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# GREEN HYDROGEN APPLICATIONS FOR ECO INDUSTRIAL PARK DESING

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(1) UPCT

Green hydrogen production is increasing significantly, being one of the renewables with large impact in recent years, promoted by the scientific community, international government policies and private sector interest. Nowadays, green hydrogen presents a variety of potential applications, due to its easy storage and versatility in comparison to other resources, as well as its potential use in different sectors, such as electricity generation, energy storage, transport sector, drinking water production, etc. With regard to the industrial sector, renewable integration is currently a priority target. In this scenario, green hydrogen emerges as a complementary solution of other renewables, mainly solar and biomass, aiming to combine renewables and produce/store such green hydrogen. This paper analyses potential applications of green hydrogen in current industrial parks, and the different combined technologies for its production and use. This combination of complementarity resources is a key point for these large industrial energy consumers. Furthermore, these hybrid solutions will allow industrial parks to reduce their dependence on fossil fuels, decrease emissions, and reduce the large energy and electric bills, which currently bear a high cost.

Keywords: green hydrogen; industrial applications; hybrid systems; industrial parks

# APLICACIONES DEL HIDRÓGENO VERDE PARA EL DISEÑO DE ECO PARQUES INDUSTRIALES

La producción de hidrógeno verde está aumentando significativamente, siendo una de las fuentes renovables con mayor impacto de los últimos años y contando con el interés de la comunidad científica, políticas de gobiernos internacionales y el sector privado. De hecho, las aplicaciones del hidrógeno son actualmente muy variadas, debido a su fácil almacenaje y versatilidad frente a otros recursos, así como a su potencial empleo en diferentes sectores, como la generación de electricidad, el almacenamiento energético, su uso en el sector del transporte, la obtención de agua potable, etc. Dentro del sector industrial, las necesidades de integración de renovables son un objetivo prioritario. En este escenario, el hidrógeno emerge con una solución complementaria a otros recursos renovables, principalmente solar y biomasa, permitiendo así combinar fuentes y generar hidrógeno verde. Este trabajo realiza un análisis de potenciales aplicaciones que presenta el hidrógeno verde en polígonos industriales y las diferentes tecnologías y fuentes combinadas para su obtención. Esta combinación de recursos y su complementariedad es un punto clave para estos grandes consumidores de energía. Es más, estas soluciones híbridas permitirán a los polígonos industriales reducir su dependencia de combustibles fósiles, disminuir sus emisiones, y reducir los grandes costes eléctricos que actualmente soportan.

Palabras clave: hidrógeno verde; aplicaciones industriales; sistemas híbridos; polígonos industriales

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## 1. Introduction

During the last years, and mainly due to the global COVID pandemic, all costs of materials, energy resources and supplies have increased considerably. Regarding the industrial sector, personal costs have increased as well, addressing a parallel expensive cost situation to be able to supply their customers. In general, extra-working hours and longer shifts, higher energy consumption and higher emissions as well as higher energy bills have been detected in this sector, with relevant increased energy and activity. However, and promoting by most of international policies and organizations, reducing emissions and environmental impact of large industries is one of the main issues to be addressed. Many industries use conventional power generation systems with relevant pollution and emission levels. Subsequently, upgrading these systems to clean renewable solutions would help considerably to reduce such both pollution and emissions of these industries. In fact, the vast majority of industrial parks are more than 30 years old. Their initial investment has already been amortised, and the modernisation of the parks to fulfil ecological needs entails the investment of large amounts of money, not usually available by the industrial companies. In this framework, industrial eco-parks comprise a group of factories and industries, located in the same area, connected to each other in order to share the energy generated in a renewable way, according to the demand of each industry. The main objective of these eco-parks is to achieve an efficient symbiosis among the factories in different sectors, in order to reduce their energy consumption and reduce the emission of pollution at industrial sites (Scheubel, C., Zipperle, T., & Tzscheutschler, P., 2017). Nowadays, industries have numerous renewable energy sources to be integrated into different processes and aiming to satisfy the internal energy demand of each of them. In addition, they can also supply surplus energy to nearby regions for other consumptions. Industrial eco-parks can export their energy to nearby urban centres, thus avoiding the waste of generated energy (Feng, J.-C., Yan, J., Yu, Z., Zeng, X., & Xu, W., 2018). Moreover, such energy could be stored for latterly use depending on the power demand and/or when renewables are not available.

According to the specific literature, humans are the main cause of climate change and governments and scientists are carrying out studies conducted to reduce this global warming and emissions. They are responsible of the recent temperature increasing, establishing a maximum of 2ºC more than the pre-industrial stage. Within this framework, this paper aims to analyse the different renewable combinations suitable to be used by industries to generate electricity and their applications. A compilation of studies and analyses of the uses of electrical energy in industry are then discussed and compared, with the aim of generating electricity in the most efficient and simple way possible. The rest of the paper is structured as follows: Section 2 gives a general description of the industrial pollution situation; Section 3 describes the industrial Spanish sector and main pollution emissions; Section 4 discusses different renewable hybrid solutions to applied in the industrial sector; Section 5 provides a brief analysis of hydrogen integration projects; finally, Section 6 gives the conclusions.

## 2. Industrial pollution in the world and in Europe

One of the main factors affecting the conditions in urban areas is the nearby presence of industrial infrastructures. In recent decades, industries have been relocated from city centres to the immediate vicinity of cities in so-called technology and industrial activity parks. This fact has addressed some negative consequences, the most relevant are the following:

- Increased traffic congestion and congestion, especially at certain times of the day.

- Deterioration of the natural habitat: fragmentation of ecosystems, increased pollution and consumption of resources.
- Deterioration of the administration-industry link, with the consequent generation of conflicts and increased misinformation of local authorities about industrial processes.
- Social problems associated with unemployment due to changes in economic activity (from the primary to the tertiary sector, etc.).

In this sense, there is a need to design strategies that allow a suitable integration of industrial and technological parks in the global approach towards sustainable development. These strategies must promote economic growth in the region, in line with an improvement in the quality of life of citizens and respect for the environment. Indeed, the most polluting countries in the world correspond to the main international manufacturers, such as China, the main exporter of all types of products, the United States, as a world power, and India, which stands out for its cheap labour force and, being an underdeveloped country, has not yet invested sufficiently in renewable energies, see Figure 1. Regarding the European Union, from 2010 to 2020, the value that industry generated for the economy, measured by gross value added (GVA), increased, indicating that European industry become less emission intensive, as the ratio of air pollutant emissions to industrial goods production decreased. To reduce pollutant emissions, natural resource use and waste generation, the European Union aims to drive a transition towards a strong, low-carbon industry based on circular material flows. Monitoring the generation and release of air pollution is key to tracking progress towards this goal. Therefore, the decrease in industrial air pollutant emissions can be attributed to European regulation, such as the EU Emissions Trading Scheme and the Industrial Emissions Directive, improvements in energy efficiency and abatement technologies, and the relocation of several highly polluting and energy-intensive factories, such as textile or metal production, outside Europe, see Figure 2.

**Figure 1. Most polluting countries in the world (own elaboration)**

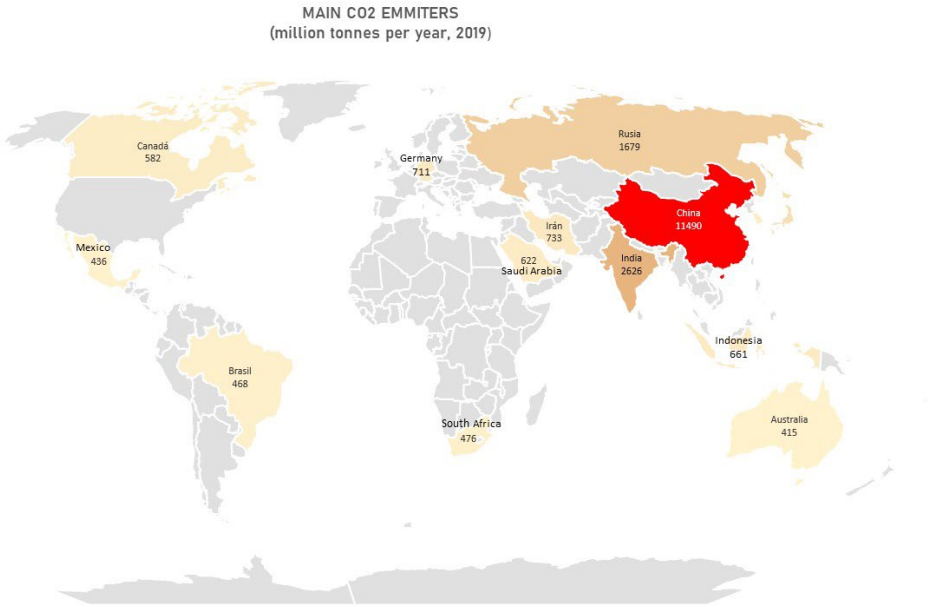



**Figure 2. Change in pollutant emissions EU-27 (Agency, E. E., 2022)**

| | Cd, Hg, Pb | $CO_2$ | $NO_x$ | NMVOC | $PM_{10}$ | $SO_x$ |
|---|---|---|---|---|---|---|
| Austria | -53.9% | -46.7% | -54.4% | 3.0% | -52.8% | -85.9% |
| Belgium | -73.7% | -16.8% | -32.4% | -51.8% | -42.9% | -40.4% |
| Bulgaria | -85.3% | -12.1% | -65.4% | -44.8% | -95.3% | -87.5% |
| Croatia | 177.0% | 46.6% | -3.8% | 371.7% | 188.9% | -14.0% |
| Cyprus | -34.3% | -9.2% | -28.4% | | -48.9% | -28.6% |
| Czechia | -62.0% | -16.5% | -50.1% | -29.8% | -63.7% | -56.7% |
| Denmark | 244.5% | -52.9% | -10.1% | 97.5% | 74.1% | -22.5% |
| Estonia | -81.4% | -31.4% | -61.8% | -86.3% | -95.3% | -81.3% |
| Finland | -85.6% | -19.6% | -38.8% | -50.5% | -41.1% | -59.5% |
| France | -50.9% | -19.0% | -47.9% | -9.6% | -14.7% | -65.5% |
| Germany | -56.8% | -12.1% | -19.2% | -8.0% | -26.9% | -26.6% |
| Greece | -3.1% | -34.9% | -40.7% | 46.2% | -85.4% | -73.4% |
| Hungary | 108.4% | -9.9% | -30.1% | -81.3% | 162.9% | -27.7% |
| Ireland | 157.5% | -16.0% | -38.2% | -18.9% | -57.3% | -82.7% |
| Italy | -67.3% | -28.3% | -48.8% | -35.0% | -78.9% | -64.9% |
| Latvia | | 13.5% | -75.4% | 65.8% | -90.2% | -73.0% |
| Lithuania | | -20.0% | -40.7% | 10.0% | -34.5% | -29.0% |
| Luxembourg | 136.3% | -38.2% | -60.2% | 90.6% | | 17.2% |
| Malta | | | -97.4% | | 6.2% | -79.1% |
| Netherlands | -85.2% | -3.9% | -28.3% | -36.8% | -48.8% | -27.7% |
| Poland | -43.9% | -7.7% | -26.4% | 11.4% | -65.0% | -70.5% |
| Portugal | -19.7% | 15.2% | -33.2% | -19.3% | -44.2% | -39.3% |
| Romania | 26.3% | -23.7% | -44.4% | -1.9% | -82.1% | -89.4% |
| Slovakia | 264.1% | -3.8% | -33.1% | 54.1% | | -63.8% |
| Slovenia | -14.5% | -21.9% | -67.9% | -13.4% | -38.5% | -68.3% |
| Spain | -70.2% | -16.6% | -38.0% | -10.3% | -45.3% | -48.9% |
| Sweden | 8.0% | -9.8% | -11.2% | -6.3% | -39.0% | -43.0% |

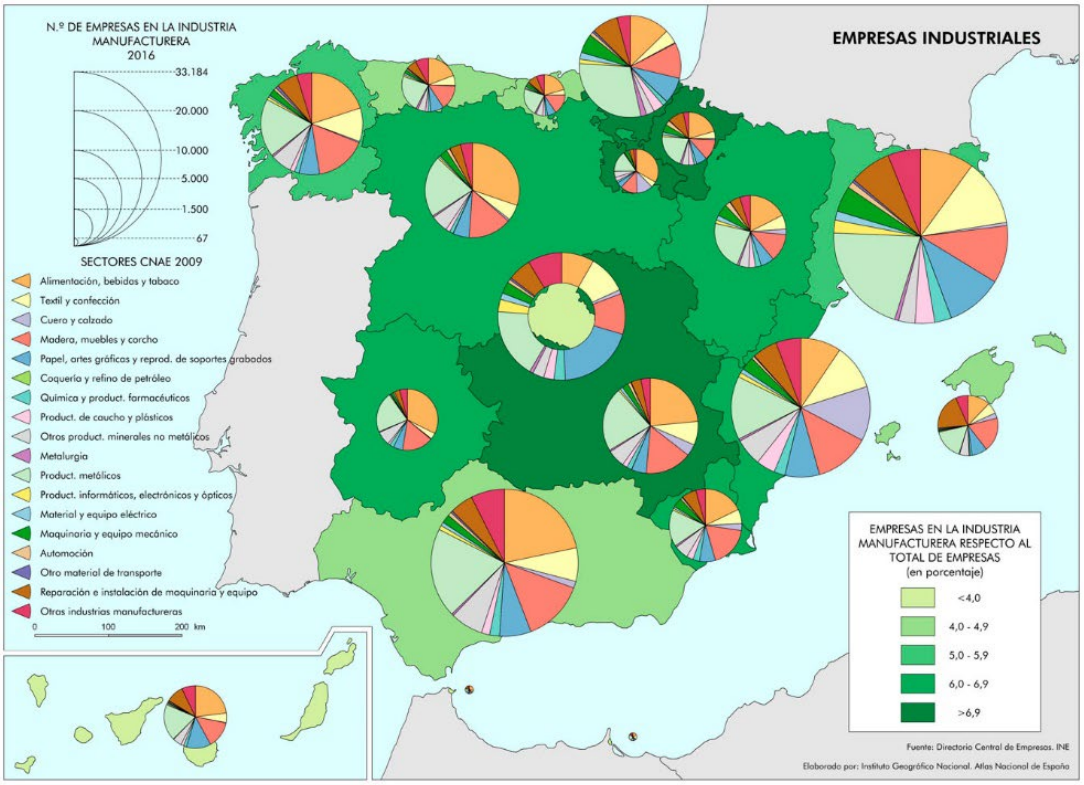
Industrial emissions are very complex to monitor, study and consider, as the effects on the environment, health and their realities are very different in European countries. Heavy metals (Cd, Hg, Pb) are emitted in relatively low quantities and have a naturally variable trend over time (Verde, L., 2022). These emissions are mainly due to mining activity. The pattern of $CO_2$ emissions is similarly decreasing in general, while some countries show an opposite situation.

Emissions of NMOVC are due to the transport sector and combustion processes for power generation, but the main source of pollution comes from the use of solvents, paints and aerosols in the chemical industry, accounting for about 24% of the total emissions produced. Emissions of pollutants associated with activities involving combustion processes ($NO_x$, $SO_x$ and PM 10), such as electricity producers, iron and steel or cement plants, are generally decreasing. This trend is increasing as the environmental performance of these industries is improved accordingly. Evidence points to EU policy as one of the key drivers of these positive developments.

## 3. Main industrial activities in Spain

The industrial sector is one of the main drivers of the country's economy, with almost 2 million workers involved, accounting for 11.5% of the total number of workers in the country. It encompasses a wide variety of activities, but the main lines of participation are the food sector, motor vehicles and the distribution of electrical energy. As can be seen in Figure 3, the metallurgical, wood and paper industries are also very influential, with high energy consumption due to the machinery used.

**Figure 3. Main industrial activities in Spain (España, A. N., 2016)**




The main causes of pollution and energy consumption in Spain are as follows:

- **Food sector:** Demanding 14% of the total energy used by industry. The dairy, sugar and olive oil sectors, etc. involve production processes demanding large amounts of electricity and heat, currently generated by fossil fuels such as gas or oil.

- **Manufacture of motor vehicles:** Spain is the 8th country that manufactures the most vehicles in the world. It is also one of the countries with the highest energy demand. In recent decades, it is precisely one of the industrial sectors that has invested the most in modernisation and automation, in order to carry out work efficiently, using industrial robots and renewable energy sources to generate the electricity consumed.

- **Power generation:** In line with other countries, electricity generation is more prevalent in all countries leading to electrified countries. Energy consumption is increasing and, despite investment in clean renewable energy, there are still many oil, coal and gas-fired power plants, which are the main culprits of pollution in power systems.

- **Textil:** Large quantities of fossil fuel products are used, in addition to the use of polluting chemicals and other plastics. Due to their high demand, large emissions are generated. However, it is one of the sectors investing in new technology development, as well as the use and integration of renewable energies.

- **Metallurgy:** The high temperatures required for metalworking are achieved through the combustion of highly polluting fossil fuels. Nowadays, the iron and steel industries are making relevant efforts to reduce their consumption, using new and more efficient machinery. However, they have not yet achieved positive figures for the environment.

- **Wood and paper industry:** They are increasing their relevance presence in a circular economy sector, in which, for example, discarded materials can be used to generate heat through biomass. Currently, there is a great deal of pollution due to their high demand. The trend is to reduce emissions and promote a sustainable use, being one of the raw materials that requires the least energy for the manufacture of its products.

In general, the main causes of pollution in industry are mostly due to the methodology and machinery used, as large amounts of electricity and heat generation are required. These technologies are in the process of improvement and innovation, with the aim of providing industry with electricity generation in a sustainable way. The Spanish government has encouraged the energy transition of the main industries by providing incentives to upgrade machinery and use more efficient systems. Regarding cogeneration, the use of fuel oil and coal is being replaced by natural gas and biomass, as they generate less pollution and promote renewables. Hybrid solutions based on conventional systems with photovoltaic (PV), wind, hydrogen and other synthetic fuels is also being pursued. In addition, the circular economy is important for this country, so that the reuse of waste from one industry can be used by another, thus avoiding the waste of unused materials and favouring a more reasonable use of energy.

## 4. Renewable Energy Combinations in Industry

Nowadays, there is a wide variety of renewable energy sources able to be used efficiently for electricity generation purposes. PV installations and wind power plants are the most mature technologies, with a great deal of experience in the industrial sector. Other renewable energy sources, such as solar thermal and geothermal, due to their higher initial capital investment, are not as widespread in the renewables market, but combined with other renewable sources become more interesting and benefits (Zhou, J., Wu, Y., Zhong, Z., Xu, C., Ke, Y., & Gao, J., 2021). During the last years, there is also a growing presence of green-hydrogen, a new renewable energy source with a lot of potential. Indeed, this resource has been an emerging energy source and its presence is set to increase exponentially over the next decade. Actually, it can be used as a storage energy solution, which is also a very interesting option. Therefore, these resources combined with other types of generation allow us to provide energy enough to cover the daily industrial demand, without the problem of intermittency and oscillations due to lack of some renewable resources, such as wind or sun.

From the specific literature, a total of 153 projects have been identified including some kind of hybrid systems based on renewable energy sources and hydrogen, considering as a renewable system as well. The vast majority of the renewable energy combinations are summarized in Table 1. Some other interesting combinations of renewable energies were the following:

- Photovoltaic and solar thermal.
- Photovoltaic, wind and batteries.
- Photovoltaic, biogas and hydrogen.
- Photovoltaic, wind and geothermal.

Figure 4 and Table 2 show the percentage share of each renewable energy source. The most renewable resources were PV and wind, together with hydrogen.

**Table 1. Combinations of hybrid systems studied (own elaboration)**

| Factor | Description |
|---|---|
| 44 % | Photovoltaic and hydrogen |
| 24 % | Wind and hydrogen |
| 23 % | Photovoltaic, wind and hydrogen |
| 8 % | Photovoltaic, wind, biomass and hydrogen |

**Figure 4. Energy Sources (own elaboration)**

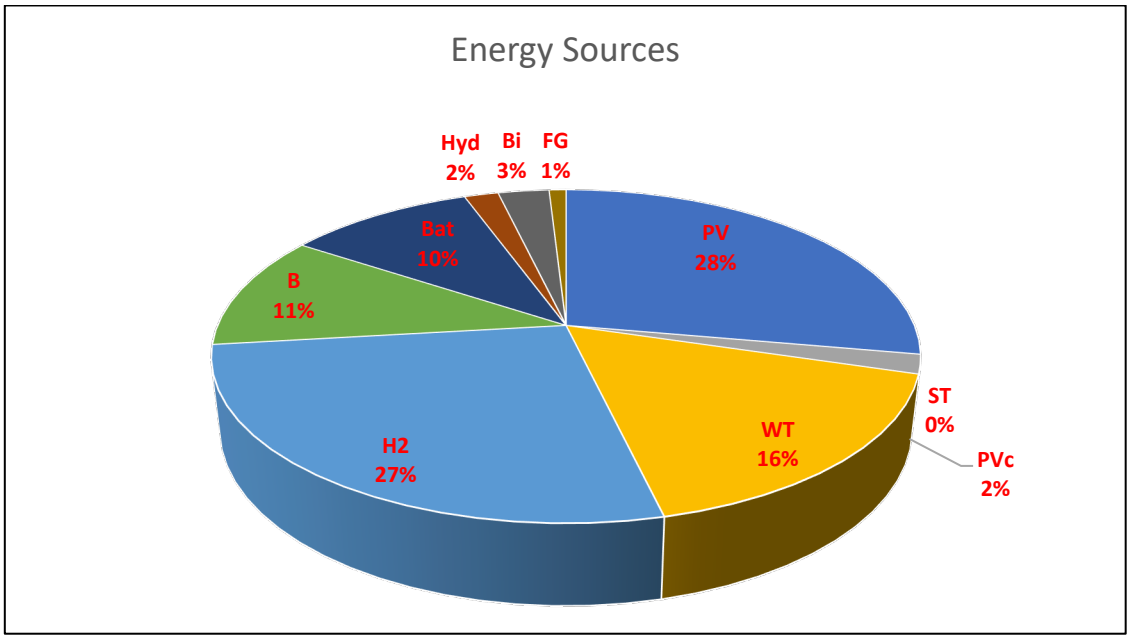


**Table 2. Energy sources studied (own elaboration)**

| Factor | Abbreviation | Description |
|---|---|---|
| 28 % | PV | Photovoltaic |
| 27 % | ST | Solar Thermal |
| 16 % | PVc | Photovoltaic Concentration |
| 11 % | WT | Wind Turbine |
| 10 % | $H_2$ | Hydrogen |
| 3 % | B | Biomass |
| 2 % | Bat | Batteries |
| 2% | Hyd | Hydropower |
| 1 % | Bi | Biogas |
| 0,5 % | FG | Fuel Gas |

From the previous results, note that 71% of the total analysis is based on photovoltaic, wind and $H_2$ generation. However, other energy sources such as batteries and biomass have increased significantly their presence in clean energy generation, and accounting for 21% of the total. Biogas, photovoltaic and solar concentration and hydropower resources have a minor integration due to high costs, which is a relevant drawback detected in this analysis. Nevertheless, there is a positive trend towards $H_2$ generation in recent years, which will increase exponentially over the next few years as the manufacturing costs of the main components are expected to be reduced accordingly. From the contributions analysed, 26% were located in Europe, one of the most developed regions in renewable energy promotion and integration, especially in PV and wind power, but it is also committed to other sources not present in electricity generation. This fact facilitates and reduces the cost of other types of generation, allowing us the poorest countries to access PV and wind power with their economic conditions. A high number of countries, such as Iran, Morocco, Egypt, Turkey, Algeria, etc. have also carried out studies and budgets for hybrid system projects and eco-industrial parks.

## 5. Industrial applications of hydrogen

There is a long list of eco-industrial park projects, but very few are implemented in real situations. This is a very interesting option where industries in different sectors are able to be reduced and optimised electricity consumption. The hydrogen field and the need to find other alternative energy sources make this energy system essential for upgrading and modernising industrial parks. Nowadays, hydrogen has multiple advantages: apart from the fact that it can be generated with 100% renewable energy, it can be used as a means of fuel, storage or transport, among others. One of the main reasons for promoting the development of eco-industrial parks is the implementation of renewable hydrogen, together with hybrid energy generation systems. This proposal is receiving considerable support from governments, as it can contribute to reduce some emissions mainly of polluting particles and to meet the objectives of sustainable development and reducing global warming. Therefore, a parallel target is then to limit the temperature increasing to a maximum of 2ºC with respect to the pre-industrial stage.

Using green-hydrogen in industrial processes is a very relevant step towards minimising the environmental footprint. Focused on Europe, the use of green hydrogen could avoid approximately 560 million tonnes of greenhouse gas emissions by 2050, generate annual revenues of around 820 billion euros, reduce around 15% of local emissions (NOx) in road transport and create around 5.4 million jobs (Butturi, M. A., Lolli, F., Sellitto, M. A., Balugani, E., Gamberini, R., & Rimini, B., 2019). The demand for hydrogen is thus high in industrial processes, especially in the chemical industry, where hydrogen is used to carry out chemical reactions and obtain the required products. The applications of hydrogen in industry can be manifold. Subsequently, this study was carried out to identify the most suitable hybrid solutions for environmentally committed industries. Figure 5 depicts and characterizes different hydrogen applications in industry.

**Figure 5. Applications of hydrogen in industry (Hidrógeno, A. E., 2018)**

| INDUSTRY & MARKET SHARE | KEY APPLICATIONS | SUPPLY SYSTEM | H2 DEMAND per YEAR |
|---|---|---|---|
|   1% | • Semiconductor<br>• Propellant Fuel<br>• Glass Production<br>• Hydrogenation of Fats<br>• Cooling of electrical Generators | • Small on-site<br>• Tube trailers<br>• Cylinders<br>• Liquid H2 | LOW<br>>0.07 Mtons |
|   6% | • Iron Reduction<br>• Blanketing gas<br>• Forming gas | • Cylinders<br>• Tube trailers | MEDIUM<br>0.41 Mtons |
|   30% | • Hydrocracking<br>• Hydrotreating | • Pipeline<br>• Large On-site | 2.1 Mtons |
|   63% | • Ammonia<br>• Methanol<br>• Polymers<br>• Resins | • Pipeline<br>• Large On-site | HIGH<br>4.3 Mtons |

### 5.1. Refining

It is used in catalytic processes for fuel extraction. During the process, hydrogen treatment and hydrocracking are used to remove sulphur, oxygen, nitrogen and metals. It is essential for the production of low sulphur fuels to reduce pollutant emissions.

### 5.2. Flat glass manufacturing

Hydrogen is used as a protective chamber to prevent the oxidation of tin, which is used to cool and harden the glass during the manufacturing process.

### 5.3. Fat hydrogenation plants

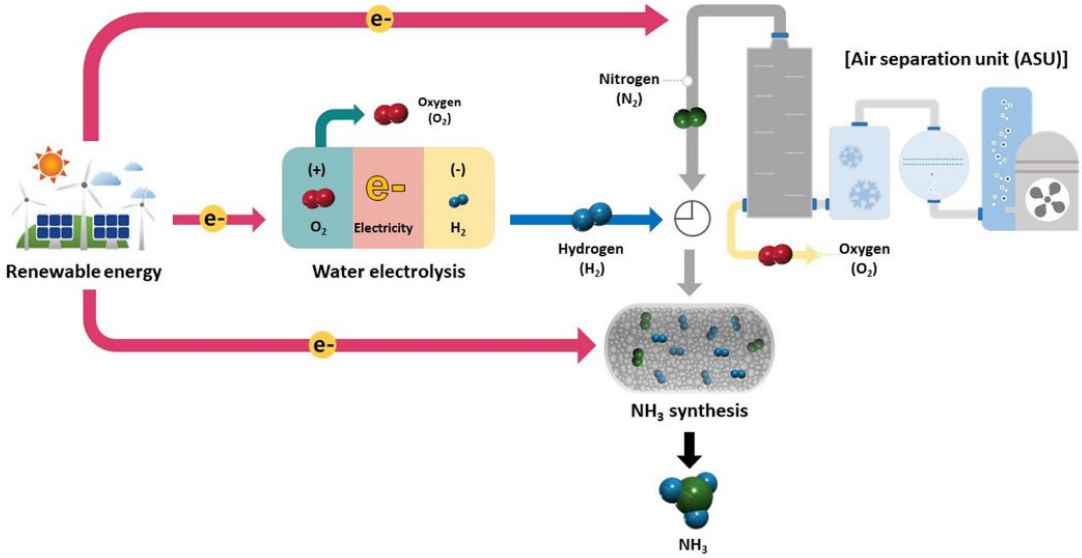
Used to transform oils into solid fats by injecting hydrogen at high pressures and temperatures in the presence of a catalyst. It is used to increase the melting point of food fat. This treated fat is more harmful to health, but cheaper than other types. Food industries introduce hydrogen into certain ingredients that naturally contain fat in liquid form, such as oils. This process is included when such ingredients are at very high temperature and with the aim to become solids. In this way, food is preserved in perfect condition for longer periods and looks like more appetising. Moreover, food is more filling and easier to cook, since it is more difficult to spoil during the cooking process.

### 5.4. Green ammonia production (fertiliser)

It is obtained by reacting nitrogen from air ($N_2$) with hydrogen from water ($H_2O$). The process requires the use of high pressures and temperatures to achieve the bonding of nitrogen and hydrogen, with the corresponding formation of ammonia. The chemistry transforms ammonia into nitric acid and nitric acid into nitrates, which are high-yield fertilisers, see Figure 6.

Chemical reaction: $N_2 + 3H_2 \rightarrow 2NH_3$

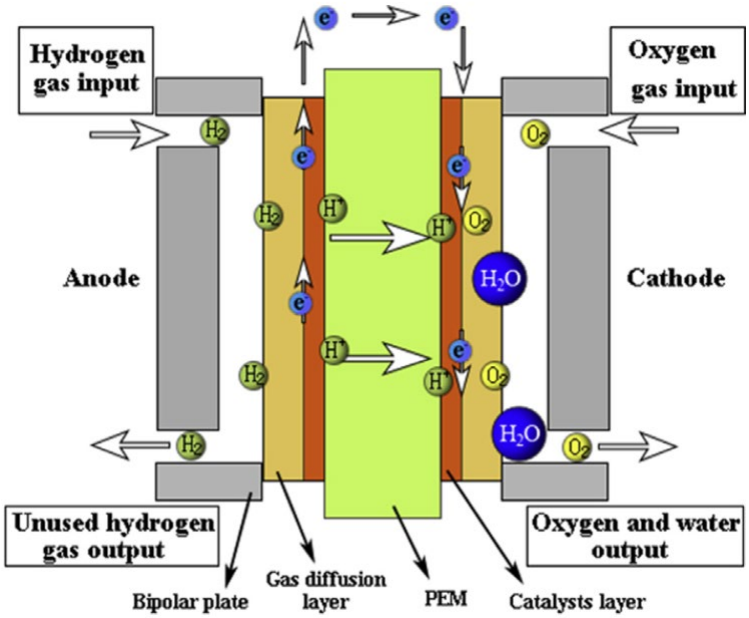
**Figure 6. Green ammonia production (Lee et al., 2021)**




### 5.5. Storage

Hydrogen is generated through a process of electrolysis, using surplus electrical energy from renewable energy sources. This hydrogen can be stored in tanks to be subsequently converted into electricity by means of a fuel cell. This generated electricity can be then used when required by industry, see Figure 7.

**Figure 7. Fuel cell (Shi et al., 2020)**




### 5.6. Alternative fuel

In a similar way to the storage method, hydrogen is generated through a process of electrolysis and the stored hydrogen can be subsequently used to generate electricity to be used in an electric motor. The electric motor can be then integrated into forklift trucks, which are widely used in industry (Caixa, L., 2022) . Indeed, they allow large loads to be moved from one place to another without the need for great physical effort, see Figure 8.

**Figure 8. Forklift truck (Toyota, 2022)**


## 6. Conclusion

The presence of renewable energies is increasing more and more in most of sectors. In general, countries are increasingly striving to achieve sustainable development goals promoting by international agreements and policies. Consequently, they are investing a great amount of money in the development of alternative electricity generation systems.

The intermittency of some renewable energies, such as photovoltaic and wind power, makes difficult to rely on these generation systems exclusively. For this reason, they are usually combined with other energy sources such as biomass, biogas, batteries, etc. aiming to guarantee that 100% of the electricity generated is from renewable energies. The increase in demand for these hybrid renewable energy systems leads to a reduction in the manufacturing costs of the components, making the installations cheaper and making easier for most of sectors (industrial, residential, tertiary) to have access to these types of installations.

Hydrogen generation is affected by these hybrid renewable energy systems. In recent years, researching is mostly conducted to the gas generation with various renewable energy sources. Electrolysers are being developed for hydrogen generation, using electricity from renewable energy and fuel cells to generate electricity with stored green hydrogen, making these hybrid hydrogen systems an alternative to conventional stand-alone systems. The first green hydrogen power plants are starting to be built, and the presence of hydrogen-hybrid systems is expected to grow in the future. In fact, green hydrogen can contribute greatly to the sustainable development of eco-industrial parks, as it has a multitude of uses in refineries, glass manufacturing, ammonia, fat hydrogenation, pharmaceuticals, storage, transport, etc. It is important to support the development of these industrial parks to improve the quality of life in the surrounding industrial and urban areas. In this framework, the use of green hydrogen will become crucial in the coming years.

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