable energy target if they deliver more than 70% greenhouse gas emission reductions compared to fossil fuels, which is the same standard that applies to renewable hydrogen produced from biomass.

[1] European Commission: EU Delegated Acts on Renewable Hydrogen.

Current status and anticipated developments in hydrogen

"Clean hydrogen proves that we can reconcile our economy with the health of our planet"
Ursula von der Leyen[32]

Current production and consumption situation

This section provides a quantitative analysis both of hydrogen production, specifying which countries are at the forefront in the production of this resource, and of hydrogen demand, reviewing what hydrogen percentages are requested by each sector.

Hydrogen production

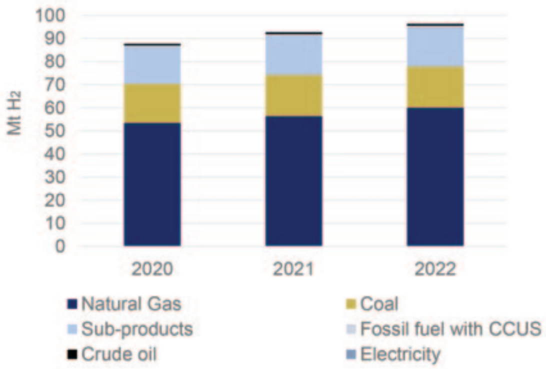
In 2022, global hydrogen production experienced a 3% increase compared to the previous year. In line with the 2021 trend, hydrogen production continued to be dominated by the use of fossil resources. Specifically, 62% of global production came from natural gas without carbon capture, utilization and storage (CCUS), while coal contributed 21% of global production. In addition, 16% of global hydrogen production was a by-product generated mainly in refineries and petrochemical industries during the naphtha reforming process.

In 2022, only 0.1% of the world's hydrogen production was carried out by electrolysis[33]. However, in recent years there has been strong growth in production capacity by this method, with approximately 600 projects announced with a combined capacity of more than 160 GW from 2022. By the end of 2022, the global installed capacity of water electrolyzers for hydrogen production reached almost 700 MW, an increase of 20% compared to the previous year (see Figure 14). Alkaline electrolyzers (ALK) accounted for 60% of installed capacity by the end of 2022, followed closely by proton exchange membrane (PEM) electrolyzers, which accounted for approximately 30%.

Finally, global installed capacity could increase more than threefold by 2023, reaching 2 GW by the end of 2023 (equivalent to approximately 0.2 million tons of hydrogen production), assuming all projects are realized as planned.

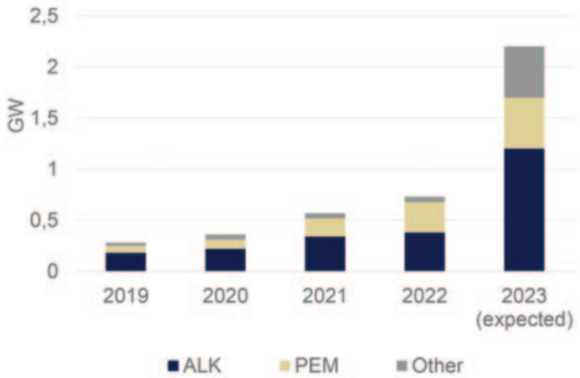
[32]Ursula von der Leyen, Presidenta de la Comisión Europea.
[33]IEA, "Global Hydrogen review" 2023.
[34]Data based on projects that have reached at least the final investment decision (FID), or are under construction.

Figure 13. Hydrogen production from its various sources.



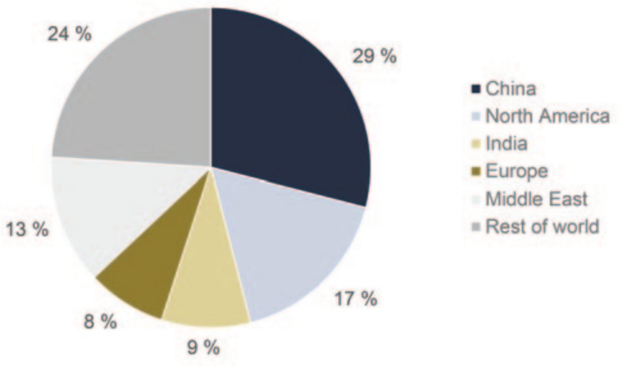
Source: IEA "Global Hydrogen Review 2023".

Figure 14. Current hydrogen production capacity by electrolysis in GW of existing plants worldwide[34].



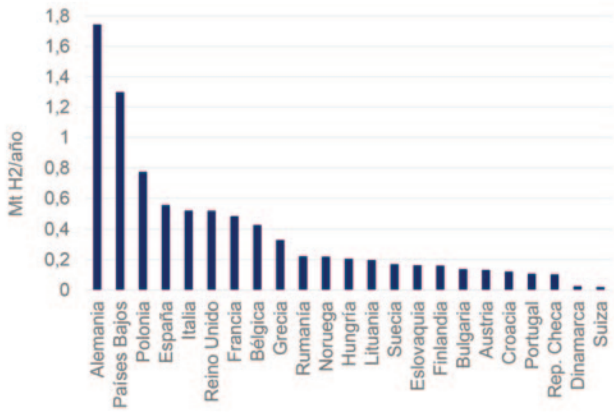
Source: IEA "Global Hydrogen Review 2023".

Figure 15. Global hydrogen demand by region in 2022.



Source: IEA "Global Hydrogen Review 2023".

Figure 16. Hydrogen consumption in Europe by country.



Source: Fuel Cells and Hydrogen Observatory (FCHO) "Demanda de Hidrógeno de Europa", mayo 2022.

Hydrogen consumption

Global hydrogen demand for 2022 reached 95 Mt (million tons), an increase of almost 3% over the previous year[35]. Hydrogen use grew significantly in all major consuming regions except Europe, due to reduced activity as a result of sharply rising natural gas prices[36].

In contrast, North America and the Middle East significantly increased hydrogen use (about 7% in both cases). In China, hydrogen use grew more modestly, but it remains by far the largest consumer of hydrogen, accounting for almost 30% of world consumption.

As in previous years, the growth in global hydrogen use is not the result of specific incentive policies, but rather of global energy trends. Virtually all of the increase has occurred in traditional applications, mainly in refining and chemical processes, and has been aligned with the increase in fossil fuel-based production.

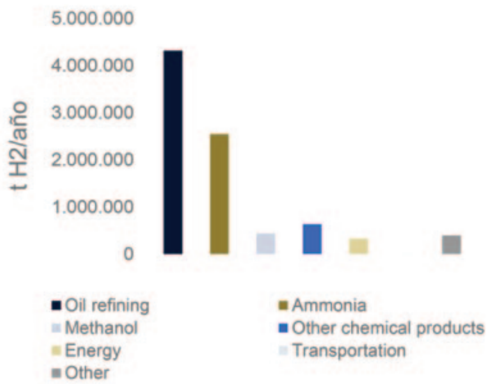
Within the European Union, Germany is the country with the highest demand for hydrogen, followed by the Netherlands, Poland and Spain (see Figure 16).

By type of activity, oil refining, ammonia production, and methanol production are the main users. However, it is oil refining that consumes most of the hydrogen produced worldwide. In Europe, for example, hydrogen demand for oil refining makes up almost 50% of all hydrogen needs in this continent.

[35] IEA, "Global Hydrogen Review 2023" (2023).

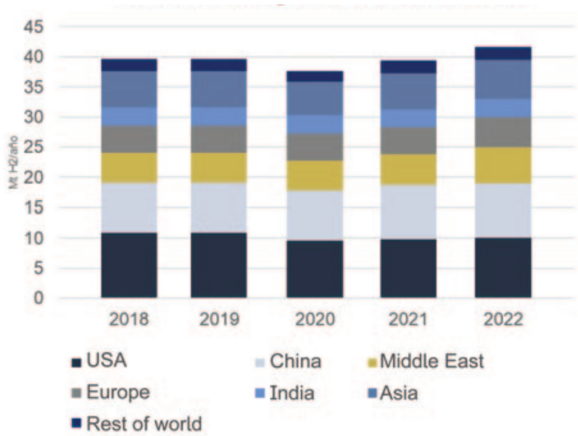
[36] The chemical industry reduced its production, bringing down H2 use in Europe by almost 6%.

Figure 17. Hydrogen consumption in Europe.



Source: Fuel Cells and Hydrogen Observatory (FCHO) "Demanda de Hidrógeno de Europa", mayo 2022.

Figure 18. Hydrogen consumption in the refining industry by country.



Source: IEA "Global Hydrogen Review 2023".

I. Hydrogen consumption in industry

a) Refining industry

Hydrogen use in oil refining reached more than 41 Mt in 2022. Refineries use it mainly to remove impurities and transform oil fractions into lighter products. Over the last six years, demand has remained at around 40 Mt H2/year, with most of the production being met by gray hydrogen and only 1% by low-emission technologies.

b) Chemical and metallurgical industry

Ammonia and methanol production and steel reduction are the main uses in which hydrogen plays an important role. Of the 53 Mt of hydrogen used in 2022, about 60% was for ammonia production, 30% for methanol and 10% for direct reduction iron[37] in the iron and steel subsector.

II. Hydrogen consumption in transportation

Although transportation is not currently one of the largest hydrogen users, this sector has seen very significant growth. In 2022, hydrogen use for road transport increased by 45% compared to 2021 (see Figure 20).

Although cars represent a lower demand for hydrogen for transportation compared to buses, it is worth noting that the production of Fuel Cell Electric Vehicles (FCEVs), which are powered by hydrogen, has increased considerably over the last 2 years. A total of 58,000 FCEVs had been registered by the end of 2022, representing a growth of more than 40% over the previous year, and 63,000 more were registered during the first half of 2023 alone. Some companies already have fuel cell electric vehicle models available on the market and continue to invest in the development of such technology. Against this backdrop, the market for hydrogen electric vehicles is expected to continue to expand over the next decade in all road segments.

The stock of fuel cell buses grew similarly to that of private vehicles, with an increase of about 40% in 2022 compared to the previous year. In June 2023, there were around 7,000 fuel cell buses worldwide, approximately 85% of which are located in China.

Globally, there were around 1,100 hydrogen refueling stations in operation as of June 2023, and hundreds more are planned. As an example, the EU Alternative Fuels Infrastructure Regulation requires hydrogen refueling stations every 200 km along major road networks and at all urban nodes from 2030.

As far as the railway sector is concerned, there are many projects in different European countries, such as Italy, Canada, Spain and Japan; for example, in Germany, there are fleets of hydrogen fuel cell trains.

As for shipping, the Getting to Zero initiative, which aims to reduce greenhouse gas emissions in the maritime sector to zero by 2050, has published numerous ongoing pilot projects and demonstrations in 2022, of which about 45 focus on the use of hydrogen, 25 on the use of ammonia and 10 on the use of methanol in shipping[38].

III. Hydrogen consumption in the energy sector

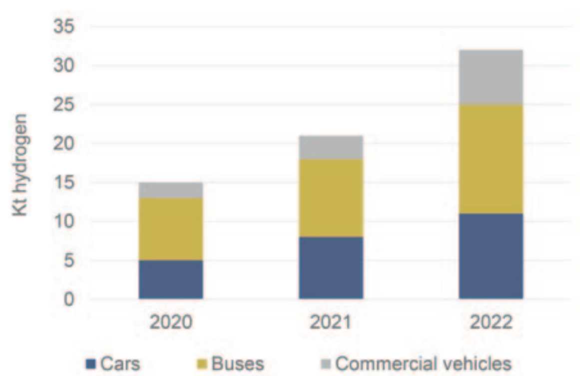
Hydrogen as a fuel in the energy sector is virtually non-existent today, with a share of less than 0.2% of the global electricity generation mix[39] (and largely not from pure hydrogen, but from hydrogen-containing mixed gases from steel production, refineries or petrochemical plants).

[37] DRI - Direct Reduced Iron.
[38] Getting to Zero Coalition. "Mapping of Zero Emission Pilots and Demostration Projects" (2022).
[39] Considering electric power produced with hydrogen in internal combustion engines (ICE) and gas turbines.

Figure 19. Hydrogen demand in the chemical industry worldwide.

Source: IEA "Global Hydrogen Review 2023".

Figure 20. Hydrogen demand in the transport sector worldwide.



Source: IEA "Global Hydrogen Review 2023." Commercial vehicles include light commercial vehicles,as well as medium and heavy-duty trucks.

IV. Hydrogen consumption in the construction sector

The contribution of hydrogen to meeting energy demand in the building sector remains negligible and, there is no significant progress in 2022. As part of efforts to meet climate targets, there is a need to shift the use of fossil fuels in buildings towards low-carbon alternatives, but options such as electrification through heat pumps, district heating and distributed renewables appear to be far ahead of hydrogen technologies.

Green hydrogen development

The level of global green hydrogen development can be measured by the installed electrolysis capacity. By the end of 2022, the global installed capacity reached almost 0.7 GW[40]. However, the great potential of green hydrogen has led to a global alignment for its promotion and use as a lever for decarbonization. The world's major economies are promoting new projects and are expected to reach capacities of between 100 and 300 GW in 2030[41], which implies a remarkable increase considering the 2GW expected to be reached by the end of 2023 with ongoing projects.

I. Worldwide electrolysis targets

As mentioned, the commitment to energy transition needs a boost in green hydrogen production. Currently, around 600 projects with a combined capacity of more than 160 GW have been announced worldwide. If all the announced projects for hydrogen produced from water electrolysis and fossil fuels with CCUS are realized, the annual production of low-emission hydrogen could reach more than 38 Mt by 2030 (17Mt being from projects currently still at an early stage). .

Half of all hydrogen to be produced by the projects announced for completion by 2030 comes from projects that are currently in feasibility stage, followed by projects that are in their very early stages of development. The world's first priority is to shift the existing demand for hydrogen in industry and refining from fossil-based hydrogen to low-emission hydrogen. If these projects go ahead, global electrolyzer capacity could reach 175 GW by the end of 2030 and even up to 300 GW (420 GW if very early-stage projects are considered).

The European Union is close to reaching the 44 GW target set in the Fit for 55 package[42] in 2021 thanks to a projected installed capacity of 39 GW by 2030 based on announced projects. However, there is still a long way to go to reach the 65 GW target set in 2022 as part of the more ambitious REPowerEU Plan. To achieve this, further progress in adding electrolyzer capacity would be necessary.

More specifically, Spain, Denmark, Germany and the Netherlands lead the way in electrolytic hydrogen production, together accounting for almost 55% of European production. In 2022, the European Commission focused on projects that promote renewable and low-carbon hydrogen supply during the second round of funding approvals for Important Projects of Common European Interest (IPCEI). The first European Hydrogen Bank auctions scheduled for late 2023 were also announced.

Australia, taking advantage of its abundant solar and wind renewable energy sources, aims to produce around 6 Mt of low-emission hydrogen through water electrolysis by 2030, with many of these projects targeting export markets.

In Latin America, hydrogen production through electrolysis is expected to reach approximately 6 Mt by 2030, according to announced projects. Chile leads the region, accounting for 45% of planned electrolytic hydrogen production from announced projects, followed by Brazil and Argentina, which together account for 30% of expected production.

In the United States, electrolyzer projects with a total capacity of 9 GW were announced in the last 12 months. In addition, China experienced significant development in electrolyzer technology and is expected to reach 1.2 GW by the end of 2023 (representing half of global installed capacity).

II. Hydrogen demand projections: climate scenarios

The European Union's main objective is to achieve climate neutrality by 2050. To this end, different scenarios have been developed to simulate how the energy system could evolve over time. The Net Zero Emissions scenario (NZE) is designed to achieve specific decarbonization outcomes, i.e. it reflects an emissions trajectory consistent with keeping the temperature

[40] IEA, "Global hydrogen review 2023" (2023).
[41] IRENA, "Green Hydrogen Cost Reduction" (2020).
[42] A set of legislative proposals and measures presented by the European Commission in 2021 to combat climate change. Its main objective is to reduce greenhouse gas emissions in the EU by 55% by 2030.

increase below 1.5 °C. The Announced Pledges scenario (APS) and the Stated Policies scenario (STEPS) are exploratory, as they define a set of initial conditions, such as policies and targets, and analyze where they lead based on different market dynamics and technological developments.

Total final energy consumption worldwide today is 442 EJ. This consumption is projected according to each different scenario. Under NZE, energy consumption would be reduced by an annual average of 0.9% from today until 2050. Under APS, it would increase until 2025 and then begin to decrease gradually. Finally, under STEPS, consumption would increase by 1.1% per year until 2030 and then continue to increase at a slower rate until 2050.

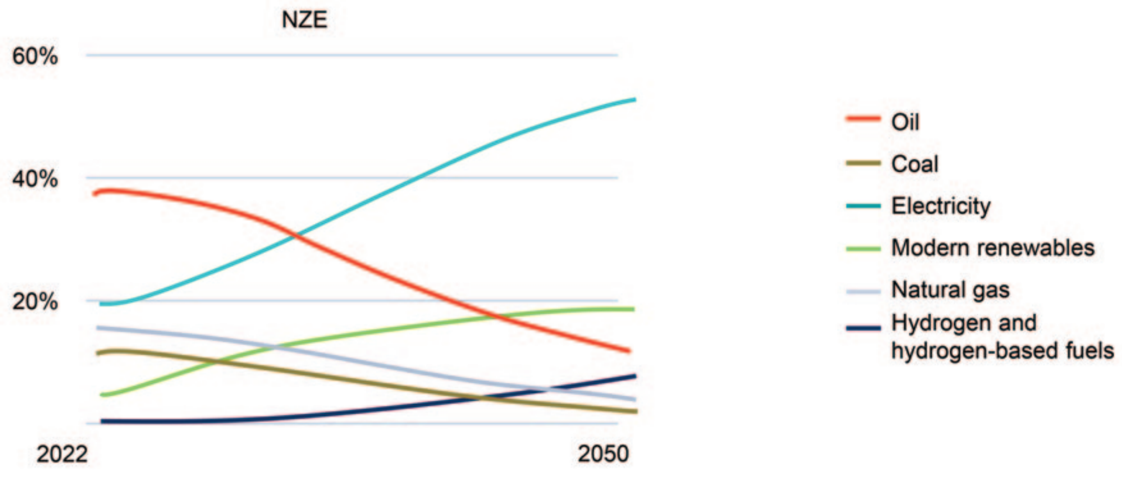
The NZE scenario states that, although the world population may increase significantly by 2030 following the trends of recent years, global energy consumption would decrease by 7% by 2030[44]. To achieve this, this scenario relies mainly on increasing energy efficiency, i.e. requiring less energy for end uses. The European Commission is aligned with this objective and considers it crucial to increase energy efficiency in order to reduce final consumption and thus achieve the EU's climate ambition[45]. Another of the fundamental pillars on which this scenario is based is the adoption and promotion of new technologies, mainly batteries, electrolysers and CCUS technologies.

The share of total world final consumption by fuel type in the NZE scenario is largely based on electricity and the increase in renewable energies, as 90% of electricity production would come from these sources. This would require a large increase in electricity system flexibility, such as batteries, hydrogen-based fuels or hydropower, to ensure reliable supplies. Moreover, as carbon neutrality implies a large decrease in fossil fuel use, fossil fuels would go from accounting for almost four-fifths of total energy supply today to just over one-fifth by 2050.

As for clean hydrogen, according to the NZE, by 2030, there would be an installed capacity of 850 GW of electrolysers and a production of 150 Mt (compared to the currently announced projects, which are expected to produce 38 Mt and could reach an installed capacity of 420 GW by 2030). By 2050, clean hydrogen production would reach 520 Mt. This shows a strong need to further boost hydrogen production in order to achieve emission neutrality targets.

[43]IEA, "World Energy Outlook", (2023).
[44]IEA. "Net Zero by 2050" (2021).
[45]European Commission. "Energy Efficiency Directive". (2023).

Figure 21. NZE scenario: Energy consumption by fuel.



Source: IEA, "World Energy Outlook" (2023).

Main hydrogen challenges

"Virtue is revealed in adversity"
Aristophanes[46]

Although it has great benefits and is set to position itself as an essential energy carrier for decarbonization, green hydrogen development faces numerous challenges along the entire supply chain.

Renewable hydrogen production

The first link in the supply chain is the production of green hydrogen itself, which poses the challenge of being costly compared to conventional alternatives. Today, the levelized cost of green hydrogen (LCOH[47]) is two to three times higher than the production costs of blue hydrogen, which is produced from fossil fuels with CO2 capture (CCUS)[48].

To understand how this cost difference could be reduced, it should first be noted that, typically, between 66% and 75% of the LCOH relates to operating costs, mainly the cost of the renewable electricity required, while capital costs represent between 25% and 33%. Therefore, the main key to lowering the cost of hydrogen production lies in reducing operating costs. These depend mainly on three factors, including the price of electricity, which is the most important, the efficiency of the installation and the degree of load.

The reduction in the price of electricity and the degree of load depend to a large extent on the regulatory framework (applicable tolls and charges, additionality criteria / emissions intensity / temporal and geographical correlation to be set to consider hydrogen and its derivatives as renewable, possibility of injection into the gas grid, etc.), while increasing the performance of the installation, and therefore reducing the amount of electricity needed to produce 1 kg of renewable hydrogen, requires improvements in electrolysis technology and a more optimized design and operation.

With respect to the contribution of CAPEX to LCOH, this may be reduced to the extent that there are falls in production costs favored by a decrease in unit costs due to technological development, changes in the materials used, the effect of economies of scale and the learning curve. There is, therefore, scope for a reduction in electrolysis costs, but in the short to medium term there could be price fluctuations caused by misalignments in the supply chain, due to the growth in demand for electrolyzers outweighing the development of production capacity.

Beyond the cost of producing hydrogen, large-scale renewable hydrogen production also faces challenges associated with the main inputs to electrolysis: water and renewable electricity.

- To produce 1 kg of hydrogen, 9-10 liters of distilled water must be supplied to the electrolyzers. If the use of water for cooling the plant and the reject water (the volume of water, rich in dissolved salts, obtained as a by-product of water purification) is also taken into account, the volume required can amount to between 20 and 27 liters per kg of hydrogen.

  This means that projects have to properly plan the water abstraction to be used. Although the volume of water required, compared to other current water uses, is very small, this is an increasingly sensitive aspect due to periods of drought and water stress, which have occurred more frequently as a result of climate change. On the other hand, projects must also obtain authorization to discharge the aforementioned reject water, which is mainly clean water with a higher concentration of salts resulting from the osmosis process.

[46] Aristophanes, Ancient Greek playwright. Born around 446 BC, he is considered one of the greatest representatives of the comic genre in classical literature.
[47] The LCOH (Levelized Cost of Hydrogen) is a variable that indicates how much it costs on average to produce 1 kg of hydrogen considering all the costs, both capital and operating, involved in its production over the lifetime of the facility.
[48] IRENA. "Green Hydrogen Overview". (2021).

- The other major challenge of large-scale hydrogen production is likely to be obtaining all the renewable electricity needed. As an indication, with current technologies, 50-60 kWh of electricity is needed to produce 1 kWh of hydrogen. If the use of hydrogen and its derivatives is also expanded into new industrial sectors and heavy transport, a lot of electricity would be needed. This requires installing a large wind and solar power capacity, in addition to that needed for the direct electrification of other sectors such as light mobility or air conditioning, with the consequent challenges of grid connection, land use, etc.

Hydrogen transportation infrastructure

At present, hydrogen is mainly transported by road, in trucks loaded with hydrogen cylinders at different pressures, or by pipeline. It is important to highlight the challenges related to the latter mode of hydrogen transport, either by injection into the existing gas network (blending) or in a network dedicated exclusively to hydrogen transport.

Existing natural gas pipelines cannot be used directly to transport hydrogen at high concentrations due to the embrittlement of the steel that this gas produces in direct contact with the pipeline. As seen previously, blending hydrogen with natural gas is considered as an option to deliver hydrogen from production facilities. However, this is always considered at very low concentrations, currently varying between 3% and 5% by volume[49], and even at these concentrations, pipeline life can be significantly affected.

Likewise, due to the operation of the gas network and fluid mechanics, it is not easy to ensure that the maximum admissible volumetric concentrations are not exceeded in sections of the network, since the real concentration of hydrogen in the gas circulating through a part of the network depends on the flows at any given time, the number and location of injection points, etc. In addition, injection points must be carefully designed and located to avoid high concentrations around them.

On the other hand, it is important to keep in mind that different types of users are connected to the same gas network, and, once hydrogen is injected into the network, it is not possible to know how much hydrogen is leaving the network at each point. Where the gas is used as a fuel, low concentrations of hydrogen are unlikely to have a significant effect beyond variations in the calorific value of the gas (since the mixing ratio is volumetric and the energy intensity of hydrogen by volume is much lower than methane, so the higher the mixing ratio, the lower the calorific value per unit volume of the resulting gas). On the other hand, those industries that use methane as an input, mainly in the petrochemical sector, may see their processes affected by the lower purity of natural gas.

An alternative (or evolution) to blending is the creation of networks dedicated exclusively to transporting hydrogen. In this sense, repurposing, or conversion of the existing gas network to transport hydrogen, allows significant cost and time savings (permitting, expropriation, etc.). However, the transition from one to the other vector poses new challenges: when should natural gas transport be stopped and the infrastructure be adapted to hydrogen?

One possibility is to start on sections that have two parallel pipelines by first transforming one of them. The limitation is that this is probably only possible in a small part of the network.

[49] Energy Sci Eng: Howarth RW, Jacobson MZ. "How green is blue hydrogen?". (2021).

Moreover, it will depend on whether production and consumption are located in the right volumes in precisely these areas. Another possibility would be not to repurpose existing pipelines, but to build greenfield hydroproducts parallel to the existing network by taking advantage of available land and rights-of-way. In this case, one of the main problems to be solved is where to build the new hydrogen compressor stations, as there is a high probability of not having enough space.

In Spain, Enagás has announced the start of the non-binding "Call For Interest" process for the first essential components of the Spanish Hydrogen Backbone Network. This process aims to assess the level of interest from key players in the energy sector in the creation of the necessary infrastructure for the transport of renewable hydrogen.

Hydrogen utilization

Another key factor for renewable hydrogen to be an effective lever in global decarbonization is that it is necessary not only to produce it, but also to transform end uses and create the demand needed to justify investment in its production and distribution. This implies the need to invest in supply infrastructure, production and storage technologies, and to create the right policies to encourage and ensure adoption.

As discussed throughout this document, most of the end uses of hydrogen are currently focused on industrial applications, such as the production of ammonia or methanol, or other uses such as oil refining. However, renewable hydrogen also needs to be used in other sectors, such as transportation and power generation.

- In the transportation sector, renewable hydrogen can be used in fuel cell vehicles to provide a clean, emission-free fuel alternative. However, to achieve mass adoption of these vehicles, it is necessary to develop a hydrogen supply infrastructure that meets the needs of users in different regions. This implies significant investment in building hydrogen stations and retrofitting existing fossil fuel stations.

- In terms of electric power generation, renewable hydrogen can be used to balance the variability of renewable sources such as wind and solar energy. However, for this to be viable, large-scale hydrogen production and storage technologies need to be developed. In addition, appropriate incentives and regulations are also needed to encourage investment in hydrogen storage projects.

- Another important factor in the transformation of hydrogen end uses is the need for a just and equitable transition. The transformation of vehicle manufacturing industries that rely on fossil fuels to use renewable hydrogen can have a major impact on the workers and communities that depend on these industries. Therefore, policies and programs are needed to ensure that they have access to employment and training opportunities for new skills in the renewable hydrogen economy.

Hydrogen market

Hydrogen is currently an industrial gas generally produced in the same facilities where it will be consumed. Therefore, there is not yet a mature market for it. This implies that there is no reference price index established in the market, which translates into higher costs paid by consumers, as there is little price transparency and competition. On top of this, there is low demand for low-carbon hydrogen at present, indicating that projects must be integrated from production to infrastructure and end use.

However, as the hydrogen sector develops, markets can be expected to develop. Although it is possible to draw certain parallels between the development of these markets and that of natural gas (based on LNG), there are some particularities:

- While fossil fuels are extracted from geological deposits located in very specific geographic areas, hydrogen can be produced almost anywhere, as long as there is water and electricity. This favors the creation of supply and dilutes the market power of producers.

- The costs of transporting hydrogen by ship (measured in amount of energy per kilometer) are much higher than in the case of LNG due to its lower energy density by volume and its very low boiling point. Additionally, if it is transported in another form (methanol, ammonia, LOHC, etc.), the corresponding conversion losses (especially relevant if it is not used directly in the same form as it is transported) must also be added. This also means that the cost of transporting pressurized hydrogen by pipeline is much lower than by ship, and therefore, the location factor is more relevant in price formation than in the case of LNG.

- Because of this, competitiveness in the markets will be strongly marked by the aggregate cost of both producing and transporting the hydrogen to the final demand or reference site (not solely or primarily by the cost of production).

Finally, it is necessary to stress that the product should not be hydrogen itself, but green/low-emission hydrogen. Therefore, there needs to be a relative standard and credible definition and certification system. Without this, it is not possible to know whether the hydrogen generated meets similar criteria, and you are not paying for dirty, or not so clean, hydrogen at the price of green.

In addition, a major challenge in establishing the hydrogen market is to meet the requirements for access to financing. In the European Union, the Innovation Fund auctions exist to support the production of non-biological renewable hydrogen in Europe. These auctions represent a key initiative to accelerate the transition to cleaner and more sustainable energy sources, but they also require a sound financial structure and careful planning to ensure that hydrogen projects can access the funding necessary for their long-term development and success. In addition, the Green Pact Industrial Plan announced the launch of the first auction for renewable hydrogen production in autumn 2023, with an Innovation Fund budget of 800 million euros intended to be paid as a fixed premium to renewable hydrogen producers. Also of note is the EU Hydrogen Bank, a European auction that will award up to 800 million euros to renewable hydrogen producers.

Finally, there are levers that could accelerate and encourage the decarbonization of industry by introducing hydrogen into these markets. One policy instrument that could help in this context is carbon contracts for difference (CCfDs) – long-term contracts to pay the difference between the current carbon price and the actual cost of CO2 reduction. At the EU level, the Commission plans to launch CCfDs as part of its REPowerEU scheme to support the shift of current hydrogen production in industrial processes from natural gas to renewables.

Regulation

Regulation plays a key role in the development and implementation of green hydrogen. Some of the main regulatory challenges are the following[50]:

- Creation of specific regulatory frameworks for green hydrogen, preventing it from being treated in the same way as other common industrial gases, for example, by limiting its production to industrial areas.

[50] HyLaw: "EU policy paper" (2019).

- Definition of what is considered green or renewable hydrogen, where the conditions and maximum greenhouse gas emissions allowed in the production process are limited, the perimeter of which must be specified.

- Development of the necessary financial and non-financial incentives to encourage investment in renewable hydrogen production facilities.

- Creation of guarantee of origin systems for renewable or low-emission hydrogen to facilitate the emergence of a hydrogen market.

- Development of specific regulations to promote transportation with zero-emission vehicles, ensuring a space for those powered by hydrogen fuel cells.

- Creation of specific frameworks for maritime transport with gas-powered ships, including green hydrogen.

- Evolution of pipeline gas transportation regulations to determine hydrogen producers' conditions for hydrogen connection / injection into the network (blending, connection and injection, equipment, maximum percentages, applicable tolls, safety considerations, etc.).

Summary of regulatory activity by continent and country.

	Europe		**North America**		**South America**		**Asia + Oceanía**	
	European Union	**United Kingdom**	**USA**	**Canada**	**Colombia**	**Chile**	**China**	**Australia**
National hydrogen strategy	EU Hydrogen Strategy REPowerEU	UK Hydrogen Strategy	National Clean Hydrogen Strategy and Roadmap	Hydrogen strategy for Canada	Hydrogen roadmap in Colombia	National Green Hydrogen Strategy	"Medium and long-term plan for the development of hydrogen energy industry (2021-2035)"	Australia's National Hydrogen Strategy
Installed capacity target for 2030	44 GW (Fit-for-55) 65 GW (REPowerEU)	10 GW	-	-	1-3 GW	5 GW	"Medium and long-term plan for the development of hydrogen energy industry (2021-2035)"	Australia's National Hydrogen Strategy
Legal and regulatory framework	Fit-for-55 Renewable Energy Directive (2009/28/EC) 2 actos delegados	Low Carbon Hydrogen Standard (LCHS) Industrial Carbon Capture Business Model (ICC BM) UK Emissions Trading Scheme (ETS)	Bipartisan Infrastructure Law (BIL) Inflation Reduction Act (IRA)	Clean Hydrogen Investment Tax Credit-	Decree 1476 of 2022	Energy Efficiency Law 21,305	14th Five-Year Plan for National Economic and Social Development and the Outline of Long-Term Goals for 2035	Commonwealth Hydrogen Regulation Guarantee of Origin scheme
Support for investment and innovation	NextGenerationEU IPCEI Hy2Tech IPCEI Hy2Use European Hydrogen Bank European Clean Hydrogen Alliance	Hydrogen Investment Roadmap Powering Up Britain: Net Zero Growth Plan	Clean Hydrogen Electrolysis Program	Net Zero Accelerator (NZA) Clean Fuels Fund	Law 2099 of 2021	CORFO	National Key R&D Programs (NKPs)	Hydrogen Headstart Program
Regulation of hydrogen in the gas network	EU Directive on Gas and Hydrogen Networks CertifyHy	Ten Point Plan for a Green Industrial Revolution	HyBlend	G-25—Policy on the use of gas meters in hydrogen-blending activities in the natural gas network	-	-	-	National Gas Law (NGL) National Energy Retail Law (NERL)
Regulations for adapting H2 to transport	'Sustainable and Smart Mobility Strategy' together with an Action Plan CertifyHy	Targeting net zero - next steps for the Renewable Transport Fuels Obligation: Hydrogen and renewable fuels of non biological origin	Alternative Fuel Excise Tax Credit Alternative Fuel Infrastructure Tax Credit Carbon Reduction Program (CRP)	Emissions Reduction Plan 2030	-	Energy Efficiency Law 21,305	-	Commonwealth regulation relevant to hydrogen mobility and transport

Detail of the regulatory framework in different geographical areas.

European Union

- **Hydrogen strategy published.** The EU strategy on the use of hydrogen was adopted in 2020 and is focused on enabling the production and use of renewable hydrogen to help decarbonize the EU economy in a cost-effective way, in line with the European Green Deal, and to contribute to economic recovery following the COVID-19 crisis. Today, the foundations set out when this strategy was adopted in July 2020 are already beingfulfilled, as the first 20 action points in the strategywere achieved within the first quarter of 2022.

  In addition, with the publication of the REPowerEU plan in the second quarter of 2022, the European Commission completed the strategy proposed in 2020, thereby strengtheningits ambitions for renewable hydrogen as a key energy carrier in the transition away from fossil fuel imports from Russia.

- **Legal and regulatory framework.** In terms of regulation, in 2021 the EU approved the "Fit for 55" package, which includes a series of legislative proposals to promote the reduction of net greenhouse gas emissions. In addition, in February 2023, the European Commission took a further step to define the regulatory framework for hydrogen and its relationship with other existing standards by specifying the definition of renewable hydrogenin two delegated acts. The first act sets out the requirements for considering hydrogen-based fuels as renewable fuels[1]. The second defines how emission reductions must be calculated when using this type of fuel[2].

  In addition, the REPowerEU set a target to produce 10 million tons of RFNBOs by 2030, equivalent to 500 TWh of renewable electricity (14% of the EU´s total electricity consumption)[3].

- Support for investment and innovation. In recent years the EU has been promoting various initiatives to encourage investment and innovation in the hydrogen market. The COVID-19 post-crisis recovery program, "NextGenerationEU" involved large investments in green transition and digitalization projects. Later in 2020, hydrogen was included into the Major Projects of Common European Interest (IPCEI Hy2Tech and IPCEI Hy2Use). Finally, in recent months, the "European Hydrogen Bank" has been consolidating a proposal that seeks to create a financial entity specializing in hydrogen projects in the European Union. Its aim is to mobilize private and public investment to accelerate the development of green hydrogen projects and contribute to the energy transition.

- **Regulation of hydrogen in the gas grid.** In 2021, the European Commission proposed to reform the 2009 EU Gas Directive as part of the proposed hydrogen and decarbonized gas markets package. The reform seeks to create a legal framework for hydrogen networks similar to that existing for gas and electricity, extending consumer rights and regulating the integration of hydrogen into EU energy networks. This proposal advanced in the EU Parliament and Council during 2022 and 2023 as part of an ongoing legislative process.

  In addition, initiatives are being promoted to build a robust system of guarantees of origin for renewable hydrogen, an example of which is CertifHy, which provided the basis for the world's first non-governmental Guarantee of Origin scheme for hydrogen.

- **Regulations to adapt hydrogen to transport.** The development of hydrogen transport in Europe is supported by the European Commission's Sustainable and Intelligent Mobility Strategy published in 2021[4], which sets out a series of milestones for achieving intelligent and sustainable transport in Europe. These milestones include at least 30 million zero-emission vehicles on Europe's roads and a doubling of high-speed rail traffic by 2030.. In addition, it is envisaged that short-distance scheduled collective transport will be carbon neutral. Hydrogen will play an important role in achieving these goals, especially

United Kingdom

- **Hydrogen strategy published.** In August 2021, the United Kingdom published its national hydrogen strategy, UK Hydrogen Strategy[5]. The document outlines the objectives and the route to follow to achieve the "Net Zero by 2050" target. Subsequently, in August 2023, the Department of Business, Energy and Industrial Strategy published an update to the strategy, increasing the installed capacity target for 2030 to 10 GW.

- **Legal and regulatory framework.** The Low Carbon Hydrogen Standard (LCHS) sets out the necessary requirements for hydrogen produced to be considered low carbon. The standard addresses both the emissions at the point of production and the methodology for calculating them. In addition, studies have been carried out to assess the impact of existing policies on the development of hydrogen production. These include the Industrial Carbon Capture Business Model (ICC BM)[6] and the UK Emissions Trading Scheme (ETS)[7].

- **Support for investment and innovation.** In 2023, the "Hydrogen Investor Roadmap"[8] was updated to provide details of hydrogen project funding, supporting up to £11 billion of private investment by 2030. In addition, in April 2023, the "Powering Up Britain: Net Zero Growth"[9] plan was published, detailing the latest developments in the delivery of financial support to encourage the first large-scale deployment of electrolytic and CCUS-enabled hydrogen production facilities.

- **Regulation of hydrogen in the gas network.** In accordance with the Gas Safety (Management) Regulations 1996, the current hydrogen content in gas networks is limited to 0.1% by volume. However, as part of the "ten-point plan"[10], the necessary tests for the blending of up to 20% hydrogen in the gas distribution network by the end of 2023 are being promoted?.

- **Regulations to adapt hydrogen to transport.** Since 2008, the Renewable Transport Fuel Obligation (RTFO)[11] has required companies to demonstrate that a certain percentage of the fuel they distribute is from renewable sources. In addition, in July 2022, the Department for Transport published the "Targeting net zero - next steps for the Renewable Transport Fuels Obligation: Hydrogen and renewable fuels of non biological origin"[12].

USA

- **Hydrogen strategy published.** In September 2022, the US Department of Energy (DOE) published a draft National Clean Hydrogen Strategy and Roadmap, laying the strategic foundation for clean hydrogen development in the United States.

[1]EU Commission, "Delegated regulation on Union methodology for RFNBOs" (2023)
[2]EU Commission, "Delegated regulation for a minimum threshold for GHG savings of recycled carbon fuels" (2023)
[3]EU Commission, "Commission sets out rules for renewable hydrogen". (2023).
[4]European Commission – "Sustainable and Smart Mobility Strategy". (2021)
[5]HM Government, "UK Hydrogen Strategy" (2023)
[6]Department for Business, Energy & Industrial Strategy, "Carbon Capture, Usage and Storage" (2022).
[7]HM Government, "Developing the UK Emissions Trading Scheme (UK ETS)" (2022).
[8]Department for Business, Energy & Industrial Strategy, "Hydrogen Investment Roadmap" (2023).
[9]Department for Business, Energy & Industrial Strategy, "Powering Up Britain: Net Zero Growth Plan" (2023).
[10]HM Government, "The Ten Point Plan for a Green Industrial Revolution" (2020)
[11]Department for Transport, "Renewable Transport Fuel Obligation: Compliance Guidance" (2022).
[12]Department for Transport, "Targeting Net Zero" (2022).

- **Legal and regulatory framework.** In November 2021, the U.S. Congress signed the Bipartisan Infrastructure Law (BIL)[13]. This landmark legislation authorizes and appropriates $62 billion for the U.S. Department of Energy (DOE), including $9.5 billion for clean hydrogen.

  In addition, in August 2022, the President signed into law the Inflation Reduction Act (IRA) that enables additional incentives for hydrogen, including a production tax credit that will further boost the U.S. market for clean hydrogen.

- **Support for investment and innovation.** To support investment and innovation, programs such as the "Clean Hydrogen Electrolysis Program" have been established to improve the economics and profitability of electrolysis technologies. In addition, $8 billion has been allocated to regional clean hydrogen centersto enable the development of networks of clean hydrogen producers and the infrastructure to connect them.

- Hydrogen on the gas grid regulation. In addition, regulation of hydrogen on the gas grid is being addressed through the HyBlend initiative, which focuses on overcoming technical barriers to blending hydrogen in natural gas pipelines. including research on the compatibility of materials, as well as technical-economic and life-cycle analysis.

- **Regulations to adapt hydrogen to transportation.** The U.S. Department of Energy has been passing certain laws and tax incentives to promote and adapt hydrogen for transportation. These include the Alternative Fuel Tax Credit, which offers a $0.50 per gallon tax credit for certain alternative fuels such as liquefied hydrogen, and the Alternative Fuel Tax Exemption, a tax incentive that applies to fuel equipment including liquefied hydrogen. It has also approved the "Carbon Reduction Program (CRP)" which includes state funding for the deployment of alternative fuel vehicles.

Canada

- **Hydrogen strategy published.** In December 2020, the Canadian government published its hydrogen strategy, setting ambitious targets in terms of production and use.

- **Legal and regulatory framework.** The Government of Canada has recently introduced three tax credits aimed at encouraging the transition to a net-zero emissions economy in its 2023 budget. Of most relevance to hydrogen is the Clean Hydrogen Investment Tax Credit, a refundable tax credit that incentivizes the production of clean hydrogen, with credits ranging from 15% to 40%, depending on the carbon intensity of the hydrogen.

- **Support for investment and innovation.** In terms of initiatives aimed at fostering innovation and propelling investment, several programs have been developed including: (1) Net Zero Accelerator (NZA), an $8 billion program that supports projects enabling large emitter decarbonization, clean technology and industrial transformation; and (2) Clean Fuels Fund, a $1.5 billion fund established in 2021 to reduce the capital investment risk required to build new or expand existing clean fuels production facilities, including facility conversions.

- **Hydrogen on the gas network regulation.** The bulletin "G-25-Policy on the use of gas meters in hydrogen-blending activities in the natural gas network" establishes the time requirements and conditions to allow injecting concentrations of 5 to 25% hydrogen into the natural gas network.

- **Regulations to adapt hydrogen to transportation.** Finally, an emissions reduction plan "Emissions Reduction Plan 2030" has been published, aiming for 35% of the country's total sales of medium and heavy-duty vehicles to come from zero-emission vehicles by 2030. This would create a significant strategic opportunity for hydrogen fuel cell vehicle manufacturers.

Colombia

- **Hydrogen strategy published.** In early 2021, the Colombian government, in collaboration with multilateral organizations and research institutes, began to develop a roadmap to establish the basis for the hydrogen market in the country. The so-called Hydrogen Roadmap[14] establishes the basis for:

  - Reaching a production capacity of between 1 GW and 3 GW of green hydrogen production and 50 kt of blue hydrogen by 2030.
  - Setting a target price for green hydrogen generation at 1.7 USD/kg.
  - Achieving40% green hydrogen consumption out of the total H2 currently consumed in the industrial sector.

- **Legal and regulatory framework.** Regarding the current regulatory status, Law 2099 of 2021, through articles 21 and 23, gives the National Government general powers to define the mechanisms for promoting innovation, research, production, storage, distribution and use of hydrogen.

- **Support for investment and innovation.** In addition, Decree 1476 of 2022 establishes provisions to define mechanisms, conditions and incentives to promote innovation, research, production, storage, distribution and use of hydrogen for public electricity services, energy storage and decarbonization of sectors such as transportation, gas, hydrocarbons and mining.

Chile

- **Hydrogen strategy published.** In October 2020,he Chilean government presented a set of policies aimed at creating a green hydrogen industry, the National Green Hydrogen Strategy. This is divided into 3 phases, each with a different objective:

  - First (2020 - 2025): the aim is to accelerate the use of green H2 in refineries, ammonia production and transport vehicles, and to encourage the adoption of blending up to 20% of hydrogen into gas networks.
  - Second (2025 - 2030): the experience gained would allow a strong entry into the international markets by exporting up to 5 GW of H2 ,produced by electrolysis, by that date.
  - Third (2030 onwards): the goal would be to position Chile as a global leader in the export of clean fuels, achieving 25 GW of electrolysis-based hydrogen production, as well as a green hydrogen price below 1.5 USD/kg.

- **Legal and regulatory framework.** In terms of regulations, Law 21,305 on Energy Efficiency, published in February 2021, defines hydrogen as a fuel, allowing the Ministry of Energy to regulate its use, review and update the electricity market regulations to allow for the participation of hydrogen in the sector, update the natural gas regulation to introduce green hydrogen quotas and facilitate the processing of permits for projects involving it.

- **Support for investment and innovation.** Within the framework of the sustainable economic reactivation and the national hydrogen strategy, CORFO (Corporación de Fomento de la Producción) promotes access to financing for hydrogen projects, accelerates the implementation of initiatives aimed at producing Green Hydrogen and facilitates the creation of industrial and commercial alliances along its value chain.

[13] BIL: Bipartisan Infrastructure Law signed by President Biden on November 15, 2021.

[14] Ministry of Energy, Government of Colombia, "Roadmap for hydrogen in Colombia" (2021).

- Regulations to adapt H2 to transport. The Energy Efficiency Law 21.305 includes tax benefits for "zero emission" cars, among which Hydrogen cars are included.

China

- Hydrogen strategy published. In 2022, the National Development and Reform Commission and the National Energy Administration jointly published the Medium- and Long-term Plan for the Development of the Hydrogen Energy Industry (2021-2035. This is the first medium- to long-term plan to implement hydrogen use in China by 2035. Years earlier, in 2018, The National Alliance of Hydrogen and Fuel Cell (NAHFC) was established. On the other hand, the Chinese government has declared the goal of achieving carbon neutrality by 2060,with emissions expected to peak in 2030.

- Legal and regulatory framework. China does not have a defined overall legislative framework for hydrogen, so some provinces have decided to include their own strategy in the 14th Five-Year Plan for National Economic and Social Development and the Outline of Long-Term Goals for 2035. The documents compile progress on local hydrogen industry development, plant construction and operation. For example, the NEV industry action plan released by Shanxi Province in 2019 outlined plans on the use of hydrogen fuel cells in vehicles, and Guangdong Province also conducted a similar exercise through the "Implementation Plan for Accelerating the Development of Hydrogen Fuel Cell Vehicle Industry" released in 2020.

- Support for investment and innovation. The largest source of investment comes from the "National Key R&D Programs (NKPs)," applied research funds, which are an important source of public funding for research and developement. Since 2016, more than 60 NKP projects focused on hydrogen technologies have been announced. These projects promote research in electrolyzer technologies and seek to improve renewable hydrogen production.

- Regulation of hydrogen in the gas network. Projects are underway to transport hydrogen through the gas grid by blending it with natural gas. The China National Petroleum Corporation has transported hydrogen in the city of Yinchuan in Northwest China. The hydrogen was successfully transported by blending it into a natural gas pipeline.

- Regulation to adapt hydrogen to transportation. Since the publication of the 13th Five-Year Plan (2016), there has been a push for the development of hydrogen-powered vehicles have been stimulated, reaching 7700 FCEVs by the end of 2020.

Australia

- • Hydrogen strategy published. Australia has developed a national hydrogen strategy that sets out a framework for the development, production and export of green hydrogen.

- Legal and regulatory framework. Today, there is a Commonwealth Hydrogen Regulation that provides regulatory guidance on understanding what federal laws apply to hydrogen projects. In addition, in the 2023-24 budget, $38.2 million was allocated for the creation of a Guarantees of Origin scheme that will certify renewable energy and track and verify emissions of clean energy products. This scheme is essential for international hydrogen trade, as it will provide a measure of reliability and sustainability for hydrogen produced in Australia. It will also help new projects secure funding and improve the effectiveness of the government's efforts to scale up renewable energy and the hydrogen industry.

- Support for investment and innovation. Australia has established the $2 billion Hydrogen Headstart program to accelerate the production and use of green hydrogen as a clean and sustainable energy source in the country, while stimulating investment in large-scale hydrogen-related projects.

- Hydrogen on the gas network regulation. In 2022, the Ministry of Energy reformed the National Gas Law and Regulations. The reforms will ensure that existing regulatory provisions and consumer protections work as intended when hydrogen and renewable gases are incorporated into the gas grid. Previously, the National Gas Law (NGL) and the National Energy Retail Law (NERL) referred only to "natural gas". With projects underway to introduce hydrogen and biomethane into the gas grid, this terminology has been updated to provide regulatory certainty for the emerging industry.

- Regulations to adapt H2 to transportation. Within the "Commonwealth regulations", there is a section solely on federal regulations governing hydrogen powered vehicles, hydrogen or ammonia powered vessels, and the transportation of hydrogen or ammonia as cargo.

Many countries are already addressing these challenges by publishing hydrogen strategies, defining concrete measures and targets to promote green hydrogen, creating a legal and regulatory framework with specific regulations for the treatment of hydrogen along the value chain and specific definitions for green hydrogen, supporting investment and innovation, promoting guarantee of origin mechanisms, promoting zero-emission vehicle transport, and so on.

- Global interest in promoting a "hydrogen economy" has grown in recent years. Although some countries have shown greater commitment than others, the regulatory and strategic vision is the same: to achieve decarbonisation through the use of hydrogen. In order to get an overview of the positioning of some countries, various ongoing actions or future proposals related to renewable hydrogen have been compiled. Among these, the following stand out:

- The Publication of National Hydrogen Strategies defines measures and objectives designed by each country to promote the production, distribution and use of hydrogen as a clean and sustainable fuel. Within these strategies, national hydrogen installed capacity targets are defined for the 2030 horizon.

- Creation of a legal and regulatory framework that includes legal measures to facilitate the production and distribution of hydrogen, as well as the establishment of safety and quality standards.

- Investment and innovation support to encourage the development of innovative and more sustainable technologies aimed at promoting hydrogen projects throughout the value chain.

- Regulation defining the technical and safety requirements for blending hydrogen with natural gas in gas distribution networks.

- Adaptation of hydrogen as a transport fuel, establishing regulations for the installation of supply points and the necessary infrastructure for transporting green hydrogen.

Finally, it should be noted that, in this new energy landscape, companies are also facing significant challenges in terms of their strategy, their operations and their commitment to sustainability.

- **Strategy definition:** organisations will need to define their strategic positioning with respect to hydrogen, understand existing projects, keep abreast of regulatory developments, analyse the potential market and potential customers or off-takers, evaluate possible commercial alliances to strengthen their position, etc.

- **Strategy implementation:** Strategy implementation will involve the development of new projects whose investment decisions will need to be accompanied by appropriate technical-economic analyses, such as assessing the optimal location for renewable hydrogen production or analysing and applying for potential financial support.

- **Project Execution:** Project portfolio management must include identifying, assessing and managing potential risks using specific management methodologies.

- **Governance and reorganization:** Implementing the defined strategy may require internal reorganization and recruitment of skilled talent. The impact on information governance and the quality of hydrogen-related data will also need to be considered.

- **Operating and managing the business:** at the operational level, it will be necessary to adapt processes and systems to control the quality, safety and profitability of projects, to develop adapted commercial strategies, to evaluate hydrogen contracts, to model prices, to evaluate the execution of hedges, etc.

- **Link to sustainability goals:** Hydrogen development is also an opportunity for companies to meet their sustainability goals through monitoring of their commitments and key indicators.

Timeline of the European hydrogen regulatory and legislative framework

En la Unión Europea se han abordado distintas acciones para adoptar un marco regulatorio sobre el hidrógeno:

- In December 2015, the Paris Agreement[51], a global climate changed agreement aiming to reduce global greenhouse gas emissions, was reached.d

- In December 2018, the European Renewable Energy Directive (RED)[52] was revised to include a new overall EU renewable energy consumption target of 32% by 2030, including a section for transport.

- In December 2019, the European Commission proposed the European Green Pact[53], a package of policy initiatives aimed at positioning the EU as the first climate neutral region by 2050. It identifies hydrogen as a means to combat climate change.

- In July 2020, the European Hydrogen Roadmap[54] was published, placing this energy source at the heart of EU plans to decarbonize the economy.

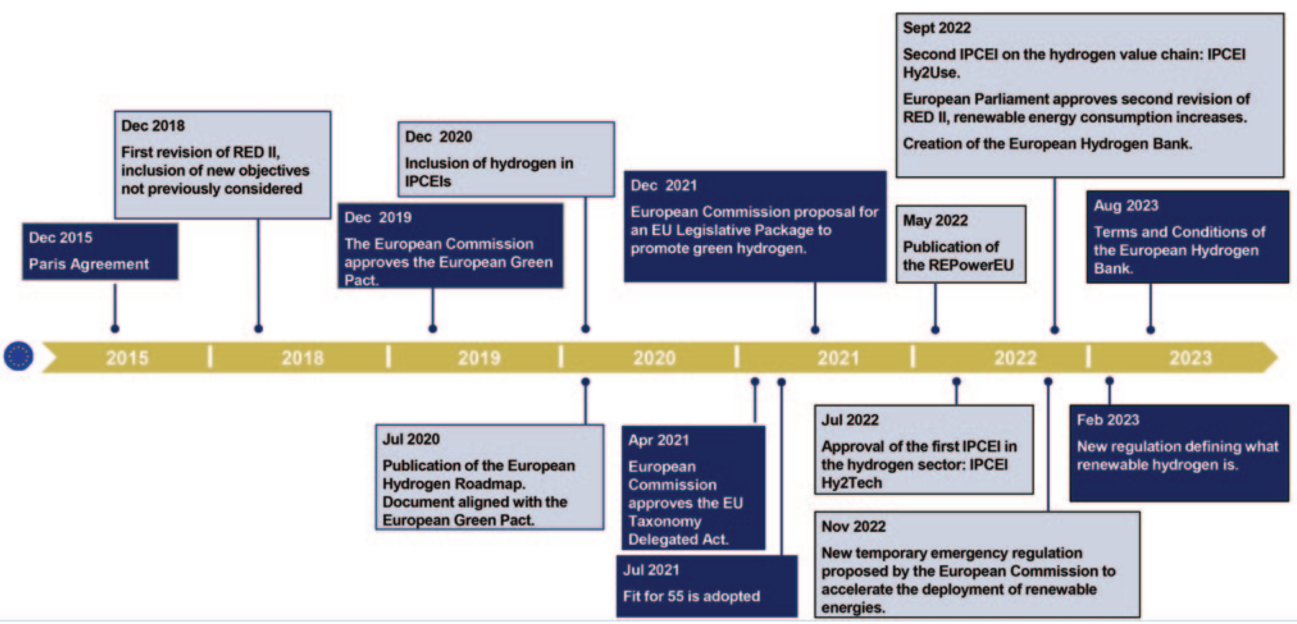
- In December 2020, hydrogen was integrated into the Important Projects of Common European Interest (IPCEI)[55] .

- In April 2021, the European Commission adopted the EU Taxonomy Delegated Act[56], encouraging renewable hydrogen production but also allowing high-efficiency blue hydrogen plants to meet European classification standards.

- In July 2021, the "Fit for 55" package[57] was adopted, a set of legislative proposals and amendments to existing EU legislation that will help the EU reduce its net greenhouse gas emissions and achieve climate neutrality.

[51]United Nations, "The Paris Agreement" (2015).
[52]RED: "Renewable Energy Directive". Approved in 2016, it is a legislative document that defines the objectives of the European Community's energy policy in the field of renewable energies and the legal framework for their development.
[53]EU Commission, "A European Green Deal" (2019).
[54]EU Commission, "Hydrogen" (2020).
[55]EU Commission, "IPCEIs on Hydrogen" (2020).
[56]EU Commission, "Acto Delegado de Taxonomía de la UE". (2021)
[57]EU Commission, "Fit for 55". (2021)

Figure 22. EU regulatory timeline



- In December 2021, the European Commission proposed an EU Legislative Package on the decarbonization of gas and the promotion of green hydrogen[58], with the aim of creating a hydrogen market and developing a dedicated infrastructure. It also provided for the creation of a European Network of Hydrogen Network Operators (ENHR) to ensure the development and management of the hydrogen network.

- In addition, in 2021, the first project for green guarantees of origin in the EU, "CertifHy", was approved.

- In May 2022, REPowerEU[59] was published, setting a target of 10 million tons of domestic green hydrogen production by 2030 and increasing the targets set by the Hydrogen Roadmap.

- In July 2022, the IPCEI Hy2Tech[60], was approved, with 41 innovation projects to develop hydrogen technologies. In September 2022, the IPCEI Hy2Use was also approved, complementing the IPCEI Hy2tech for the development of hydrogen infrastructure.

- In September 2022, the European Parliament approved the revision of the RED II[61] to increase the share of renewable energy in the EU's final energy consumption by 45% in 2030 (compared to the 32% originally proposed).

- In November 2022, the European Commission proposed new temporary emergency regulations to accelerate the deployment of renewable energy sources[62].

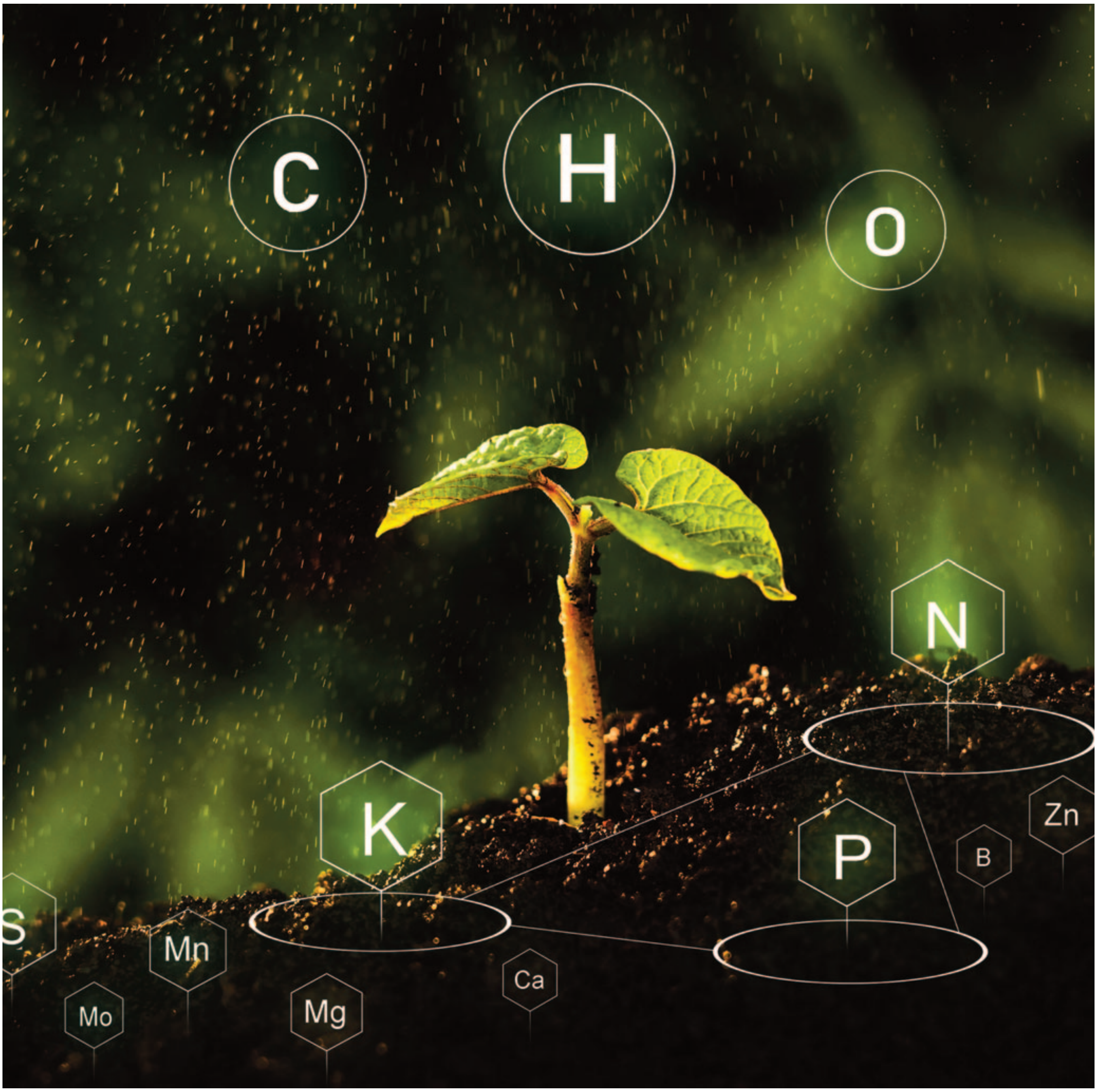
- In February 2023, the definition of renewable hydrogen was set out in two delegated acts. The first act sets out the requirements for hydrogen-based fuels to qualify as renewable fuels[63]. The second defines how emissions reductions from the use of this type of fuel should be calculated[64].

- In August 2023, the terms and conditions of the European Hydrogen Bank were published, which aims to encourage and support investment in renewable hydrogen production.

[58] EU Commission, "Questions and answers on the hydrogen and decarbonized gas package" (2021).
[59] EU Commission, "REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition" (2022).
[60] EU Commission, "Remarks by Executive Vice-President Vestager on IPCEI in the hydrogen technology value chain". (2022).
[61] Balkan Green Energy News, "European parliment votes to raise renewables 2030 target to 45 %". (2022).
[62] EU Commission, "REPowerEU: Commission steps up green transition away from Russian gas by accelerating renewables permitting (2022).
[63] EU Commission, "Delegated regulation on Union methodology for RFNBOs" (2023).
[64] EU Commission, "Delegated regulation for a minimum threshold for GHG savings of recycled carbon fuels" (2023).

Applied analytics for hydrogen feasibility: use case

"What you can measure, you can manage"
Peter Drucker[65]



Use case: optimal site selection for hydrogen projects

This section presents a Use case focusing on the identification and selection of optimal hydrogen project locations. Implementing this model would enable hydrogen market players to accurately assess the advantages and disadvantages of different renewable hydrogen production sites, thus facilitating more informed and robust decision making.

Model introduction

The Chair of Hydrogen Studies at Comillas Pontifical University (ICAI-ICADE), of which Management Solutions is a trustee, has developed an application based on GIS tools[66] (Geographic Information Systems) that allows the optimal location of sites for the construction of renewable hydrogen projects to be identified according to different criteria.

The application makes it possible to calculate a H2 compatibility index to assess the suitability of the sites. The following use case has been developed for Spain, but the technology is applicable to any region, subject, of course, to the availability of the necessary information or, in the absence of it, to the necessary adaptation of the variables to be evaluated.

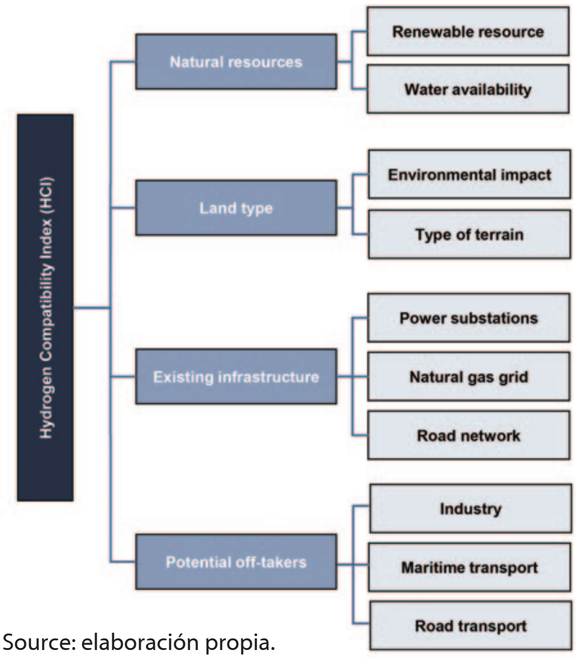
First, the map of Spain was divided into 2x2 km2 squares (although the size could be adjusted depending on the area studied) , and the model generated was used to evaluate hydrogen production compatibility for each of them.

The proposed model would allow hydrogen market participants to identify the strengths and weaknesses of potential locations for renewable hydrogen production, leading to better decision making. In addition, this model could help to answer some questions, such as:

- How do different locations compare in terms of their suitability for renewable hydrogen production?
- What are the most promising locations for green hydrogen production?
- Where are future off-takers expected to be located and what is their potential demand?
- How can the best locations be chosen to avoid conflicts in water use, land use or environmental impact?
- Where can a renewable hydrogen plant be built to maximize efficiency and profitability?
- What is the potential for renewable hydrogen production in different areas?
- How can the costs of transporting green hydrogen from the plant to the points of use be minimized?

[65]Peter Drucker, Known as the father of modern management, Peter Drucker is recognized for his contributions to the field of business management.
[66]Geographic Information Systems

Figure 23. Model variables



Source: elaboración propia.

Model explanation

The model developed to calculate the optimal location for the construction of a hydrogen project is based on the study of a set of variables.

The following is an analysis and development of how these variables are applied as inputs in the model.

Natural resources

Availability of solar and wind energy

The model evaluates H2 production alternatives using solar or wind energy sources according to the capacity factor[67] of each renewable source. Depending on the geographical area, this capacity factor will vary. A higher capacity factor implies a higher potential utilization of the electrolyzer and therefore a higher capacity for hydrogen production by electrolysis.

Because it is sometimes difficult to compare two locations on the basis of capacity factors alone, these can be converted to levelized cost of hydrogen (LCOH). The LCOH is the estimated cost per kg of hydrogen taking into account the investment costs (CAPEX) and hydrogen production, related to the operating hours and therefore the capacity factor.

The lower the LCOH, the cheaper it will be to produce hydrogen at the site studied. In addition, the LCOH allows direct comparison between wind and solar energy for hydrogen production.

Water availability

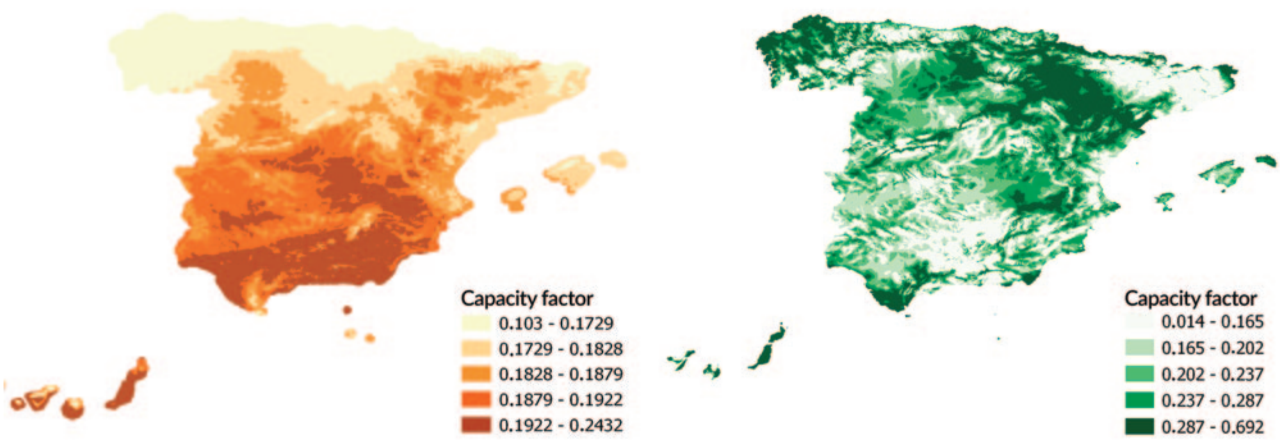
Similarly, water availability is a key feedstock for renewable hydrogen production. In this case, information on surface water availability (Figure 26, left graph) and WWTP locations (wastewater treatment plants; Figure 26, right graph) has been used, but other developer preferences such as distance to water sources or type of water could also be included.

Nature of the land:

Environmental Sensitivity Index (ESI). This index measures the environmental impact of building a renewable energy plant in a given location based on various factors that influence environmental vulnerability such as soil quality or the presence of protected natural areas, among others. The index classifies the territory into five categories of environmental sensitivity (Maximum, Very High, High, Moderate and Low), and locations with maximum sensitivity are excluded from the model.

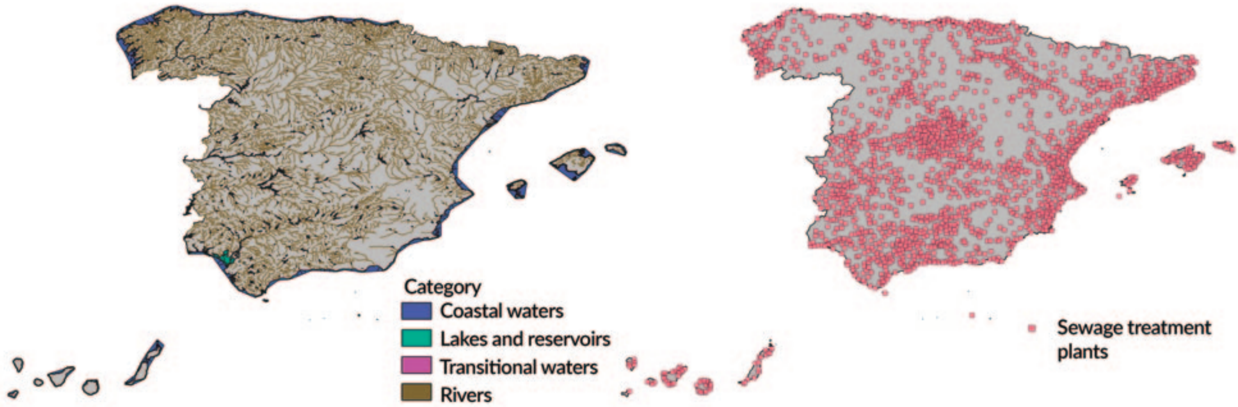
[67] Capacity factor: Measures the frequency with which a plant operates at maximum power. A plant with a capacity factor of 100% produces power all the time.

Figure 24. Solar and wind capacity factor in Spain in 2021.



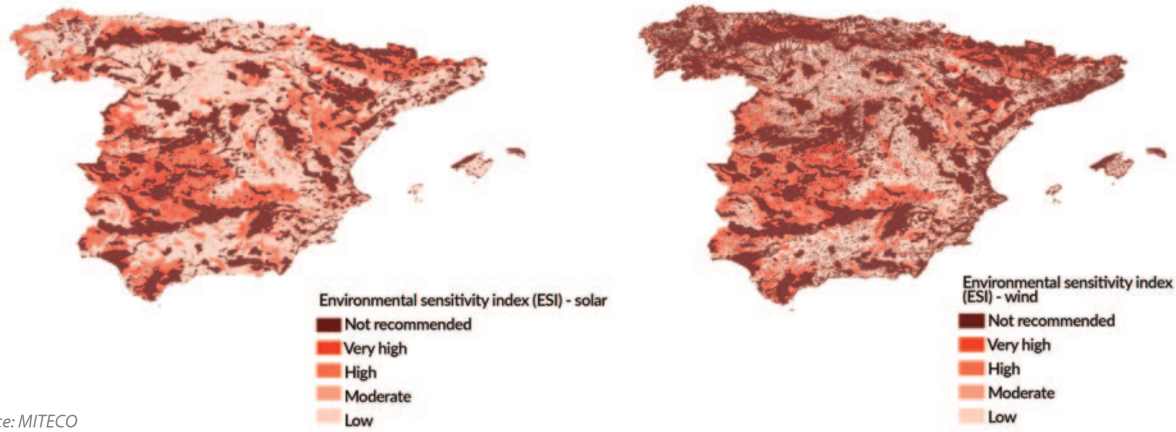
Source: Global Solar Atlas and Global Wind Atlas

Figure 25. Distance to different water supplies in Spain.



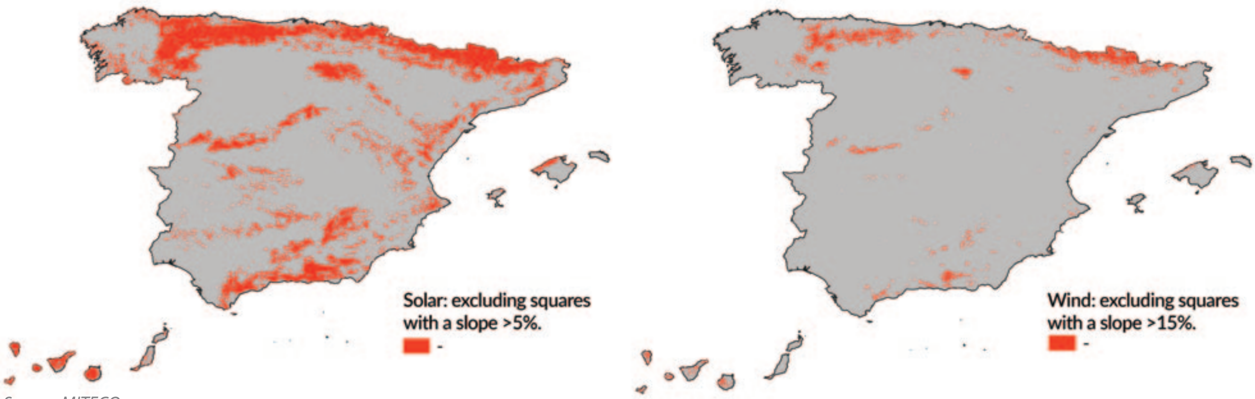
Source: MITECO

Figure 26. Environmental sensitivity index (ESI) in Spain.



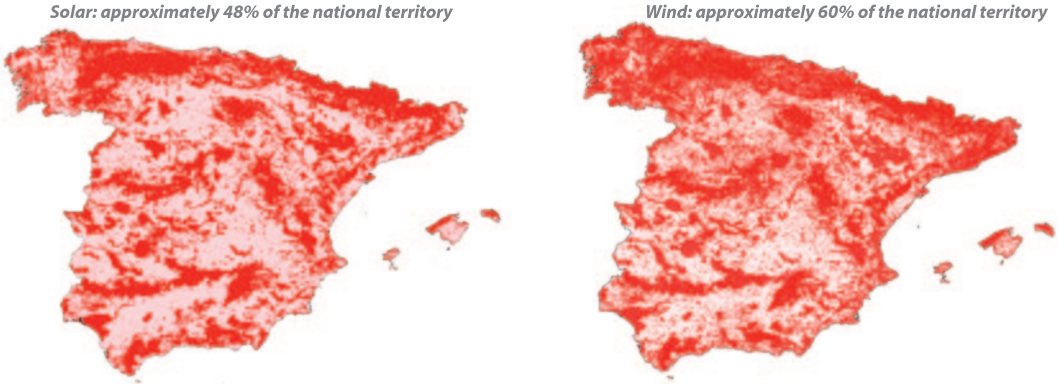
Source: MITECO

Figura 27. Excluded sites based on their slope.



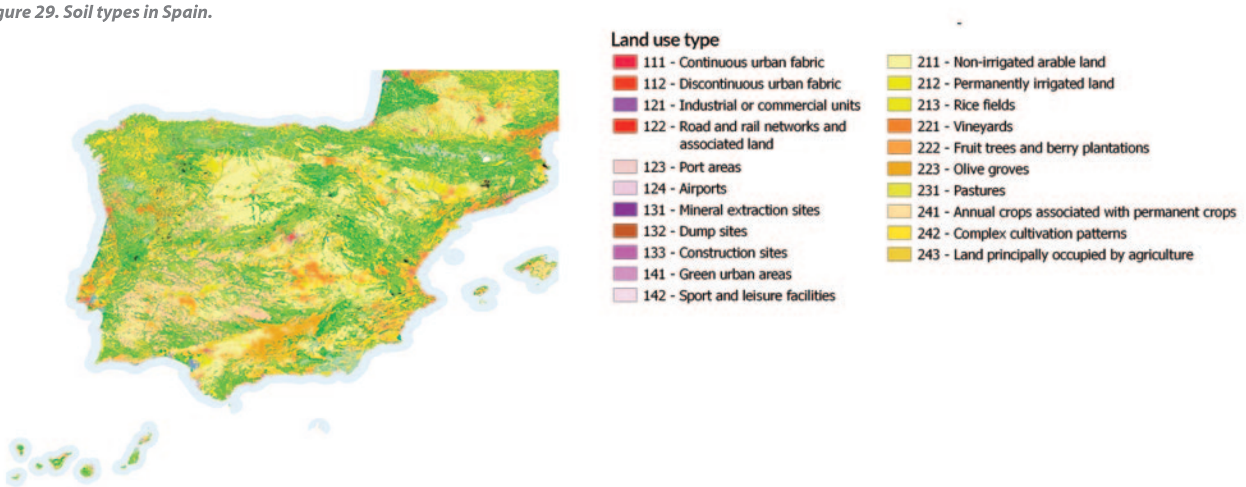
Source: MITECO

Figure 28. Land suitability in Spain.



Source: MITECO

Figure 29. Soil types in Spain.



Source: Copernicus program.

This factor is relevant for hydrogen production plants with dedicated renewable sources, as the environmental impact study is one of the most complex administrative processes for this type of project. Although the model does not exempt from the relevant environmental assessment procedure, it does allow for an indicative approach from the early stages of the project.

Slope of the site. Based on existing scientific literature, sites above a certain slope (greater than 5% for the construction ofsolar plants and 15% for wind plants) are excluded.

Land suitability. Combining the sites excluded because of their ISA with those excluded because of their slope, about 48% of the grid squares would be excluded for hydrogen production from dedicated renewable energy and about 60% for wind energy production. These figures reflect the areas that would not be suitable for installing dedicated renewable hydrogen production facilities due to environmental and topographical constraints.

Land type. For each of the grids, the type of land is characterized according to its use (dry land, irrigated land, natural grasslands, meadows, urban centers, etc.).

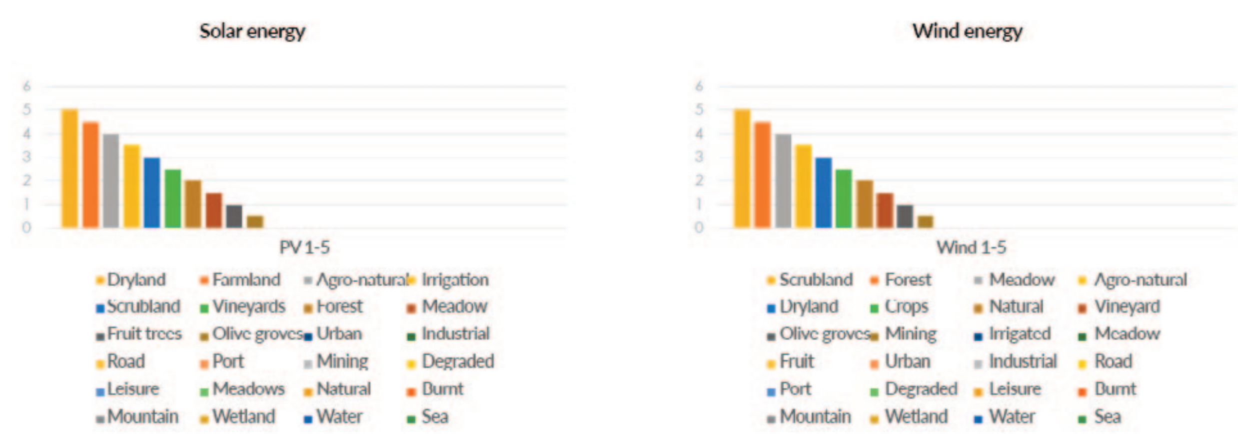
In addition, land use is linked to its suitability for the construction of solar and wind farms and a score is calculated from 0 to 5, with 0 being "never used for such construction».¡

Existing infrastructure

Power grid: distance to substations

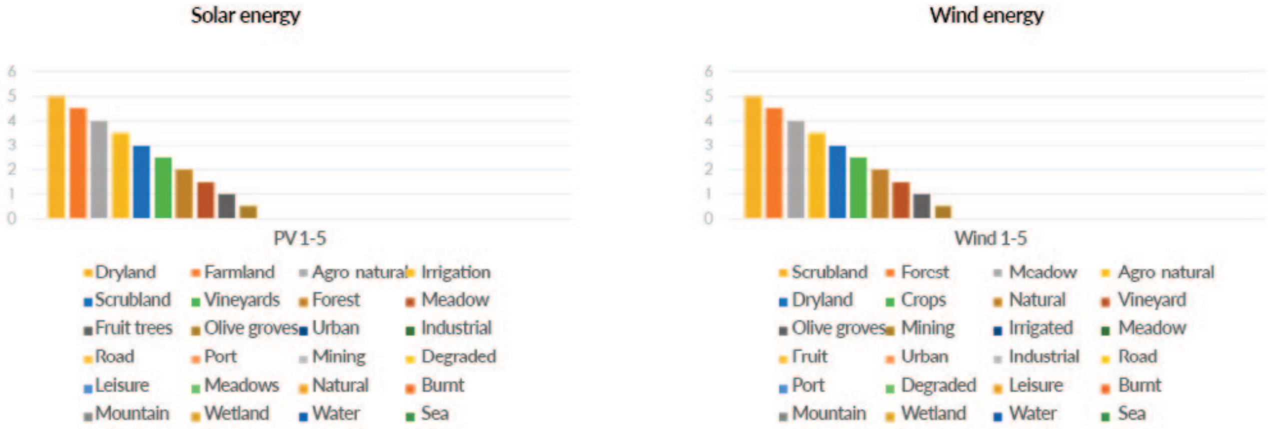
A very common approach in green hydrogen projects is to oversize the renewable production plant with respect to the electrolyzer. For this reason, there will be times when the electrolyzer cannot consume all the energy produced, in which case the excess energy must be fed into the power grid, with the distance to the substation being an important criterion, as the greater the distance, the higher the cost and the greater the electricity losses due to transport.

Figure 31. Classification of land type according to whether it is used for solar or wind energy prodution.



Source; Land Use Database Assessment for the location and spatial distribution of solar and wind energy in Spain (2018).

Figure 31. Distance to electrical substations in Spain.



Source: REE Available and occupied access capacity at transmission grid nodes 20 June 2022.

In addition to the distance to an electrical substation, the connection capacity for production available at each node may also be relevant. In the example, this information is taken from the monthly publications released by the system operator (Redeia).

Natural gas network: distance to the network

Distance to the gas transmission network may be a useful variable for two reasons. Firstly, it may be because an important aspect in many projects (although there is still a great deal of uncertainty about its technical feasibility and acceptable limits). Secondly, because the future hydrogen transport infrastructure is expected to follow the same routes as the existing natural gas network, it is an important variable when considering potential hydrogen transport options, as is already the case with the backbone network currently under consideration.

Road network

Information on the road network is included according to the type of road (highway, national road, etc.) and whether it is part of the Trans-European Transport Network (TEN-T). It is important to have a nearby road network for both the construction and operation of the plant. This would facilitate the transport of hydrogen by tanker truck to the final points of consumption.

Potential off-takers

Industry

The model takes into account the distance to potential industrial hydrogen consumers, analyzing the presence of industries close to the sites. Additionally, an estimate is made of the potential hydrogen demand in some of these industries (refining, ammonia, steel, ceramics production, glass and cement production). This estimate is based on public information about the production capacities, emission factors or energy consumption of the different facilities.

Maritime transportation

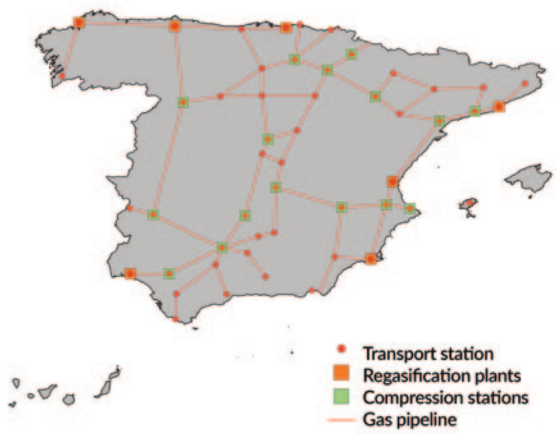
Hydrogen and hydrogen derivatives such as ammonia or methanol will play a key role in the decarbonization of maritime transport. For this reason, relevant information on the main ports in Spain has been included, such as:

- Information on the traffic and size of vessels docking at each port, as well as the demand for fuel at each port.
- Information on the availability of infrastructure for exporting ammonia and methanol in the different ports. With minimal adaptations, these ports could supply these fuels to ships.

Ground transportation

Estimating where and what the future demand for hydrogen for land mobility will be is complex, although it seems clear that heavy transport will concentrate the greatest demand for hydrogen in this segment. For this reason, information on the

Figure 32. Distance to natural gas network. Fuente: REE Capacidad de acceso disponible y ocupada en los nudos de la red de transporte 20 junio 2022.



Source: Scigridgas proyect.

intensity of heavy vehicle traffic on the country's main highways or on existing or planned logistics nodes has been included in the model.

Model applications

This model has two possible direct applications:

Map of interactive layers/movements

Visualizing the value of the different criteria for each node or grid allows the strengths and weaknesses of different sites to be easily identified. This can make it easier to compare several pre-defined potential sites, or even to locate nearby alternatives. For example, Figure 36 shows suitable locations for both wind and solar energy using the following criteria:

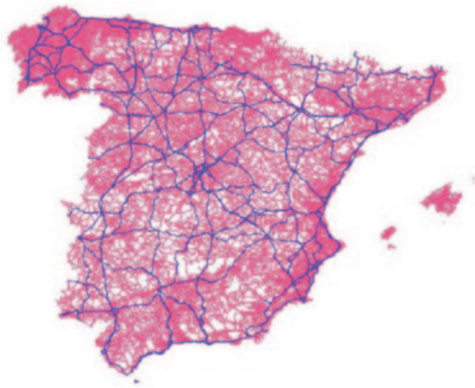
Calculating the hydrogen compatibility index (HCI)

Using the variables defined above, the H2 Compatibility Index (HCI) can be calculated by multiplying the value of each criterion (previously normalized) by its specific weight:

$$ICH2 = \sum Criterion_i * Weight\_criterion_i$$

These weights can be assigned either by multi-criteria decision methods, where experts are consulted and weights are assigned by a comparative method (e.g. analytical hierarchical process), or by allocation based on current projects, where weights are assigned based on the location of existing projects. These weights could be value-specific taking into account preferences (e.g., dedicated renewable plant, different types of off-takers, type of transportation, etc.). In addition, the weighting or inclusion of these criteria will depend on each specific case. For example, in the case of hydrogen production for shipping without hydrogen injection into the grid, the criterion of distance to hydrogen injection points would not be considered.

Figure 33. Road network



Source: MITMA

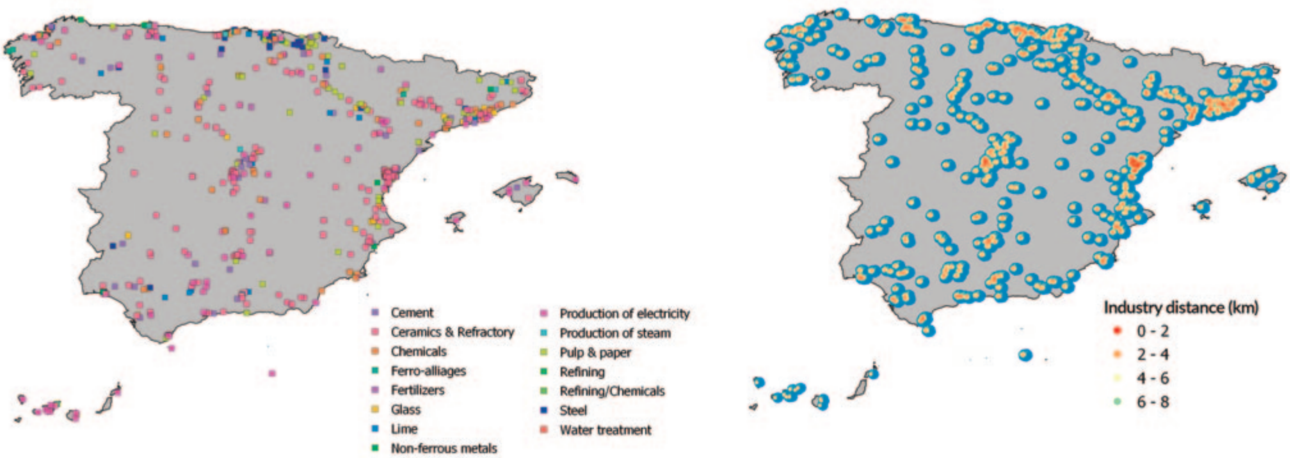
Some examples of criteria are:

- -Solar/wind capacity factor
- -Environmental sensitivity index
- -Type of terrain (dryland, irrigated, etc.)
- -Distance to electricity substations
- -Distance to gas grid injection points
- -Etc.

Distribution of existing projects

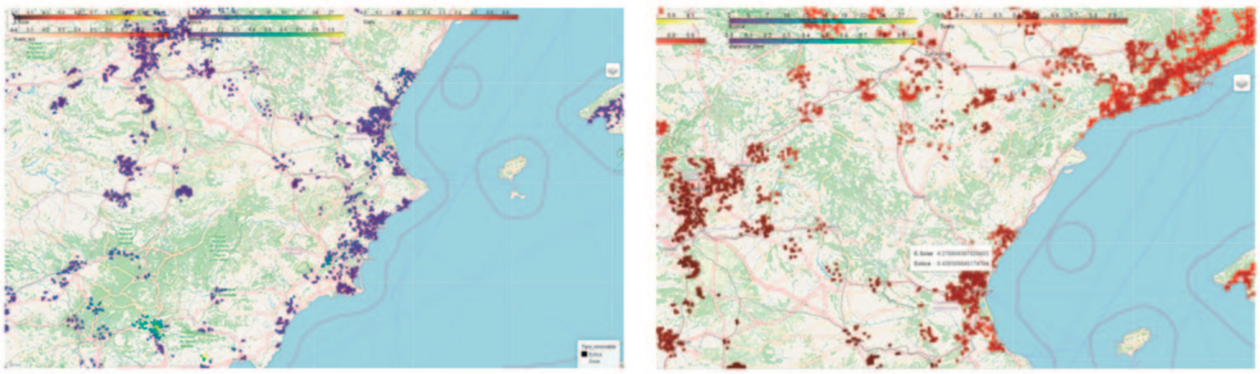
The hydrogen sector is experiencing unprecedented growth in Spain and Europe. As part of its mission to disseminate information, the Chair of Hydrogen Studies created the Hydrogen Projects Visualization Platform, a tool that provides an overview of existing or planned hydrogen production projects in Spain and Portugal, including relevant information such as:

Figure 34. Potential consumers within Spain.



Source: European Pollutant Release and Transfer Register (E-PRTR).

Figure 35. Example of suitable sites by selecting the ISA and distance to substation variables.



Wind energy *Solar energy*

- Status of projects.
- Investment.
- Electrolysis capacity.
- Year of completion.
- Connection scheme and installed renewable generation capacity (if applicable).
- Promoter.
- Type of off-taker: industrial (e.g. ammonia, methanol, refining or steel), land mobility, maritime mobility, among others.

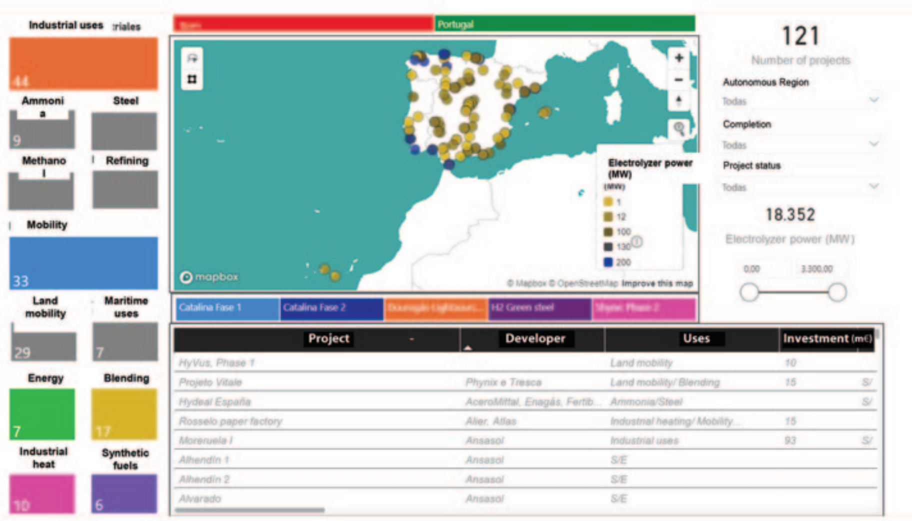
This initiative contributes to the fulfillment of the Hydrogen Roadmap by making it possible to monitor compliance with its targets in terms of electrolysis capacity, number of hydrogen plants, number of vehicles or investment.

The information provided in these maps has been prepared using the best publicly available information from external accredited information sources. The map is updated regularly, although due to the limited public information available, it may not be accurate for some individual projects. However, it is useful as an overview of the deployment of the hydrogen economy in Spain.

The interactive tool is available via the web[68]. Figure 38 shows an image of the interface created.

[68]Hydrogen Studies Chair https://www.comillas.edu/catedra-de-estudios-sobre-el-hydrogeno/mapa-proyectos

Figure 36. Web interface of the map of renewable hydrogen production projects in Spain and Portugal.



Conclusion

"Green hydrogen is key to decarbonizing the economy"
United Nations Industrial Development Organization (UNIDO)[69]

The continued growth of the world's population and the ongoing industrialization to raise the living standards of citizens in the global economy will continue to put upward pressure on energy demand in the coming years. To mitigate this effect and make progress in both efficiency and decarbonization, it will be necessary to increase production and consumption, innovation and implementation of new forms of energy, with the associated climate and environmental impacts.

The use of renewable energies can contribute to the decarbonization of the economy. However, it also entails environmental impacts and challenges in terms of accumulation and storage of the electricity produced.

In this context, green hydrogen is emerging as a key player in the transition towards a sustainable and emission-free economy. It is positioning itself as a structural solution to the variability of renewable energy production and the decarbonization of some sectors with difficult electrification, as well as an essential component of other applications to reduce greenhouse gas emissions.

In order to meet the NZE scenario, 850 GW of electrolyser capacity would need to be installed by 2030, which is double the projected capacity based on currently announced projects (420 GW). This shows that there is still a long way to go to make this energy vector a key player in the energy transition.

Furthermore, the recent discovery of natural deposits of white hydrogen around the world[70] has raised the possibility that white hydrogen may also be an important energy source. The coexistence of green and white hydrogen represents a promising approach to meeting the challenges of the energy transition. These two types of hydrogen can provide a more diversified and efficient route to a sustainable energy future.

Today´s vision of an economy based on renewable hydrogen is faced with major challenges, requiring strategic and collaborative responses to technical and economic difficulties in production, transport, consumption and regulation.

In view of the need to reduce production costs, investment in research and development is crucial, as it would make it possible to overcome the economic and technological barriers that currently prevent large-scale production of renewable hydrogen.

At the same time, it is necessary to create a sustainable and diversified demand for renewable hydrogen by promoting its use in sectors such as industry, transport and power generation.

Infrastructure is proving to be a critical element on the road to the hydrogen economy. Adapting and modernizing existing facilities, as well as planning new infrastructure, plays a key role. Strategic location and interconnection efficiency are decisive.

On the other hand, establishing a legal and regulatory framework is essential to facilitate hydrogen production and distribution. Certification and quality standards, publication of national hydrogen strategies with specific installed capacity targets, support for investment and innovation in sustainable technologies, regulation of hydrogen use in the gas grid, and adaptation of hydrogen as a transportation fuel are key measures to ensure sustainability and transparency throughout the supply chain.

Finally, practical tools and applications that can support decision making, such as the selection of optimal locations, facilitate the adoption of new business processes, as companies adapt to this new economy.

In summary, green or renewable hydrogen is emerging as an essential pillar in the transition to a sustainable economy, but only through collaborative efforts, investment in technology and regulatory support will it be possible to overcome current challenges and unlock its full potential as a transformational energy carrier.

[69] 2022. UNIDO is a specialised United Nations agency whose mandate is the promotion, stimulation and acceleration of industrial development.
[70] "World's largest white hydrogen deposit found in France" – World Economic Forum (sep. 2023).

Glossary

Autothermal reforming: a process similar to steam reforming, but in this case the heat required to reach high temperatures is achieved without external energy input.

Blending: the process of mixing different gases in specific proportions to create a gas mixture with desired properties and composition.

CCfD: Carbon Contracts for Difference.

CCUS: Carbon Capture Usage and Storage.

E-Fuels: Synthetic fuels that are produced by capturing carbon dioxide from the atmosphere and converting that CO_2 into liquid or gaseous fuels using renewable electricity.

FCEV: Fuel Cell Electric Vehicle.

Fuel gasification: a process by which coal or biomass is burned at high temperature, producing H_2, CO, CO_2 and other gases.

GIS: Geographic Information Systems.

IAE: International Energy Agency.

IRENA: International Renewable Energy Agency.

LCOH: Levelized Cost Of Hydrogen.

LNG: Liquefied Natural Gas.

LOHC: Liquid Organic Hydrogen Carriers LOHC: Liquid Organic Hydrogen Carriers.

Partial oxidation: a process involving incomplete combustion of a fossil fuel (natural gas, oil), producing H_2 and CO.

Photocatalysis: photochemical process involving the absorption of sunlight by a catalyst or substrate to carry out oxidation-reduction reactions.

Photoelectrolysis: photochemical process using a photocatalytic electrode, which is a material that absorbs sunlight and also acts as an electrode to facilitate the electrolysis reaction to produce hydrogen.

RFNBO: Renewable Fuel of Non-Biological Origin.

Steam reforming: a process in which water vapor is mixed with a fossil fuel (usually natural gas or oil) at high temperature. The fuel decomposes, producing H_2 and CO_2

Thermolysis: thermal process for hydrogen production where thermal energy from, for example, solar ovens is used to thermochemically dissociate water.

Water electrolysis: process by which an electric current separates the water molecule into two oxygen molecules and one hydrogen molecule.

WWTP: Wastewater Treatment Plants.

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Presión a la cual las tasas de reacción de formación y descomposición del compuesto son iguales

RED: "Renewable Energy Directive". Aprobada en 2016, es un documento legislativo que define los objetivos de la política energética de la Comunidad Europea en el campo de las energías renovables y el marco legal para su desarrollo

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