# SMART HY AWARE PROJECT

## RECOMMENDATION REPORT FOR INNOVATIVE MODELS FOR ENERGY PRODUCTION AND STORAGE FROM HYDROGEN

## Index

# SUMMARY

This document contains a description of the activities of the partners of SMART-HY-AWARE Interreg action in the field of Hydrogen Production and Storage. Firstly, the role of hydrogen in the energy transition and the relative support policies are introduced. All the production and storage technologies are then described. A very special application consisting of the creation of integrated systems based on the hydrogen technology for production, storage, and final uses (i.e., Hydrogen Valley) is also reported as a virtuous example. The implementation of the technologies and applications in the SMART-HY-AWARE regions are reported at the end of each section. Finally, the report will give an outlook on the main technological/commercial barriers to the development of Hydrogen transition, thus indicating the main actions to be implemented to remove such barriers.

# INTRODUCTION

## Hydrogen Role in Decarbonising the EU Energy System

Hydrogen is expected to play a crucial role in achieving EU objectives regarding decarbonisation of the EU Energy System. According to the European Green Deal, a greenhouse gas emissions' reduction of at least 55% must be reached by 2030, aiming at a net-zero emission energy system by 2050.

Hydrogen ($H_2$) has historically been used to produce chemical products, mainly in oil refining and for the synthesis of plastics and fertilisers. Nowadays, hydrogen represents less than 2% of Europe's energy consumption and it is mostly produced through natural gas, resulting in significant amounts of CO2 emissions.

$H_2$ has the potential to be part of the energy transition of challenging sectors, such as hard to abate industries, power generation, and transport (light and heavy vehicles, shipping, aviation).

Renewable hydrogen, or Green Hydrogen, can be generated via electrolysis using renewable energy sources to split water into hydrogen and oxygen. Blue $H_2$, even if cleaner than Brown and Grey $H_2$, requires a Carbon Capture and Storage process (CCS) to neutralise $CO_2$ emissions. From this perspective, only Green Hydrogen represents a sustainable and completely compatible with net-zero emission objectives solution.

Furthermore, Green hydrogen can enhance the flexibility of the EU's electricity sector, while supporting Renewable Energy Sources (RES) contribution to the global electricity generation system. H2 production by RES (mainly solar and wind sources) provides a long-term and large-scale storage of renewable energy, allowing to keep the latter not only in large quantities when available, but also for a long period of time. Thus, hydrogen is configured as an energy vector that balances the actual mismatch between supply and demand when power generation is either exceeding or not satisfying users' needs.

## EU Directives and Support Policies

### EU Strategy for Energy System Integration and EU Hydrogen Strategy

The European Commission presented an EU Strategy for Energy System Integration[1] in 2020, as part of the European Green Deal, aiming at linking the various energy carriers with each other and with end-use sectors. In this way, the strategy is enabling optimisation of the whole energy system though increased efficiency and to achieve a cost-effective decarbonisation of EU countries.

[1] EU Strategy for Energy System Integration: https://energy.ec.europa.eu/topics/energy-system-integration/eu-strategy-energy-system-integration_en

The global strategy for energy system integration includes a dedicated strategy on hydrogen[2], explaining a vision for the creation of a European hydrogen ecosystem from research and technological innovation to scale up the H2 value chain to an international level.

- Key Actions

The EU Hydrogen Strategy lists 20 action points[3] that were implemented by the first quarter of 2022. Key actions presented by EU Commission mainly regard:

- Development of a European roadmap and investment agenda, supporting strategic investments in clean hydrogen projects.
- Boosting H2 demand and, consequently, promotion of production plants' scale up by facilitating the use of hydrogen in end-use sectors such as transport (Sustainable and Smart Mobility Strategy) and by introducing common low-carbon standards.
- Design of a hydrogen infrastructure, accelerating the planning of a European $H_2$ network and demonstrating innovative hydrogen-based technologies, focusing on renewable hydrogen production, storage, transport, and distribution.
- International Cooperation, encouraging definition of standards and regulations, while promoting cooperation processes on renewable hydrogen with partner extra-EU.

## REPowerEU Plan and the Hydrogen Accelerator

In May 2022 the European Commission published the REPowerEU[4] plan, finalising the implementation of the EU hydrogen strategy and increasing the goals for green hydrogen as a key energy vector to move away from Russia's fossil fuel imports.

The Commission also outlined a "hydrogen accelerator" concept to promote the scaling up of the renewable hydrogen value chain, enhancing energy transition and decarbonisation of the EU's energy system.

The REPowerEU plan's objective is to produce 10 million tonnes of renewable hydrogen in the EU by 2030 (increased from the 5.6 million tonnes established by the Renewable Energy Directive, revised in 2021) and to import 10 million tonnes of renewable hydrogen from third countries.

The Commission's targets could be achieved by establishing a global European hydrogen facility to create secure investments and business opportunities for the green hydrogen market. Renewable hydrogen partnerships can also foster the import of green H2 from third countries, encouraging the decarbonisation process.

## National Strategies and Regulations

Energy transition and decarbonisation represent an essential target for most of the largest economies and developing countries. In response to the urgency of solving the issue, a growing number of

[2] EU Hydrogen Strategy: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

[3] Key Actions of the EU Hydrogen Strategy: https://energy.ec.europa.eu/topics/energy-system-integration/hydrogen/key-actions-eu-hydrogen-strategy_en

[4] REPowerEU: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

countries are ratifying strategies and regulations on greenhouse gas emissions reductions and decarbonisation pathways to amend their energy systems within the next years.

Through the National Energy and Climate Plans (NECPs)[5], EU members are required to outline how they are going to address the EU's climate and energy targets, by a combination of energy efficiency, renewables, greenhouse gas emissions reductions, interconnections, and innovative technologies.

# Chapter 1 Hydrogen Production Technology

## Green Hydrogen Production

### Water Electrolysis

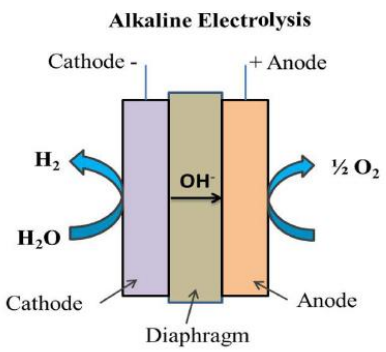
Hydrogen can be produced from water by electrolysis which is an established and well-known method. A typical electrolysis unit or electrolyser consists of two electrodes (cathode and anode) immersed in an electrolyte. When electrical current is applied between the electrodes, water splits and hydrogen is produced at the cathode, while oxygen is evolved on the anode side.
Since the required energy input is provided by electricity, the chemical reaction is endothermic, and its overall equation [1] is reported below:

$$2H_2O \rightarrow 2H_2 + O_2$$

The water electrolysis can be undertaken by three different types of electrolysers: alkaline, proton exchange membrane (PEM), and solid oxide electrolysers (SOE).
The alkaline electrolysis systems are more commonly used than the other water electrolysis methods, and on a larger-scale, since they have the lowest capital cost. However, their low efficiencies make the electrical energy cost too high [2].
Alkaline electrolysers use a liquid electrolyte service of which there are different electrolyte types: potassium hydroxide (KOH), sodium hydroxide (NaOH) and sodium chloride (NaCl). The separating diaphragm between the two electrodes is made of the asbestos material with a small thickness and due to the usage of the asbestos materials the water electrolyser operation temperature is limited to 80˚C [2].
Hydrogen and hydroxide are generated at the cathode part, then the hydroxide is moved to the anode part generating oxygen. The anode and cathode part reactions can be expressed as follows:

**Anode reaction:** $4OH^- \rightarrow O_2 + 2H_2O$

**Cathode reaction:** $2H_2O + 2e^- \rightarrow H_2 + 2\,OH^-$




[3]

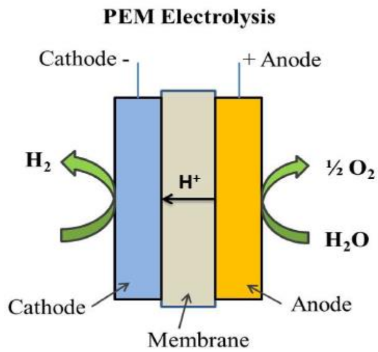
[5] National Energy and Climate Plans (NECPs): https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en

The gas-liquid separation unit (diaphragm) is used to separate the generated hydrogen gas outside the electrolyser. The alkaline electrolysers process efficiencies register a range of 60% - 80% with low operating pressure (3-30 bar). The corrosion problem is the main challenge of this method, due to the alkali solution. In consequence, new anti-corrosive materials are being developed as well as an alternative diaphragm material. As a result, a new approach to alkaline electrolysis is under development. There are two basic types of ion exchange membranes (IEM) according to the type of ion: the anion exchange membranes (AEM) and the cation exchange membranes (CEM). Both are made up of polymers instead of an asbestos diaphragm. However, while CEM contain fixed anion groups and exchangeable cations in the polymers, the AEM contain fixed cation groups and exchangeable anions in the polymers. IEMs are broadly applied in various industrial applications. A desirable IEM is expected to possess high conductivity/low resistance, high ion exchange capacity (IEC), high permselectivity, high dimensional stability/low membrane swelling and water uptake, as well as high chemical, mechanical and thermal properties.

A PEM electrolyser consists of two porous electrodes (named 'carbon cloth') and a membrane that allows the conduction of the ions and isolates electrically the two electrodes, separating the products of the oxidation anodic reaction (oxygen) from those of the reduction cathodic reaction (hydrogen). The proton exchange membrane (PEM) electrolysis systems are more efficient than alkaline electrolyser and it overcomes the corrosion issues occurring in the alkali solutions. However, the manufacturing cost of PEM is high compared with alkaline electrolysers systems, since the deionized water with high purity has been also required for the water electrolysis process. The PEM reactions are expressed as follows [2]:

**Anode reaction:** $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

**Cathode reaction:** $4H^+ + 4e^- \rightarrow 2H_2$




[3]

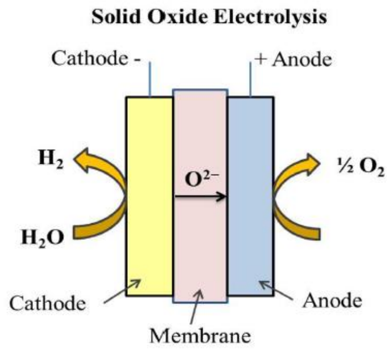
The PEM water electrolysis has great advantages such as compact design, high current density, high efficiency (80-90%), fast response, small footprint, operates under lower temperatures (20–80 °C) and produced ultrapure hydrogen (99.99%) and oxygen as a by-product [3]. Recent investigations have demonstrated that the PEM electrolysers have been successfully used with fluctuating power supply sources (renewable energies), thanks to the quick performance of the PEM membrane [2].

The solid oxide electrolyser (SOE) runs in a regenerative mode to achieve the electrolysis of water by using a solid oxide, or ceramic electrolyte to produce hydrogen and oxygen gas. This technology is currently the most promising to produce hydrogen from water, thanks to the high efficiency of conversion (90-100%), due to the high operation temperatures that can reach 1000˚C and its high operating pressure. In fact, it was investigated that the electrolyser efficiency increases by increasing high temperature [2].

In the SOE system, hydrogen is generated at the cathode part and the oxide anions are passed to the anode where oxygen will form through the solid electrolyte. The following reactions take place in an SOE:

**Anode reaction:** $O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$

**Cathode reaction:** $2H_2O + 2e^- \rightarrow H_2 + O^{2-}$




[3]

Corrosion, seals, thermal cycling, and chrome migration are the major challenges faced by the SOE technology [2].

## NATIONAL IMPLEMENTATIONS

### HUNGARY

Electrolysis is not used in Hungary nowadays at in industrial scale, but there are some small-scale applications, and there are plans for large projects:

Small scale electrolysers (from 100 W to 10 kW range) are operating in few pilot projects, and/or in rare niche applications:

- laboratory scale PEM electrolysis: ThalesNano Ltd manufactures laboratory scale (small PEM) electrolysers with capacity ~10-100 W; or 0–60 $mL_{H2}$/min) for in situ hydrogen generation for laboratory purposes, e.g., for hydrogenation reactions, or for analytical purposes. Its great advantage is that no on-site hydrogen storage is necessary in the laboratory and can provide hydrogen at high pressure (up to 100 bar).
- Paks Nuclear Power Plant has been using hydrogen as a cooling agent in its generators (8 pcs altogether). An onsite alkaline electrolyser (max. capacity: ~60 kW) produced the necessary hydrogen. A few years ago, the alkaline electrolyser was dismantled as it had reached the end of its life cycle, and the power plant switched to merchant hydrogen, provided by an industrial gas supplier.
- "Energy container": is pilot equipment providing continuous and 100% renewable power to a hunting lodge in off-grid area, in Gemenc Forest belonging to the Duna-Dráva National Park. The hunting lodge is far from the grid, so an energy container was installed here, including a 10 kW photovoltaic unit, and for the short term (~1-2 days) energy storage it uses batteries, for longer (~8-10 days) energy storage it uses hydrogen. The two energy storage options ensure a continuous power supply to the building, and the PV panels are providing the renewable energy. All the technologies are installed in a 10 ft container, which includes a ~1 kW capacity PEM electrolyser, hydrogen storage and a small fuel cell (~1,5 kW) which can recharge the batteries.

Planned, large scale electrolysers: recently several projects won subsidies in the frame of Energy Innovation Fund, and some of them using hydrogen technology. The following are relevant from the point of electrolysis:

- "Akvamarin" project delivered by Hungarian Gas Storage Ltd., which plans to install a 2,5 MW capacity PEM electrolyser in Kardoskút, where one of the underground gas storage sites is located. Green hydrogen will be produced, and the company will examine the effects of the natural gas hydrogen blend on the natural gas storage and will use hydrogen in its own technologies to replace – at least partly – natural gas. This project is in procurement stage; start of operation is expected in Q2/2022,
- Virtual Power Plant Ltd. will use a ~2,3 MW PEM electrolyser in Szabadszállás near to a photovoltaic power plant, to produce green hydrogen. The project will test and study the grid service capacities produced by electrolysis and the hydrogen storage system. The provided green hydrogen will primarily be used in (public) transport, but can be used also in home energy supply, or for industrial feedstock. This project is also in procurement stage; start of operation is expected in Q1 2022. (There are plans to upscale this project, but no public decisions available yet.)
- beyond the above-mentioned projects there is "informal" information available on several domestic electrolysis projects in MW+ scale (or even in tens of MW scale), but these are not public yet, and these project plans do not have final investment decision (FID) at present. According to the National Hydrogen Strategy adopted in June 2021, Hungary plans to have 240 MW electrolyser capacity in 2030.

Solid Oxide Electrolysis is not used in Hungary at present, and no information is available to suggest that SOE will be used in planned projects in the short or medium term.

**SPAIN**

During the last years, many efforts were made in the region of Aragon to promote and improve this technology from the Foundation for the Development of New Technologies in Aragon, FHa, a research centre focused on the development of hydrogen and fuel cells in the region. For instance, the ELYGRID Project[6] (2011–2014, FHa was the project coordinator) aimed at reducing the global price of hydrogen, produced by renewable electrolysis, mainly by employing solar energy source. The overall objective was to increase the process efficiency by around 20% as well as to achieve a remarkable reduction (about 25%) of the final hydrogen price. Another project with great relevance in the Aragon context was ELYNTEGRATION[7] (2015–2019, FHa as project coordinator), focused on design and development of a high-power alkaline electrolyser, with a hydrogen production capacity of 4.5 ton/day and characterised by high robustness, flexibility, and efficiency.

In addition to these projects, a project related to the installation of an alkaline electrolyser in renewable generation facilities has recently become known. The CSFH2 Plasencia del Monte project has been announced, in which it is expected to install a 40 MW alkaline electrolysis system, operating for 8000 hours/year, and achieving hydrogen production of approximately 6000 ton/year.[8] The electrolysis plant will be powered by either a 48.99 MW photovoltaic field system or a renewable-based electric grid. This is the first step in the project promoted by the company Dhamma Energy,[9]

[6] ELYGRID Project, Grant Agreement nº 278824. http://www.elygrid.com/
[7] EYNTEGRATION Project, Gran Agreement nº 671458. http://elyntegration.eu/
[8] RESOLUCIÓN de 23 de junio de 2021, del Instituto Aragonés de Gestión Ambiental, por la que se adopta la decisión de no someter al procedimiento de evaluación de impacto ambiental ordinaria y se emite el informe de impacto ambiental de la Planta Solar Fotovoltaica de 48,99 MWp, de autoconsumo del Proyecto "CSFH2 Plasencia del Monte" de Planta de Producción de hidrógeno H2, en el término municipal de La Sotonera (Huesca), promovido por Angus Enterprises, SL. (Expediente INAGA 500201/01B/2020/05169). http://www.boa.aragon.es/cgi-bin/EBOA/BRSCGI?CMD=VERDOC&BASE=BOLE&PIECE=BOLE&DOCS=1-40&DOCR=27&SEC=FIRMA&RNG=200&SEPARADOR=&SECC-C=&PUBL-C=&PUBL=20210929&@PUBL-E=
[9] Dhamma Energy. https://www.dhammaenergy.com/

to use this renewable hydrogen in the Zaragoza (Aragon) - Pau (France) train connection. This project is of recognised interest by the Spanish Government in the Renewable Hydrogen Roadmap. The hydrogen production facility is expected to be commissioned in October-November 2022.[10]

ELY4OFF[11] project (2016–2019, FHa as project coordinator) was the development and demonstration of an autonomous PEM electrolysis system isolated from the grid. In addition, the PROMETH2[12] project (2020–2023) in which FHa is involved, currently aims at to assess the viability of PEM electrolysis when coupled with a system for the renewable methanol production. Another objective included in this project is to reduce the current technology price below 500–700 €/kW by replacing critical materials, usually found in commercial stacks, with non-critical and cost-effective materials. The consortium will develop its own innovative stack.

In the eGHOST[13] project (2021–2023) in which FHa is involved, new specific guides for Solid Oxide electrolysis (and for PEM electrolysis too) are under development, highlighting eco-design recommendations as well as environmental, social, and economic aspects on its life cycle.

**SCOTLAND**

Aberdeen has two publicly available hydrogen refuelling stations: Kittybrewster Station and the Aberdeen City Hydrogen Energy Storage (ACHES) Station. Both hydrogen refuelling stations produce hydrogen via water electrolysis using alkaline electrolysers.

The Kittybrewster station was built by BOC and opened in 2015 when ten Van Hool buses arrived in Aberdeen. The station is operated and maintained by BOC and is the largest and most reliable dedicated bus refuelling station in the UK.

Kittybrewster uses three HyStat-60 (~300kW) alkaline electrolysers, each capable of producing up to 60 Nm3/h of hydrogen. Hydrogen is produced in the electrolysers at approx. 10 bar, this is stored in intermediate buffer storage that sits between the electrolysers and compressors. It can dispense up to 360kg hydrogen per day and has the capacity to store 420kg on-site. The station has dispensed over 160 tonnes of hydrogen over the last four years, making it one of the busiest Hydrogen Refuelling Stations in Europe. In 2018 the station was upgraded to allow the refuelling of cars and vans at 700 bar, in addition to buses.

The ACHES refuelling station is a dedicated car and van refuelling station, but with both 350 bar and 700 bar refuelling available, it can also refuel larger vehicles. It was built by Hydrogenics, opened in 2017 and is owned by Aberdeen City Council.

The station has four HySTAT alkaline electrolysers which can produce 130 kg of hydrogen per day. Mains water is purified and demineralised on site. The electrolysers split the water into hydrogen and oxygen. The oxygen is vented to air and the hydrogen is sent to the compressors. The hydrogen is produced at 10 bar pressure and is of 99.999% purity. The operating range is 40-100% and the efficiency is < 5.2 kWhe/$Nm^3$. The electrolysers are stored in 40 FT HC ISO container housing.

[10] R.J. Campos, *Aragon deserves to have solar plants for hydrogen.* https://www.heraldo.es/noticias/aragon/2021/01/12/philippe-esposito-empresa-dhamma-energy-ferrocarril-hidrogeno-plasencia-monte-1414402.html

[11] ELY4OFF Project, Grant Agreement nº 700359. http://ely4off.eu/
[12] PROMETH2 Project, Grant Agreement nº 862253. http://promet-h2.eu/
[13] eGOHST Project, Grant Agreement nº 101007166. https://eghost.eu/

## Thermolysis and Thermochemical Water Splitting

In the thermolysis process, water is directly split using thermal energy as the energy input. The temperature is raised to 1400°C or higher, the vapor molecules begin to be broken down as if they will decompose into hydrogen and oxygen gases. The temperature should be raised to 2500–3000°C to produce hydrogen for industrial applications. This process is chemically given as follows [2]:

$$H_2O + heat \rightarrow H_2 + \frac{1}{2}O_2$$

The thermolysis energy efficiency is about 50% and it has considerably high production costs due to the high temperature unless the heat is generated by solar source or from biomass combustion. However, this method can release high amounts of $SO_2$ which leads to high acidification potential [4].

The thermochemical water splitting process is the combining effect of the thermolysis process and the chemical reactions. This means that water can be split by using both the thermal energy and some other chemical materials. This allows to reduce the water decomposition temperature to 900˚C. Different thermochemical cycles have been studied such as copper-chlorine, Zinc-zinc oxide, nickel-manganese ferrite and the sulfur-iodine process. For example, the sulfur-iodine process is reported below [2]:

| | |
|---|---|
| The first reaction is the sulfuric acid which is decomposed at 300˚C to 500˚C to release water without a catalyst, | $H_2SO_4\,(aq) \rightarrow H_2O(g) + SO_3(g)$ |
| Then, $SO_3$ is separated at 800˚C to 900˚C to release oxygen, | $SO_3(g) \rightarrow SO_2(g) + \frac{1}{2}O_2$ |
| The next reaction is done at low temperature to produce the sulfuric acid, | $SO_2(g) + I_2 + 2\,H_2O(l) \rightarrow 2HI(g) + H_2SO_4\,(aq)$ |
| Finally, hydrogen is produced from iodine decomposition within a tempera-ture range of 425˚C to 450˚C, | $2HI(g) \rightarrow H_2(g) + I_2(g)$ |

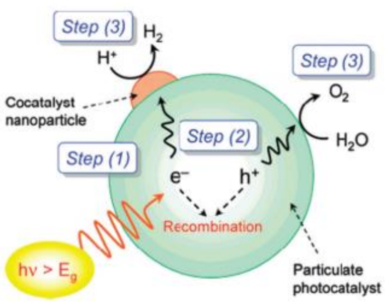
## Photonic technology

The photonic technology produces hydrogen by using the solar energy. It can be divided into two methods the photocatalytic and the photoelectrolysis water splitting (or photoelectrochemical water splitting).

The hydrogen production by the photocatalytic water splitting process is a direct method to produce hydrogen from water using the ordinary light, but it has low efficiency (0.06% [3]). The main reactions of this process are:

**Photo-reduction** $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

**Photo-oxidation** $2H_2O \rightarrow 4H^+ + 4e^- + O_2(g)$



[5]

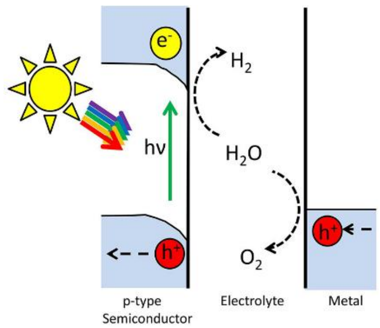
As illustrated in the Figure, the three steps are:

- Step 1: the photocatalyst absorbs photon energy and generates photoexcited electron–hole pairs in the bulk;
- Step 2: the photo-excited carriers separate and migrate to the surface without recombination;
- Step 3: the adsorbed species are reduced and oxidized by the photogenerated electrons and holes to produce $H_2$ and $O_2$, respectively.
  The titanium oxide ($TiO_2$) is used in the photolysis reactions.

The photoelectrolysis water splitting directly decomposes water into hydrogen and oxygen by using the sunlight. The photoelectrolysis systems are like the photovoltaic systems. In fact, both technologies use the semiconductor materials (p-type and n-type). The generated electric current is destined to decompose water into hydrogen and oxygen.

The reaction is illustrated as follows:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2(\mathrm{g})$$




[6]

It has been investigated that the achieved conversions efficiency is between 18.3%, and 30% [2].

## Biomass

Biomass energy is used to generate hydrogen fuel as a renewable energy source. In fact, the hydrogen in the biomass is approximately 6%–6.5% by weight (this value is about 25% in natural gas) [1]. A wide variety of biomass resources are used for the energy conversion. These can be grouped into four categories:

1. Energy plants: herbaceous energy plants, woody energy plants, industrial plants, and agricultural and water plants.
2. Agricultural residues and wastes: plant and animal waste.
3. Forest waste and residue: wood processing, cutting and tree and bush residues.
4. Industrial and urban waste: urban solid waste, sewage sludge, and industrial waste.

The biomass technologies for hydrogen production can be divided into *thermochemical processes* (pyrolysis, gasification) followed by the reforming processes and the *biological hydrogen production processes*.

The thermochemical processes involve a certain amount of combustion heat to produce hydrogen. For this reason, they are considered endothermic reactions, and they consist of the following processes:

- Pyrolysis or Gasification
- Reforming

Pyrolysis produces solid, liquid and gaseous bio-products starting from solid fuels (biomasses and coal), while the gasification is executed at higher temperatures to get totally gaseous fuel.

The reforming process involves the production of a gas mixture with a high content of gaseous hydrogen starting from other combustible gases (e.g., gases obtained by pyrolysis or gasification). The main components of the resulting gas are hydrogen, methane, carbon monoxide and carbon dioxide.

The reforming processes can be:

- Steam reforming (SR)
- Dry Reforming (DR)
- Reforming with partial oxidation (POx)
- Autothermal Reforming (AR)

The main sequential steps of the reforming process are:

1. Purification of the gas
2. Adiabatic Pre-reforming
3. Reforming (SR, DR…)
4. Water Gas Shift or Fischer-Tropsch

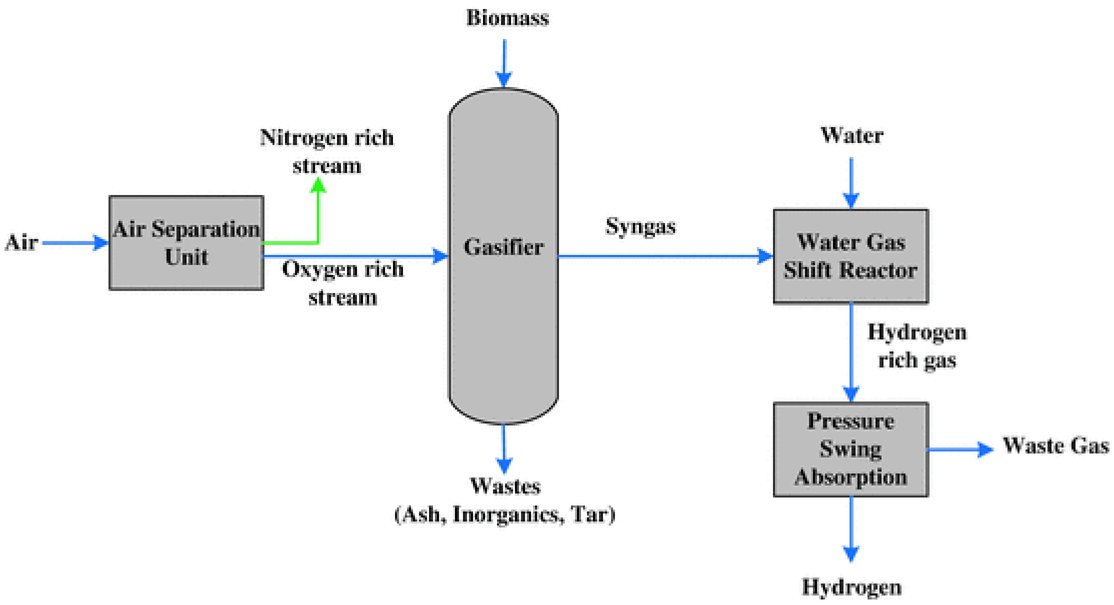
In the biomass pyrolysis, a liquid like the petroleum called bio-oil is obtained. The bio-oil contains very reactive oxygenated compounds due to carbohydrates and lignin present in the biomass. These compounds can be converted into various products including the hydrogen. The impurities of the process are $H_2S$, $CO_2$, HCN, Ni/Fe carbonyls, carbon, and ash.

The biomass can be gasified at elevated temperatures (over 1000K or 730 °C) [1]. The gas and charcoal are produced by the partial oxidation of the biomass. The charcoal is eventually converted to $H_2$, CO, $CO_2$, and $CH_4$. The conversion process can be illustrated as follows:

$$Biomass + heat + steam \rightarrow H_2 + CO + CO_2 + CH_4 + hydrocarbons + charcoal$$

Unlike pyrolysis, the gasification of solid biomass is carried out in the presence of $O_2$. Besides, while the gasification aims to produce gas products, the pyrolysis aims to produce the bio-oil and coal. The produced gases can be used to produce hydrogen by a steam-gas shift reaction or by the Fischer-Tropsch reactor. In this way, the production efficiency of hydrogen increases. The gasification process is valid for biomass with a moisture content of at least 35% [1]. One of the significant problems of biomass gasification is the formation of tar during the process. Unwanted tar can lead to tar aerosols with a more complex structure, and the formation of polymerization. This situation is not suitable for hydrogen production by steam reforming. Today, there are three methods to minimize tar formation. These are: (i) the appropriate design of the gasifier, (ii) the appropriate control and operation, and (iii) components/catalysts. Operating conditions such as the temperature, gasification material, and residence time play an important role in tar formation and its decomposition. The tar thermally fragments at temperatures above 1000°C. The use of some additives (dolomite, olivine, and coal) in the gasifier helps the reduction of the tar. When dolomite is used, the tar can be eliminated 100% [1].

Hydrogen production from biomass through gasification is like hydrogen production from fossil fuels. However, since the moisture must be vaporised from the biomass, the thermal efficiency of the gasification process is typically low, achieving a high hydrogen production yield from the dried biomass. The gas by-product of the process is $CO_2$, but the carbon dioxide released from the biomass is "neutral", this means it does not increase the $CO_2$ concentration in the atmosphere. comparing to greenhouse gases (GHGs).




Hydrogen Production from Biomass Gasification [7]

The interest in bio-hydrogen production has increased in the last few years due to the attention on sustainable development and waste minimisation. The biological hydrogen production process represents another biomass method to produce hydrogen.

Anaerobic bacteria which grow in dark fermentation bioreactors or algae in the photo fermentative process can be used.

The main processes include the photolytic process to produce hydrogen from water using green algae, the hydrogen production using the dark-fermentative process of anaerobic digestion, the two-stage dark/fermentative process, the photo-fermentative processes and the WGS method for hydrogen production. The biological methods have been presented with a low environmental impact and high hydrogen production efficiency. By using the anaerobic microorganisms, the dark fermentation reaction is carried out to convert the carbohydrate to hydrogen and other final products. The following is the chemical reaction equation [2]:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2\,CO_2 + 4H_2$$

## NATIONAL IMPLEMENTATIONS

### SPAIN

In the Aragon region there were two main projects focused on hydrogen production from biomass.

In the VERTEGAS[14] project (2017–2018, FHa as project coordinator), the main task was to conduct a viability assessment on the biomass residues exploitation for biogas production, paying special attention on a business case developed in the waste management installation of Huesca, GRHUSA, installations, as well as on the evaluation of its repeatability in other areas. Successively, the biogas upgrading to more refined fuels, such as hydrogen, has been evaluated from an energetic and economic point of view. Another important project to mention is GreenCarbon[15] (2016–2020), an academic project in collaboration with different industrial partners. The principal focus was developing novel tailor-made biomass-derived carbons for several applications. Among the wide range of lines of investigation included in the project across Europe, a part of the research carried out in Aragon dealt with hydrogen production from a bioliquid, a subproduct derived from a previous step of biomass pyrolysis, through a steam reforming process catalysed by carbon-based catalysts.

### GREECE

Greece has capacity for energy production from renewable sources, according to Regional Operational Programme ERDF 2014-2020, Sterea Ellada OP- T04 Low carbon economy.
The Regional Unit of Phocis is located in Central Greece (Sterea Ellada), with the Municipality of Delphi being one of the biggest regional authorities in Phocis Region. Municipality of Delphi through SMART-HY-AWARE, investigated best practices regarding hydrogen mobility and how these can be applied to the region. The goal was to individuate ways of producing the required energy for the hydrogen production from renewable energy sources of the region, such as local agricultural waste (biomass) or solar energy.

The Municipality of Delphi aims to improve, through SMART-HY-AWARE, the policy instrument T04 by conducting a study that will incorporate a more holistic approach to a local low carbon economy. Thus, it will not only look into the issue of sustainable transport alone. Instead, it will incorporate into the cycle, the energy required to produce hydrogen from electrolysis through the use of energy production coming from local biomass waste such as olive trees and olive oil refinery waste as well as solar energy.
Consequently, a study was carried out to identify the possibility of producing electricity from the aforementioned resources and detailing the suitability of this specific type of biomass including the capital expenditure required for such infrastructure.
The Municipality of Delphi has a strong agricultural production; its citizens predominantly work in the sector of cultivating olives. The latter constitutes over 52% of the cultivated land in the Municipality. The city of Amfissa, located in the Municipality, hosts the largest single olive grove in Greece. With the region of Continental Greece offering satisfactory sun radiance and several hours of sunlight, the Municipality suggests that photovoltaic systems could have further penetration into energy production of the area. These two factors of local biomass capacity and solar energy offer a strong starting point for generating electric energy from resources with a smaller carbon footprint than coal.

[14] VERTEGAS Project, funded by AEI (Agrupación Empresarial Innovadora). https://hidrogenoaragon.org/es/proyectos/vertegas/
[15] GreenCarbon Project, Grant Agreement nº 721991. http://greencarbon-etn.eu/

## Hydrocarbons Reforming Technology

In hydrogen production processes from fossil fuels, hydrocarbons, steam, and in some cases, air or oxygen are heated and combined in a reactor. Hydrogen is recovered from both water and hydrocarbons; $H_2$, CO, and $CO_2$ are formed by the breakup of water molecules and hydrocarbons. Another method is the decomposition of hydrocarbons into hydrogen and carbon by being heated without the steam or air.

The hydrogen production technology by using the hydrocarbon fuels can be divided into a steam reforming process (SR), the partial oxidation process (POX), and the auto-thermal reforming process (ATR).

### Steam Reforming

Nearly, 50% of the hydrogen produced worldwide is derived from natural gas, primarily via steam methane reforming. The steam reforming process is known as the hydrocarbon's conversion with steam into hydrogen, carbon oxides, methane, and unconverted steam mixture. The typical feedstock ranges from natural gas, LPG (Liquefied Petroleum Gas) and liquid fuels including naphtha and in some cases kerosene. In recent years steam reforming is also seen as an option for converting the primary feed into a gas suitable for a fuel cell. Different steam reforming reactor types have been used for specific applications. The steam reforming process is considered the preferred hydrogen production process, the steam reforming process reactions are endothermic reactions, the operating temperature is typically lower than the POX and ATR methods while it can be produced a high H/CO ratio [2].

The hydrogen production from methane using the steam reforming process is considered the common industrial method where it is given a high thermal efficiency up to 85%[2].

| **Steam Reforming Process Reactions** | **Reaction description** | **Standard enthalpy of reactions [kJ·mol−1]** |
|---|---|---|
| $CH_4 + H_2O \leftrightarrow CO + 3H_2$ | Steam reforming | 206 |
| $CO + H_2O \leftrightarrow CO_2 + H_2$ | WGS | -41 |
| $CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ | $CO_2$ reforming | 247 |
| $C_nH_m + nH_2O \leftrightarrow nCO + (\frac{m}{2} + n)H_2$ | Higher hydrocarbons steam reforming | 1175 |

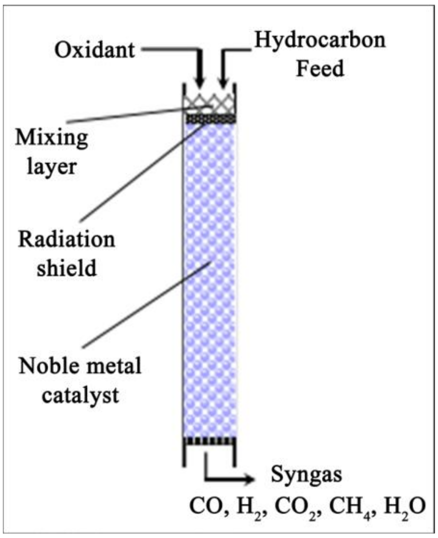
### Partial Oxidation

The reaction of the partial oxidation (POX) method is an exothermic reaction. In the POX method the hydrogen produced is sent to the water-gas shift (WGS) reactor, and then it is purified by using a suitable purification method. The efficiency of the POX process is lower than the steam reforming process. In addition, the operation cost is too high due to high quantities of pure oxygen involved. The hydrogen production from the partial oxidation of hydrocarbon using catalysts has been utilised in commercial applications and automobile fuel cells. The effect of addition ruthenium (Ru) on the molybdenum (Mo) catalysts has been investigated to produce syngas from methane ($CH_4$) via partial oxidation process. The POX reactors efficiencies have been recorded based on the higher heating values for methane fuel is 60% - 75% [2].

**Overall chemical reaction:** $C_nH_m + \frac{n}{2}O_2 \leftrightarrow nCO + \frac{m}{2}H_2$

**Example:** $CH_3OH + \frac{1}{2}O_2 \rightarrow CO_2 + 2H_2$

$\Delta H = -193.2\ [kJ \cdot mol^{-1}]$

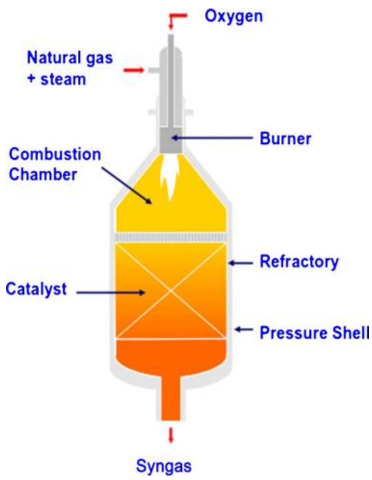



[2]

## Auto-Thermal reforming

The auto thermal reforming process has been done at low pressure compared with the POX reforming process. The heat required in the catalytic zone to drive the steam reforming reactions has been generated using the POX process. A significant advantage of the auto-thermal reaction process is the production of a large amount of hydrogen gas while the starting and stop are very rapidly with respect of the POX process. In the auto-thermal reaction process, the temperature must be controlled to prevent the coke formation by using both the steam to carbon ratio and the oxygen to fuel ratio.

| Auto-thermal Reforming Process Reactions | Reaction description | Standard enthalpy of reactions [kJ·mol−1] |
|---|---|---|
| $CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O$ | Combustion | -519 |
| $CH_4 + H_2O \leftrightarrow CO + 3H_2$ | Steam Reforming | 206 |
| $CO + H_2O \leftrightarrow CO_2 + H_2$ | WGS | -41 |




[2]

The gasification process is presented to be a sequence of thermochemical transformations taking place at high temperatures between the organic part such as coal and the gasifying agent like oxygen, steam, air, carbon dioxide [2]. The heat needed for the gasification process has been made by using the carbonaceous material. The water gas shift (WGS) process has been used to separate hydrogen and converting carbon monoxide into the carbon dioxide.

| **Auto-thermal Reforming Process Reactions** [2] | **Reaction description** [2] | **Standard enthalpy of reactions [kJ·mol−1]** [2] |
|---|---|---|
| $2CO + O_2 \leftrightarrow CO_2$ | Oxidation of CO | −566 |
| $2H_2 + O_2 \leftrightarrow H_2O$ | Oxidation of $H_2$ | −483.6 |
| $CO + H_2O \leftrightarrow +CO_2 + 2H_2$ | WGS | −41 |
| $CO + 3H_2 \leftrightarrow +CH_4 + H_2O$ | Methanation/hydrogenation | −206 |
| $CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$ | Combustion | −802.6 |

### Pyrolysis

The pyrolysis process involves the decomposition of organic substances through the heat. The decomposition reactions are performed at temperatures between 350 and 400˚C depending on the coal properties. The other hydrocarbons thermal decomposition occurs at high temperatures such as methane thermal decomposition temperature at 1400˚C or higher. Significantly, the temperature of the pyrolysis process can be reduced by using the transition metal catalyst like (Ni, Fe, Co).

The chemical reaction of the pyrolysis process can be generally expressed as follows [2]:

$$C_nH_m \rightarrow nC + \frac{1}{2}mH_2$$

Water and air aren't used in the chemical decomposition of hydrocarbons through the pyrolysis process. Consequently, carbon oxides do not appear in the by-product's reaction. It was presented that the pyrolysis process has the flexibility to use any organic fuel. Although the pyrolysis process advantages, there is a major potential fouling problem due to the formed carbon and it can be reduced by using appropriate reactor design.

## NATIONAL IMPLEMENTATIONS

### HUNGARY

In Hungary the only method used at present for (grey) hydrogen production is steam methane reforming (SMR). No POX or autothermal reforming technology is used. The three largest SMR units are:

- oil refinery, Százhalombatta (belonging to the MOL Gorup),
- fertilizer plant, Pétfürdő (belonging to Nitrogénművek Ltd.),
- chemical complex, Kazinbarcika (belonging to BorsodChem Ltd.)

All these plants producing hydrogen in the order of magnitude ~20-60 kt/y each with SMR method. Exact (installation-level) production quantities are confidential business information, so only the aggregated (country level) production volume is known, which is estimated ~100-150 kt$_{H2}$/y. Expert opinion, that the built-in capacity of the domestic SMR units is higher, and altogether could make possible 200+ kt/y hydrogen production.

Beside the above mentioned large SMR units there are two smaller ones (<1,0 kt/y) in Hungary, but their capacity is also included in the above-mentioned domestic capacity:

- for chemical industry[16], Pétfürdő (Huntsmann Co.),
- for metallurgy and glass manufacturing, Budapest (Tungsram Ltd.)

**SCOTLAND**

St Fergus Gas Terminal in Aberdeenshire, North East Scotland is currently exploring the large scale adoption of Steam Methane Reforming (SMR) with Carbon Capture and Storage. The 'Acorn' Project proposes to take North Sea natural gas and reform it into clean burning hydrogen with the first hydrogen plant online in 2025. The hydrogen will blend with the natural gas that is piped through the UK's National Gas Transmission System to transport the fuel into Aberdeen and beyond. In time, this will grow to a 20% blend. The project will also make use of 420km of legacy oil and gas infrastructure to return captured $CO_2$ to under the seabed. The $CO_2$ will not only be captured by gas processing units when making hydrogen from SMR but will also offer a CO2 storage location for other hard to decarbonise industries and sectors. The project is estimating that between 5-10 Mt of $CO_2$ will be captured per year by 2030. Approximately 30% of the UK's $CO_2$ storage lies within 50km of the St Fergus pipeline corridor and so it offers a significant opportunity for both SMR and CCS to make 'blue hydrogen'. Hydrocarbons Reforming Assisted by using Plasma Technology

Plasma can be defined as an ionized gas and it is used for hydrogen production. Most plasma proposed for hydrogen production from gaseous fuels are generated by electron beam, dielectric-barrier discharge, gliding arc, plasmatron arc and microwave discharge. The plasma reformers work at 2000°C and their advantage is that alcohols and all hydrocarbons, including heavy oil fractions, can be reformed and the organic materials are broken down in air and oxygen-free environment, and as a main product, hydrogen is obtained by thermal dissociation, without forming carbon dioxide. Hydrogen is easy to be separated since the carbon produced as a by-product has a granular structure. In addition, alcohols can provide significant advantages when used as a liquid fuel for hydrogen generation due to a high hydrogen to carbon ratio, low boiling point, low temperature for hydrogen conversion, no Sulphur content, high water solubility and biodegradability. The reforming of alcohols for producing hydrogen has been investigated in a wide variety of plasmas.

The plasma technology can be classified into thermal and non-thermal plasma according to the energy level (temperature, plasma state, and electronic density) and it can be realized with and without catalyst.

## Thermal Plasma technology

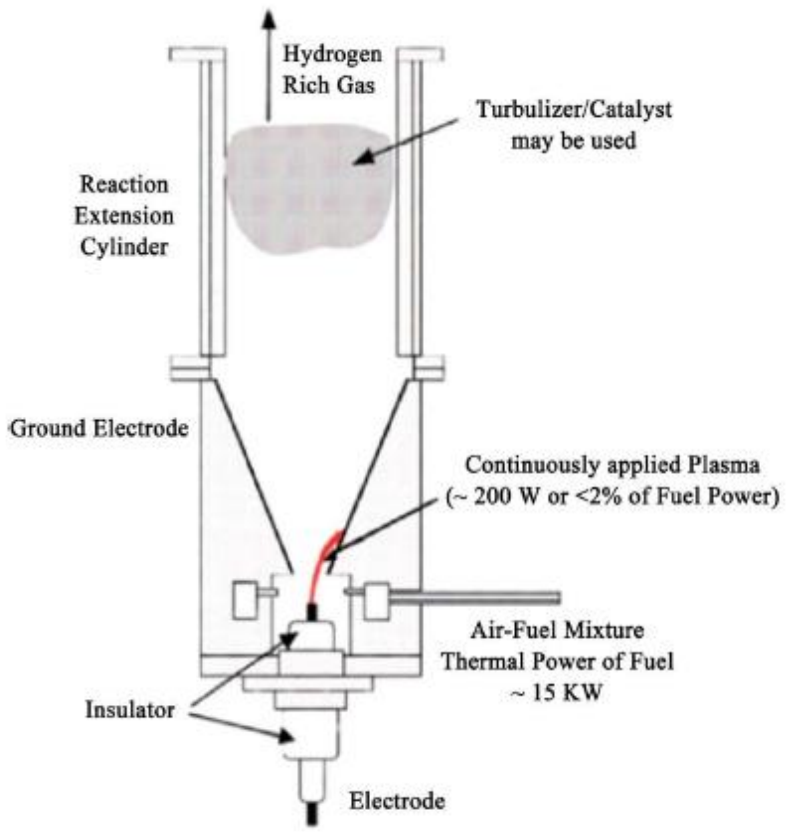
Thermal plasma can be applied to different applications which require high temperature such as vehicles ignition systems, lighting applications, gasification of solid fuels. The major advantage of using these plasmas is that most of them have sufficiently high temperatures to vaporise the alcohols inside the plasma or to vaporise them prior to feeding them into the plasma. The cost of generating such high temperature plasmas seems to be competitive compared to thermal/catalytic steam reforming processing. However, since the thermal plasma technology involves high temperature, its use is limited for some liquid fuels reforming due to the electrode erosion. Thermal plasma has an important range of application that includes synthesis of nano powders, destruction, and treatment of hazardous waste, metallurgy application (smelting operations and re-melting application in large furnaces), surface modification and coating, chemical synthesis. Thermal degradation (gasification) of the organic carbon-based materials have been carried out at a temperatures range of 400˚C to 1500˚C. It has been investigated that thermal plasma technology can be used in waste treatment such as healthcare wastes, steel making waste…. etc.

[16] For methil-ciklohexane, amines production.

## Non-Thermal Plasma technology

The non-thermal plasma method (figure below [2]) is more suitable for the hydrocarbons reforming and producing syngas. According to the non-thermal plasma method, the chemical reactions happen at low input power and at low temperatures. In non-thermal plasma technology, the electron temperature can reach 10,000 to 100,000 K and at the same time, the gas temperature is at the room temperature. Different reactors have been used for applying the different plasma technologies like the dielectric barrier discharge (DBD) reactors, gliding arc discharge, corona and microwave. It has been utilized in hydrocarbons reforming such as diesel, methane, and biofuels.

The gliding arc discharge has the highest efficiency among the non-thermal plasma method. The gliding arc discharge which has two electrodes and a simple feeding electrical system. The arc is formed while the gas enters the reactor and the high voltage is applied. The arc is pushed down by the gas along the reactor length and is turned off at the reactor end, and then the new arc is formed again at the reactor gas inlet. It has been investigated that the gliding arc discharge method can be used the DC or AC currents, in addition, a simple feeding power supply system compared with the other non-thermal plasma systems.




Scheme of Gliding Arc reactor

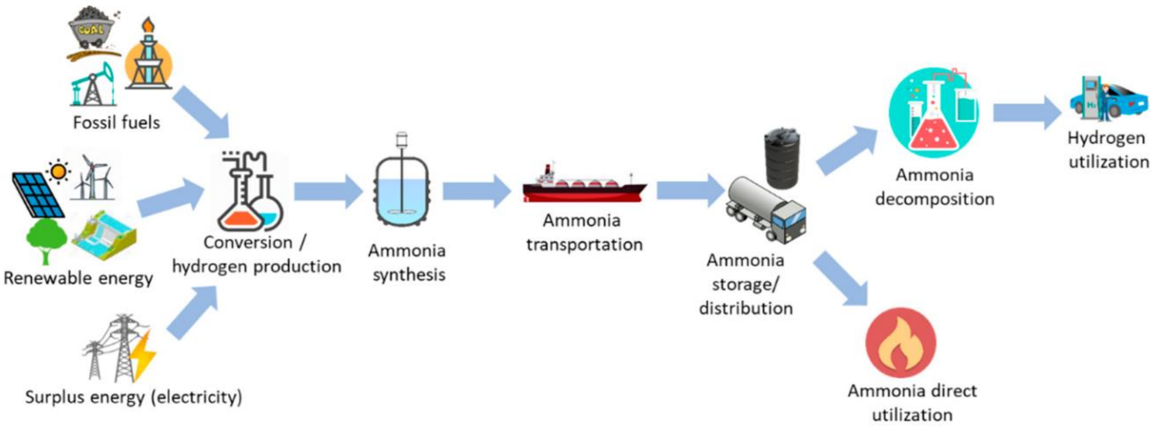
## Hydrogen Production using Ammonia [$NH_3$]

### Plasma technology

Hydrogen production from ammonia ($NH_3$) using high electron energy obtained by atmospheric pressure plasma is a promising method for producing purified hydrogen from ammonia. In fact, this technology can produce a 99.99% of pure hydrogen gas at normal temperature, atmospheric pressure and without using a catalyst. Moreover, it has low-cost, low environmental impact and highly efficient hydrogen production equipment based on ammonia gas. The flowing ammonia gas is decomposed into hydrogen and diatomic nitrogen through the plasma field as follows [2]:

$$NH_3 + e^- \rightarrow \frac{1}{2} N_2 + \frac{3}{2} H_2$$

The Ammonia Decomposition technology implies a cylindrical plasma reactor without catalytic materials. The hydrogen is produced from $NH_3$ at atmospheric pressure plasma membrane reactor (PMR) by dielectric barrier discharge. The PMR has been composed of a quartz glass tube and a palladium separation membrane to improve the efficiency of hydrogen production from ammonia decomposition.




Production, Storage and Utilization of hydrogen from ammonia[8]

### Reforming of Ammonia

Hydrogen can also be produced from the ammonia reforming technology. Ammonia is unstable at high temperatures and begins to decompose at 200 °C. The slightly endothermic decomposition reaction is shown in the following equation [8]:

$$2NH_3 + 92.4\ kJ \rightarrow N_2 + 3H_2$$

Thermodynamically, 98-99% conversion of ammonia to hydrogen is possible at temperatures as low as 425 °C. However, in practice, the rate of conversion depends on temperature as well as catalysts [8]. The formation of $NO_X$ is unlikely to be significant [8]. Thermal decomposition or catalytic cracking is the most common means of hydrogen generation from ammonia, especially for small case generation.

## Hydrogen as subproduct of industrial processes

This type of application is marginal but, somewhere it can constitute an interesting source of 'alternative' hydrogen production

### NATIONAL IMPLEMENTATIONS

**SPAIN**

In the Aragon region, the company Ercros (Sabiñánigo), dedicated to the production of various chemical products, obtains hydrogen in the electrolysis plants of sodium chlorate and chlorine-soda/potash. This hydrogen is already used as a feedstock in the production of hydrogen peroxide, hydrochloric acid and ammonia. Ercros has signed its commitment to the GetHyGa initiative, which aims to create a hydrogen ecosystem in Aragon.[17]

In addition, the company Iberfoil,[18] dedicated to the lamination of aluminium, has announced an investment project to be launched in Sabiñánigo. It envisages the development of smelting furnaces that will allow the use of up to 100% locally produced hydrogen from renewable resources as fuel. These furnaces will be used in a new aluminium scrap recovery process.[19]

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[17] Ercros, *Ercros advances in its commitment to green hydrogen in Aragon.* *http://www.ercros.es/index.php?option=com_content&view=article&id=3310:ercros-avanza-en-su-compromiso-con-el-hidrogeno-verde-en-aragon&catid=22:noticias&lang=es*

[18] Iberfoil. https://www.iberfoil.com/

[19] Iberboil, The Alibérico Group presents in Huesca its circular economy Project Iberfoil Integra. https://www.iberfoil.com/el-grupo-aliberico-presenta-en-huesca-su-proyecto-de-economia-circular-iberfoil-integra/

## Technology Readiness level of the technologies

The available technologies for the hydrogen production are assessed according to their Technology Readiness Level (TRL), which represents a widely accepted standard for ranking the maturity of the different solutions. For the sake of clarity, the definition of TRL [4] is outlined in the following Table:

| TRL | Definition | Description |
|---|---|---|
| 0 | Idea | Unproven concept, no testing has been performed |
| 1 | Basic research | Principles postulated and observed but no experimental proof available |
| 2 | Technology formulation | Concept and application have been formulated |
| 3 | Applied Research | First laboratory tests completed; proof of concept |
| 4 | Small scale prototype | Built in a laboratory environment |
| 5 | Large scale prototype | Tested in intended environment |
| 6 | Prototype system | Tested in intended environment close to expected performance |
| 7 | Demonstration system | Operating in operational environment at pre-commercial scale |
| 8 | First-of-a-kind commercial system | Manufacturing issues solved |
| 9 | Ready for commercialization | Technology available for consumers |

All the main technologies, analyzed in the present document, are summarized in the following table according to the feedstock, energy source, efficiency and maturity. In particular, the technologies are listed in order of technological maturity:

| Hydrogen Production Technology | Feedstock [2] | Energy source | Efficiency [2] | Maturity [2] |
|---|---|---|---|---|
| Steam reforming | Hydrocarbons | Thermal Energy | 70% - 85% | Commercial (TRL 8-9) |
| Partial Oxidation | Hydrocarbons | Thermal Energy | 60% - 75% | Commercial (TRL 8-9) |
| Biomass gasification | Biomass | Thermal Energy *(combustion, CPV, geothermal sector, nuclear reactor, electrolysis, cogeneration)* and Chemical Energy | 35% - 50% | Commercial (TRL 8-9) |
| Alkaline electrolyzer | $H_2O$ + Electricity | Chemical Energy and Electrical Energy *(from Renewables: wind power, PV, CPV)* | 60% - 80% | Commercial (TRL 8-9) |

| | | | | |
|---|---|---|---|---|
| Autothermal reforming | Hydrocarbons | Thermal Energy | 60% - 75% | Near term (TRL 7-8) |
| Ammonia decomposition | Ammonia | Chemical energy | 28.30% | Near Term (TRL 7-8) |
| PEM electrolyzer | $H_2O$ + Electricity | Chemical Energy and Electrical Energy *(from Renewables: wind power, PV, CPV)* | 55% - 70% | Near term (TRL 7-8) |
| Aqueous phase reforming | Carbohydrates or lignocellulosic biomass | Chemical Energy | 35% - 55% | Med. Term (TRL 5-6) |
| Solid oxide electrolysis cells | $H_2O$ + Electricity + Heat | Chemical Energy and Electrical Energy *(from Renewables: wind power, PV, CPV)* | 40% - 60% | Med term (TRL 5-6) |
| Plasma reforming | Hydrocarbons (or alcohols) | Electrical and Chemical Energy | 9% - 85% | Long term (TRL 4-5) |
| Photolysis (Photocatalytic water splitting) | Sunlight + Water | Direct Solar energy and Chemical Energy | 0.50% | Long term (TRL 4-5) |
| Dark fermentation (Photobiological water splitting) | Biomass (algae) + Sunlight | Direct Solar energy and Chemical Energy | 60% - 80% | Long term (TRL 4-5) |
| Photo fermentation (Photobiological water splitting) | Biomass (wastes) + Sunlight | Direct Solar energy and Chemical Energy | 0.10% | Long term (TRL 4-5) |
| Microbial electrolysis cells (Photobiological water splitting) | Biomass (microorganism) + Electricity | Electrical Energy *(from renewables: wind power, PV, CPV)* | 78% | Long term (TRL 4-5) |
| Thermochemical water splitting | $H_2O$ + Heat | Thermal Energy *(from CPV and Nuclear reactor)* and Chemical Energy | NA | Long term (TRL 4-5) |
| Photo electrochemical water splitting (or photoelectrolysis) | $H_2O$ + Sunlight | Direct Solar Energy and Electrical Energy *(from semiconductors as in PV applications)* and Chemical Energy | 12.40% | Long term (TRL 4-5) |

# Chapter 2 State of art of Hydrogen Storage

## Storage of Hydrogen in Geological Units

### Deep Geological Structures

Storage in deep geological units is already used for oil, natural gas and compressed air and recently, the interest has grown for the hydrogen applications. The reason is attributable to the high volumes available to respond to the needs of the seasonal market on a national scale. In fact, it can be functional both for ensuring the basic service over time and for peak needs. In the first case, recovery operations of a predominantly seasonal type will be used, in the second case, the storage must be able to meet the demand in the short term, with modulation of the flow rate even several times during the same day. Moreover, the geological units protect the system from breakdowns, international disputes and problems that may arise in the distribution or production sector.

However, since hydrogen is a small and reactive molecule, its storage requires more studies about the interaction with existing anthropogenic structures, the evaluation of the environmental impacts, the tightness and impermeability of the tanks and any variations of the rocks in terms of mechanical behaviour (stress and deformations). In addition, these geological structures must require an adequate capacity for storing and containing the gas, which means high porosity with an impermeable cover. Finally, there must be high permeability so that the gas can be injected and withdrawn with suitable regimes for civil or industrial needs.

### Depleted Oil Fields

When the hydrogen must be stored in depleted oil fields, some focal points should be considered. The calorific value per unit volume of hydrogen is about five times lower than that of methane. Consequently, for the same available volume, it is possible to store a smaller amount of energy. Furthermore, due to the lower compressibility of the gas, a smaller volume of mixture can be stored under the same conditions of pressure (P) and temperature (T).

During the first storage cycle, the loss of a small quantity of hydrogen injected is foreseeable by dissolution in the fluid already present in the rock and in the cap rock. Chemical reactions are possible between hydrogen and the ions dissolved in the formation fluid; these reactions are very slow at reservoir conditions of pressure and temperature, but they can be accelerated by the presence of bacteria and microorganisms which, acting as catalysts of chemical reactions, lead to the formation of acid metabolic compounds and have negative effects on the pH of the formation fluid and on the rock. The hydrogen molecule is highly reactive and can react with a wide variety of chemical compounds. The most common reagents are sulphates, carbonates and oxides that are found within the formation and cap rock.

### Salt caverns

The storage of natural gas in the underground cavities has been practiced for decades and the acquired knowledge can easily be used in the case of hydrogen storage.
Salt caves are currently considered a valid underground storage option thanks to their low need for cushion gas, the large holding capacity of the rock salt and the inert nature of the rock which guarantees the non-contamination of stored hydrogen. Storage in saline cavities also allows flexible operations with fast injection and dispensing cycles. In addition, salt mines contain gases thanks to their very impermeability and require the creation of a cavity in depth with the dissolution of the salts. The saline cavities, compared to depleted deposits, offer a smaller volume and can satisfy an

intermediate storage request between the short and the long term. Currently, to reach the desired volumes for this type of storage, it is necessary to create several cavities. They have proved to be an excellent solution to meet peak loads, as they are able to supply large quantities with a few hours' notice.

### Lined Rock Caverns (LRC)

Lined Rock Caverns (LRC) are man-made underground caverns, consisting of a concrete and steel structure. The construction involves the drilling of a well or corridors from the surface to the desired position and then the removal of rock material according to the design geometry. The surface is covered with concrete (like a tunnel) and then internally coated with steel. In this way, the mechanical stress is supported by the concrete, while the steel lining allows for waterproofing.

## NATIONAL IMPLEMENTATIONS

### HUNGARY

In Hungary no Salt Caverns or Lined Rock Caverns exist. In the Carpathian Basin only porous geological formations exist, as for example depleted oil or gas fields. Some of them were transformed in Hungary to natural gas storage. Hungary has – even in Central-European level – considerable natural gas storage capacity: approx. ~6 billion m3 natural gas storage capacity exist, while the domestic natural gas consumption is 9 billion m3/y. This means that there can be a huge strategic potential in domestic underground hydrogen storage, and it promises the possibility of seasonal energy storage. However, at present there is no underground hydrogen storage in geological formations in Hungary, neither in the form of pure hydrogen, nor in natural gas / hydrogen blend. But intensive research has started to examine whether the domestic porous geological formations are adequate for hydrogen storage. The Hungarian Hydrogen Strategy – adopted in 2021 – manages this issue as a strategical direction. And as mentioned in Chapter '1/a' large scale research project (e.g., 'Akvamarin Project') has started to study the hydrogen tolerance of a chosen geological storage site (in Kardoskút, South-East of Hungary), and the connected gas grid elements (pipes, gas engine etc.). These first research or pilot projects are cautious and carried out with rather low hydrogen concertation (approx. <1%). However, there is governmental intentions to start further domestic pilot projects in the near future to examine all possible aspects of underground hydrogen storage, its technical geological and financial feasibility (also including the hydrogen tolerance of other gas grid elements: pipes, compressors, pressure regulators, domestic end use gas appliances; not least the necessary legal regulatory background).

### SPAIN

In Aragon, between 2012-2014, the FHa coordinated the HyUnder project[20], which studied the viability and business models associated with the use of hydrogen stored massively underground, in salt caverns, to balance the grid when large amounts of renewable generation are added to the electricity mix, analysing the situation for six different countries: Germany, Spain, France, the Netherlands, the UK and Romania. The project evaluates this solution on a technical, economic, and social level as the basis for future implementations.
FHa is currently participating in the HyStories project[21] (2020-2022) which addresses the main technical feasibility questions for underground storage of pure hydrogen in aquifers or depleted fields, and will provide market, societal and environmental insights on the deployment of underground

[20] HyUnder Project, nº Grant Agreement 303417. http://hyunder.eu/publications/
[21] HyStories Project, nº Grat Agreement 101007176. https://hystories.eu/

storage of hydrogen in Europe. FHa is also involved in the MefHySto project[22] (2020-2023), which addresses the metrological and thermodynamic issues that would arise from a possible large-scale underground storage of hydrogen, as well as the conversion of existing underground storage facilities for natural gas to hydrogen.

## Storage of Hydrogen in Pressure Tanks

The hydrogen in pressure tanks is one of the most used storage solutions. This method required in-depth studies on the materials and geometries of the tanks in order to design the most appropriate and safe tanks useful for its use in both the transport and stationary sectors. In fact, the storage pressure affects the thickness, dimensions and weight of the containers, the choice of materials and costs.

According to the application, there can be two different storages:

a. Low and medium pressure (< 200-300 bar)
b. High pressure (> 300 bar)

In the industrial field, hydrogen is stored in steel cylinders, depending on the required volume at pressures of 200 - 300 bar. Storage can be very important and can reach a few tens of tons of hydrogen and more.

On board vehicles, hydrogen is stored at a pressure of 350 bar (buses, trains) and 700 bar (passenger vehicles and heavy transport). High pressures are required to achieve high energy density. In the refuelling stations, storage of large volumes at medium pressure (about 200 bar) and storage at high and very high pressure (about 500 and 1000 bar) are foreseen in order to quickly refuel vehicles, at 350 and 700 bar respectively. Both passenger vehicles and bus and heavy transport stations are increasingly being designed for large supplies of $H_2$ (up to 8 tons / day)

### NATIONAL IMPLEMENTATIONS

**HUNGARY**

In Hungary at present only low and medium pressure tanks (<300 bar) are used for hydrogen storage. These are co-called 'Type-I' steel cylinders. In many cases this – compressed gas – hydrogen is stored in hydrogen trailers (semi-trailers), which has the capacity of 3 600 – 4 500 Nm$^3$, and usually store on 200 bar. At larger domestic industrial $H_2$ producers there are maximum max. 6-7. trailer-ports established, which means that in this form theoretically max. ~2 – 2,5 $t_{H2}$ can be stored onsite, but in real-life operating conditions the stored amount is ~500-1 500 $kg_{H2}$.

The only one Hungarian hydrogen refuelling station – located and operating in Budapest- is also supplied from a hydrogen semi-trailer mentioned above, and do not have a stationary large-scale hydrogen storge tank, since this is a kind of test refuelling station. However, from 2022 it is expected, that new hydrogen refuelling stations will be equipped with stationary hydrogen storage tanks with capacity of ~200 $kg_{H2}$ or even more.

At small scale pilot projects mentioned in Chapter "1/a" (see: 'energy container' project description) hydrogen is stored in standard gas cylinder (200 Nm$^3$, 30 bar), since in this cases storage of approx. ~10 $kg_{H2}$ is enough storage capacity.

[22] MefHySto Project, EMPIR. Project Number: 19ENG03. https://mefhysto.eu/

**SPAIN**

Many companies establish in Aragon works on solutions for storage and distribution hydrogen.

Carbotrainer[23], is a cylinder manufacturer with a carbon fibre cylinder manufacturing plant. It currently offers both cylinders and cylinder blocks at 200 and 300 bar. It participates in European projects related to hydrogen technologies such as GetHyGa[24], Shaky[25], Shinefleet[26].

In addition, the CALVERA Group[27] integrates all the processes for the manufacture of high-pressure compressed hydrogen transport and storage equipment. It supplies the necessary equipment for the distribution and dispensing of hydrogen, including compressor stations, hydrogen transport trucks and complete HRS for all types of vehicles, with supply pressures of 300 or 700 bar. Of note is its participation in European projects such as BigHit[28], NG-POD[29], or in the first HRS with a supply pressure of 700 bar in Spain.[30]

**SCOTLAND**

At the Kittybrewster Hydrogen Refuelling Station (HRS) and ACHES HRS in Aberdeen, the hydrogen is stored in pressure tanks. After an intermediate buffer storage, compressors charge storage bundles to the appropriate pressures.

Kittybrewster has two different storage bundles, one at 500 bar to refuel buses, the other at 900 bar to refuel cars.

ACHES has the capacity to store an additional 150kg of hydrogen on site. The station can dispense hydrogen at both 700 and 350 bar. For 350 bar refuelling there is a capacity of 100 kg with a maximum pressure of 500 bar. For 700 bar refuelling there is a capacity of 50 kg with a maximum pressure of 1050 bar.

## Storage of Liquid Hydrogen

### Cryogenic storage

The storage of liquid hydrogen represents one of the most mature and consolidated storage technologies. It allows higher densities than the storage in pressure tanks. Liquid hydrogen containers are generally designed with a spherical or cylindrical shape, because they allow a smaller surface space for the same volume.

Hydrogen liquefies at ambient pressure at a temperature of -253 °C (20 K), therefore the pipes and containers for the transport and storage of liquefied hydrogen must have very strict thermal insulation requirements. The simplest liquefaction process is the Joule-Thompson expansion cycle. Through this process, the gas is compressed to ambient pressure and then cooled in a heat exchanger before passing through a valve where it undergoes the Joule-Thompson expansion process. Once liquid is removed, the gas returns to the compressor via the heat exchanger. Hydrogen can be liquefied for power generation for both the stationary applications and vehicle fuelling. The main drawbacks of this

[23] Carbotrainer. https://www.carbotainer.es/es/

[24] Carbotrainer, *Carbotainer participates in the GetHyGA initiative of the Government of Aragon.* https://www.carbotainer.es/es/detail-News-012.php

[25] Carbotriner, *Carbotainer bottles will store $H_2$ produced in the Anagas-led Shaky Project.* https://www.carbotainer.es/es/detail-News-011.php

[26] Carbotriner, *Carbotainer participates in the Shinefleet Project as a global solution to hydrogen mobility for heavy vehicle fleets*. https://www.carbotainer.es/es/detail-News-010.php

[27] Calvera Group. https://www.calvera.es/

[28] Calvera, *BIG HIT Project*. https://www.calvera.es/project/experimental-village/

[29] Calvera, *NG-POD Project*. https://www.calvera.es/project/ng-pod/

[30] Calvera, *700 bar HRS in Madrid*. https://www.calvera.es/project/hidrogenera-700-bar-madrid/

storage system are the possible leakage of the liquid hydrogen and the considerable energy expenditure of the entire process. Ultimately, the storage of liquid hydrogen is not easy to manage due to the large amount of energy required to cool and maintain it. at the desired temperatures. However, it represents an advantage in terms of commercial solution since it allows greater energy density than other commercial solutions.

### LOHC

The Liquid Organic Hydrogen Carriers (LOHC) are organic molecules capable of carrying out the hydrogenation and dehydrogenation reactions in relatively mild temperature conditions (below 100 ° C and below 50 bar). These systems have the great advantage of managing the system in the liquid state, but they require the use of specific catalysts and specific reactors to carry out the hydrogen charge and discharge reactions.

### NATIONAL IMPLEMENTATIONS

**HUNGARY**

There is no liquid hydrogen ($LH_2$) storage in Hungary, and there is no hydrogen liquefaction plant either. For completeness we mention, that one of the Hungarian glass manufacturing plants had used liquified hydrogen earlier, supplied by $LH_2$ trailer from abroad, but the use of $LH_2$ had been terminated approx. ~20 years ago.

LOHC storage is not present in Hungary now, but there is relatively great interest to this novel solution, for example in the refinery industry. There is an initial interest and examination of LOHC based storage and transport: for example, some Hungarian companies can be interested in the "Blue Danube @ Green Hydrogen" IPCEI[31] project, which would transport hydrogen in LOHC form on the Danube, but no concrete domestic project is outlined, and even less exist Final Investment Decision on domestic LOHC project. So, in medium term this situation can change, and probably there will be domestic LOHC storage, transport, and usage.

**SPAIN**

In the Aragon region, the Institute of Chemical Synthesis and Homogeneous Catalysis (ISQCH),[32] a joint research center of the University of Zaragoza and CSIC, participated in the HYPROSI project,[33] in which a patented procedure by the same researchers enabled the safe storage and transport of hydrogen for use in fuel cells using LOHC. The patented process was successfully tested on a prototype fuel cell car.[34]

## Hydrogen Carriers

The storage of hydrogen is possible using suitable materials (solid or liquid) capable of reversibly interacting with hydrogen under certain conditions of temperature and pressure. These materials are called hydrogen carriers. Hydrogen storage on solid matrices is a safer method than all the other techniques. Consequently, this method is considered suitable, not only for portable and automotive applications, but also for stationary uses. The materials are classified according to their ability to bind with hydrogen. The mechanisms are called physisorption and chemisorption.

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[31] IPCEI: Important Projects of Common European Interest, which can be established also for hydrogen technologies.
[32] ISQCH. http://isqch.unizar-csic.es/ISQCHportal/
[33] Polytechnic University of Valencia, HYPROSI. https://www.upv.es/noticias-upv/noticia-10497-hyprosi-es.html
[34] R&I WORLD, *Hydrogen car prototype*. https://ruvid.org/ri-world/hydrogen-car-prototype/

### Metal Hydrides (MH)

Metal hydrides absorb large amounts of hydrogen through chemical bonds. The technologies for the storage of hydrogen based on metal hydrides are characterized by compactness, intrinsic safety originating from modest equilibrium pressures, simplicity and flexibility. Hence, hydrogen storage in MH is a promising option capable of effectively solving $H_2$ storage problems. Nevertheless, the low storage density is considered the main obstacle to their use in vehicular applications. The slow charging and discharging of hydrogen storage tanks, due to poor heat transfer, is a further disadvantage of these systems and requires special design. In addition, their high cost, high sensitivity to passivation, high pyrophoricity and high weight still make them unsuitable to replace high pressure systems.

### Chemical Hydrides (CH)

Ionic and covalent hydrides are also called complex hydrides. These have high gravimetric capacities and good thermodynamic characteristics, but they often lose their good initial characteristics after a few tens of charge and discharge cycles. In addition, they are difficult to manage safely, and the hydrides can decompose into highly stable elements.

## NATIONAL IMPLEMENTATIONS

### HUNGARY

In Hungary, Metal Hydrides or Chemical Hydrides storage are not used. Really rare exception is a Metal Hydride Bottle which is used only for an educational hydrogen module. Besides we have information - from approx. ten years ago - on a hydrogen fuel-cell bicycle prototype and a hydrogen fuel-cell boat prototype, which used Metal Hydrid storage, but these stored only 0,5 – 1,0 $kg_{H2}$, and remained at prototype level. So, no MH and CH storage is widespread in reality.

# Chapter 3 Hydrogen Valleys

## Hydrogen Valley

A Hydrogen Valley is a circumscribed geographical area, city region or industrial zone that combines and integrates several hydrogen applications. In this area, a substantial part of the hydrogen value chain should be implemented, from $H_2$ production, storage, and distribution to its end-uses.

### NATIONAL IMPLEMENTATIONS

#### ITALY

In the Lazio region, there are two main projects focused on hydrogen value chain: Hydrogen Demo Valley (ENEA-Casaccia) and LIFE3H-Hydrogen Valley (Port of Civitavecchia).

The ENEA Hydrogen demo Valley[35] (HdV) is a three-year project (2021-2024) part of Mission Innovation Hydrogen. The HdV implementation aims to create an infrastructural hub for testing and demonstration of hydrogen technologies covering production, storage, distribution and utilization of hydrogen and blends of natural gas and hydrogen, for applications in the energy, industrial and transport sectors. The ENEA Casaccia Research Centre, located in the north of Rome, is suitable for the creation of a hydrogen integrated infrastructure that allows to demonstrate the feasibility, functionality, sustainability, and safety of a hydrogen-based ecosystem.

The infrastructure will be composed of:

- two gas pipelines, fully equipped with auxiliaries and serving various end uses: one pipeline for pure hydrogen and the other for blends of natural gas and hydrogen. This network will connect the sources of hydrogen production (driven by renewable energies) with the end use applications distributed throughout the centre to give rise to a true hydrogen ecosystem.
- Hydrogen generation systems: a 200 $kW_p$ photovoltaic plant will be installed coupled to a 200 $kW_e$ electrolyser for the generation of green hydrogen to be distributed (in pure form or blended) through the respective pipelines. Innovative systems for hydrogen production will be identified and implemented (solar reforming, high-temperature electrolysis, etc.) that can be hooked up to the pipelines.
- End use applications will consist of boilers, a microturbine and fuel cells for blend utilization, and of a hydrogen refuelling station (HRS) for the pure hydrogen, as a mobility hub for people and goods within and outside the centre, as well as heat and power and storage applications.

In the timeline of three years, the main result of the project will be the creation of a multipurpose platform for testing and validation of technologies related to the hydrogen supply chain on a significant scale.

LIFE3H, "Hydrogen demonstration in city, port and mountain area to develop integrated hydrogen valleys"[36], (2021-2025) is a European project focused on the demonstration and exploitation of three Hydrogen Valleys, starting from the implementation of clean $H_2$ buses fuelled with surplus $H_2$ coming from local industrial productions thus closing the economical circle locally. The project will

[35] ENEA Hydrogen Demo Valley:https://www.eai.enea.it/archivio/pianeta-idrogeno/enea-hydrogen-valley-towards-an-infrastructural-hub-in-italy.html

[36] LIFE3H project: https://webgate.ec.europa.eu/life/publicWebsite/project/details/5600

demonstrate new transport solutions to increase air quality, reduce emissions, facilitating mobility, economic growth & environmental sustainability while protecting human, building and natural areas.

The Port of Civitavecchia is a symbol of the transition to zero-emission maritime mobility; the infrastructure hosted the world's first LNG ship and the first zero-emission ferry in port. According to the LIFE3H timetable, by 2023 the Port of Civitavecchia will be the destination of two hydrogen-powered eight-meter buses.

## SPAIN

### GETHYGA-PAVINGAN ENERGY AND TECHNOLOGY WAY ON HYDROGEN ALONG ARAGON

The GetHyGA Initiative is an Action Plan of the Aragon Hydrogen Master Plan for the creation of an industrial ecosystem, or hydrogen valley, in Aragon. It has been promoted by the Department of Industry, Competitiveness and Business Development of the Government of Aragon through the Foundation for the Development of New Hydrogen Technologies in Aragon (FHA). The actions are based on the objectives of decarbonisation or electrification of those sectors that must reduce or eliminate the carbon footprint of their activities and processes, as well as on actions necessary for the development and creation of wealth in the region.

### METHODOLOGY APPLIED

✓GetHyGA has focused on public-private collaboration, foreseeing a cooperative development through multiple partnerships between the actors of change (companies, energy and hydrogen sector, educational and training entities, R&D&I, public administrations, etc.).

✓In particular, the project is expected to involve all parts of the value chains of the industrial Aragonese environment or those with industrial interests in the region.

✓The initiative includes the production, transport, storage, consumption and integration of hydrogen in industrial processes and in the different areas of energy production and consumption.

✓GetHyGA will contribute to the rebalancing of economic activity and employment to reverse the trend of population decline in certain areas of the region and involve other regions and other EU countries.

In July 2021, the presentation of the GetHyGa Initiative took place, in which 78 entities signed the letter of adhesion and 76 initiatives have been defined. This is the result of a year of work in which each of the projects proposed by each entity have been defined and evaluated.  All these projects are defined in the project report together with the main contacts of all the participating entities.

| Objetivo y ámbito dentro del objetivo | Detalle del ámbito | Nº Proyectos | Presupuesto |
|---|---|---|---|
| A. Energía y medioambiente | 1. Producción de hidrógeno | 12 | 1 438 517 000 € |
| | 2. Almacenamiento y transporte | 10 | 155 772 450 € |
| | 3. Aplicaciones | | |
| | a. Descarbonización del sector industrial | 5 | 90 800 000 € |
| | b. Descarbonización del sector de la movilidad | 8 | 160 467 799 € |
| | c. Descarbonización del sector transporte y Logística | 4 | 278 900 000 € |
| | d. Descarbonización del sector primario – Agricultura y ganadería | 3 | 28 900 000 € |
| | e. Descarbonización del sector turístico y cultural | 3 | 43 492 857 € |
| | f. Infraestructuras singulares demostrativas | 4 | 28 678 265 € |
| | Subtotal Aplicaciones | 27 | 631 238 921 € |
| | Subtotal A. Energía y Medioambiente | 49 | 2 205 528 371 € |
| B. Reindustrialización y reconversión industrial | | 9 | 39 163 877 € |
| C. Fomento de la I+D+i | | 9 | 15 266 609 € |
| D. Formación, capacitación y talento. Infraestructuras del conocimiento y Empleabilidad | | 4 | 23 302 750 € |
| E. Definición de políticas regionales | | 4 | 30 827 626 € |
| TOTAL 1 | | 75 | 2 334 089 233 € |

## SCOTLAND

### ABERDEEN HYDROGEN HUB

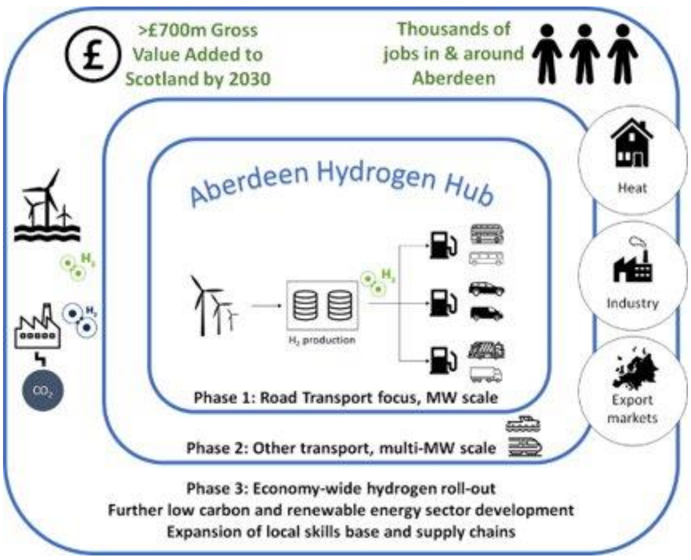
Aberdeen City Council started its hydrogen journey in 2013. By 2019 the Council realised that in order to encourage commercial entrants into the hydrogen market and reduce the cost of hydrogen, it must be produced at scale. In 2019, as part of Interreg North Sea Region HyTrEc2 Project, Element Energy was commissioned to consider whether there was a business case to allow a commercial supplier to enter the market. This project has become known as the Aberdeen Hydrogen Hub.

The Aberdeen Hydrogen Hub is split into three phases:

- Phase 1 – provision of a resilient, cost-effective supply of green hydrogen on a commercial basis to the market to support the existing and proposed transport projects.

- Phase 2 – Expansion in the short to medium term to connect to larger volume utilisation of hydrogen – trains, trucks and marine.

- Phase 3 – Whole system approach to supply and demand. Innovation, skills and transition hub to support expansion of the local supply chain. Pursue the ambition for Aberdeen to be the centre of a brand new Energy production business, exporting H2 to the world.




Between December 2020 and March 2021 Aberdeen City Council undertook a market engagement exercise to speak to commercial suppliers and their interest in Aberdeen for the production, supply and distribution of renewable diesel parity hydrogen. There was interest from different areas of the market and discussions with 14 companies took place. Key issues for Aberdeen City Council which emerged from the discussions include:

- Establishing the best site location for a hydrogen production facility;
- Provision of some level of anchor demand;
- Consideration of some sort of energy agreement or power purchasing agreement for green energy;
- Consideration of the Council being a joint investor.

The Aberdeen City region has attracted UK and Scottish Government funding for projects as part of the move towards energy transition. In addition to the Scottish Government funding (£4.5m) for the additional 10 buses to increase hydrogen demand, the Council have nominally been awarded £11.5m from the Scottish Government to develop Aberdeen as a "Hydrogen Hub."
In March 2021, Aberdeen City Council made an announcement that they were also going to commit £23.4m to match Scottish Government's £15m – as part of a £38.4m investment package in the Hydrogen Hub. In June 2021 a tender was published on Public Contracts Scotland to search for a Joint Venture Partner (or a consortium of partners) to work alongside the Council to develop Aberdeen as a Hydrogen Hub. At COP26 in November, Aberdeen City Council announced bp as the preferred bidder and they were formally appointed in February 2022 as the Council's Joint Venture Partner.

bp and Aberdeen City Council are currently at Front End Engineering and Design in preparation for building the Hydrogen Hub alongside a solar array to power the Hub. Future plans include connecting to offshore wind as the Hydrogen Hub grows and working .

The Joint Venture Partners are now working towards raising demand across the north east of Scotland in various ways:

- Infrastructure Feasibility
- Distribution Feasibility
- Heat Feasibility
- Fleet Study
- Rail Feasibility
- Maritime
- Trimodal refuelling
- Initial discussions with the airport
- Training Centre

The main focus has been on transport in the initial phase and as such Hydrogen Demand for Fleet vehicles has been one of the key priority areas that has been explored as part of the Smart Hy-Aware project.

Given the volume and range of hydrogen projects currently being developed in the north east of Scotland (Aberdeen Hydrogen Hub producing hydrogen from solar power and offshore wind, Acorn Hydrogen producing SMR Hydrogen and CCS, and two offshore hydrogen production projects with Vattenfall and ERM Dolphyn (Deepwater Offshore Local Production of HYdrogeN) being developed, Smart Hy-Aware have also set up, with Opportunity North East, the North East Scotland Hydrogen Ambition (NESH$_2$A) Group. This group is effectively establishing Aberdeen and north east Scotland as a Hydrogen Valley with all stakeholders working with the Council to ensure Aberdeen continues to be an innovative hydrogen world leader.

# Chapter 4 Partners' Action Plans

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| **PARTNER** | **DEVELOPMENT AGENCY OF ARAGON** |
| **POLICY INSTRUMENT** | **Hydrogen Master Plan of Aragon Region 2021-2025.**<br><br>One of the main objectives of this Plan is to identify the main strategic lines and establish the actions for their deployment in the period 2021-2025, analysing the potential of the region in this area, the emerging markets and identifying specific opportunities adapted to the socioeconomic reality of the region.<br><br>The following are the lines of work on which the Government of Aragon has decided to work and which have been reflected in the latest edition of the Master Plan:<br><br>• Hydrogen Production<br>• Hydrogen Storage, Transport and Distribution<br>• Hydrogen Applications: mobility sector and others<br>• Market Deployment and cross cutting issues: Training&Awareness<br>• Hydrogen valleys |
| **BEST PRACTICES SELECTED** | Aberdeen Hydrogen Buses: https://www.interregeurope.eu/policylearning/good-practices/item/5961/hydrogen-buses<br><br>Aberdeen Hydrogen Refuelling Stations: https://www.interregeurope.eu/policylearning/good-practices/item/5962/hydrogen-refuelling-stations/ |
| **AP GOALS** | The objective of the Action Plan will be to demonstrate the technical and economic feasibility of the implementation of a hydrogen fuel bus route with two vehicles to provide sustainable public transport and connect the center of the regional capital city of Huesca with its main technological and commercial hubs, as well as public education centers.<br><br>The two buses will refuel at an existing hydrogen refueling station in operation at the facilities of the Aragon Hydrogen Foundation, which will be adapted and upgraded.<br><br>The action aims to improve the Hydrogen Masterplan of Aragon through new projects in the line of "Promotion of hydrogen mobility". Specifically within the section "Demonstrative mobility projects in local captive fleets". Through the implementation of the "Hydrogen Bus City of Huesca" demonstration project, a contribution is being made to various objectives of the Plan, such as the deployment of hydrogen technologies in Aragon through specific opportunities adapted to the socio-economic reality of the region, in this case the city of Huesca. |
| **HYDROGEN PRODUCTION AND STORAGE** | Hydrogen could be produced in the same way as it is now supplying the current hydrogen refueling station, by isolated solar PV production. Now is storage in low and high pressure tanks. |

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| **PARTNER** | **ABERDEEN CITY COUNCIL** |
| **POLICY INSTRUMENT** | **ABERDEEN CITY REGION HYDROGEN STRATEGY AND ACTION PLAN 2015-2025**<br><br>Aberdeen is one of Europe's pioneering regions when it comes to the deployment of hydrogen technologies. The City Council aims to stimulate the City's economy through the development and commercialisation of fuel cell vehicles. The Hydrogen Strategy and Action Plan aims to maintain and build on the city's existing progress with hydrogen rollout in the region.<br><br>The Strategy identifies seven objectives to help achieve this aim:<br><br>▪ Vehicle Deployments -A range of local stakeholders deploy hydrogen vehicles<br><br>▪ Renewable Hydrogen - Hydrogen produced from renewable energy sources is widespread throughout the region<br><br>▪ Refuelling Infrastructure-An accessible, convenient and safe refuelling infrastructure network is deployed across the City and beyond<br><br>▪ Non Transport Applications - Non transport applications are tried and tested including stationary power<br><br>▪ Supply Chain / Market Development - A robust, local hydrogen supply chain is developed which utilises the areas existing energy expertise<br><br>▪ Communication and Education - A greater understanding and acceptance of hydrogen technologies encourages widespread adoption<br><br>▪ Policy and Regulation-Hydrogen technologies are embedded in all relevant areas of policy and supported at national level<br><br>The city has 2 operational refuelling stations: Kittybrewster built in 2015 and ACHES built in 2017. |
| **BEST PRACTICES SELECTED** | The Regional Development Agency of Aragon is delivering and expanding a network of hydrogen refuelling points through the Pyrenees region, known as the **'Hydrogen Corridor for the Pyrenees Region'**.<br><br>The H2PiyR (Hydrogen Corridor for the Pyrenees Region) project's objective is to connect the Pyrenees regions of Spain and France through hydrogen refuelling infrastructure with those in central and northern Europe to establish a strategic opportunity for economic growth and development in the region in the short to medium term. H2PiyR positions Aragon in the European hydrogen corridor network. |
| **AP GOALS** | The goal of the Action Plan is the creation of a strategic network of hydrogen refuelling points throughout North East Scotland. |

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| | As part of Smart Hy Aware Aberdeen City Council together with Opportunity North East and Scottish Enterprise commissioned Cenex to undertake a study on hydrogen demand in North East Scotland.<br><br>One of the recommendations from the study was to explore the expansion of regional hydrogen refuelling stations along the strategic road network to serve regional hydrogen demand.<br><br>Based on H2PiyR Project, Aberdeen City Council will create a strategic network of hydrogen refuelling points throughout North East Scotland.<br><br>In order to deliver this action, Aberdeen City Council will complete the following sub-actions:<br><br>• Assess at least 3 sites across North East Scotland for remote refuelling and technical capability<br>• Approach the market for adaptation and upgrade of existing hydrogen assets to enable tube trailer refuelling<br>• Purchase and/ or lease tube trailers<br>• Develop at least 1 remote hydrogen refuelling site across North East Scotland. |
| **HYDROGEN PRODUCTION AND STORAGE** | To facilitate this network hydrogen could be supplied by the Aberdeen Hydrogen Hub (after 2024), Aberdeen City Hydrogen Energy Storage (ACHES) and/ or The Exhibition Centre Aberdeen (TECA) Energy Centre from 2022 onwards.<br><br>Currently ACHES can produce up to 130kg of hydrogen a day and has the potential to be upgraded to improve storage, tube trailer access, safety modifications and training for the operator to allow for facilitated tube trailer refuelling as well as vehicle refuelling. These improvements would enable tube trailer refuelling to allow hydrogen fuel to be distributed to strategic refuelling points around North East Scotland.<br><br>Aberdeen City's exhibition and conference centre 'The Event Complex Aberdeen' (TECA) has an onsite Anaerobic Digestion (AD) Plant and Energy Centre and has capability to produce up to 400kg of hydrogen per day, although none is being produced at present. Commissioning of the electrolysers, additional storage and site access improvements would enable tube trailer refuelling to allow hydrogen fuel to be distributed to strategic refuelling points around North East Scotland. |

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| **PARTNER** | **PROVINCE OF ZUID-HOLLAND** |
| **POLICY INSTRUMENT** | **KANSEN VOOR WEST III 2021-2027**<br><br>The policy instrument KvW-III does at this moment not provide in the development of low and zero carbon emission transport and the instrument lacks an integrated vision on the combination of energy transition, transport and economic development. Hydrogen trucks can combine these three objectives and are contributing to the (regional) economy and growth development in Zuid-Holland. The application of hydrogen trucks is still in its early start-up phase and the connecting link to this subject was found in the Dutch NewWays Zuid-Holland program. NewWays aims at realising a modal shift from road transport to water-and rail transport including a green form of transportation. It's therefore connected to the RH2INE project that aims at the implementation of hydrogen inland shipping. For SHA the province will use the NewWays Zuid-Holland program to select a number of use cases where the last-mile transportation from inland ships to the final transport destination can be carried out by hydrogen trucks. And by doing so, making the complete logistic chain more sustainable. |
| **BEST PRACTICES SELECTED** | ▪ Policy Engagement with Hydrogen Technology in Aberdeen<br>▪ Hydrogen fuel cell refuse truck development-PBN<br>▪ GetHyGa: Pavingan Energy and Technology way on Hydrogen along Aragon-Development Agency of Aragon |
| **AP GOALS** | KvW-III allows for investments in the development and promotion of hydrogen-electric mobility in two ways.<br><br>Under Priority (1) Innovation, the policy instrument aims to stimulate the development of innovative mobility concepts.<br><br>Under Priority (2) Climate, the policy instrument aims to stimulate the implementation of alternative (more sustainable) fuel applications such as hydrogen, through showcases, fieldlabs or demonstration projects.<br><br>KvW-III works with calls for proposals, and although the policy instrument has now been finalised, specific calls will have to be devised in the upcoming years. Through Smart Hy-Aware the aim is to identify possible infrastructural, technological and/or market uptake barriers for the introduction of hydrogen trucks as a means of last-mile transportation in order to design a KvW-III call that aims to tackle one or more of these issues as a necessary step towards implementation.<br>The aim of the Action Plan is therefore to design a call for proposals in KvW-III to support (financing new projects) the development of hydrogen truck applications in the Zuid-Holland area. The achievement for this action plan is to have official approval of the terms of references of the call for proposals and therewith securing the launch of the call. Each year there will be 2 moments (spring and fall) for new calls for proposals to be launched. For the current reign of the provincial executive the launch of calls for proposals has to a large extent already been determined. It is therefore most realistic to launch a call for proposals regarding last-mile hydrogen trucks by autumn 2023. |

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| **PARTNER** | **MUNICIPALITY OF DELPHI** |
| **POLICY INSTRUMENT** | **Delphi Sustainable Urban Mobility Plan (Delphi SUMP).**<br><br>Delphi SUMP is a dedicated operational scheme to support the implementation of future zero-carbon transport and green energy transition initiatives in the jurisdictional borders of Delphi with special focus and respect in the world heritage site with Natura and CORINE areas by 2030. This strategic implementation action plan operates as a dedicated policy instrument supported financially by the 'Regional Operational Programme (ROP) ERDF 2014-2020 Continental Greece OP-T04 Low carbon economy as it provides a targeted framework on energy transition projects aiming to decarbonize Greece's energy production in the long-term (by 2050). Plus, the continuation of ROP 2014-2020 will be updated in ROP ERDF 2021-2027 Continental Greece and will be deployed during 2023.This assures that all implementation actions defined within the Delphi SUMP framework are totally covered by the Municipality of Delphi annual budget (own funds) and the 'Regional Operational Programme (ROP) ERDF Continental Greece. |
| **BEST PRACTICES SELECTED** | ▪ Policy Engagement with Hydrogen Technology in Aberdeen.<br>▪ North East Scotland Hydrogen Ambition (Aberdeen)<br>▪ Population Engagement with Hydrogen Technology in Aberdeen.<br>▪ Methodology to create a Regional Hydrogen Master Plan (Aragon)<br>▪ Italian Hydrogen and Fuel-Cell Association -H2IT (Lazio Region)<br>▪ Elaboration of Hungary's National Hydrogen Strategy 2030 and its approval by the State-PBN |
| **AP GOALS** | One of the major steps of the SUMP implementation process is the active participation and engagement of key public and private stakeholders in the green energy sector (specifically in the exploitation of biomass, RES and hydrogen applications in the transport sector). Taking this into account, the goal of the Action Plan is the creation of a coordinated hydrogen ecosystem **("Delphi green hydrogen association")** to capitalize the good practices, knowledge and expertise gained from SMART HY-AWARE Interreg Europe Project, from relevant previous studies applied in Phocis region and implement new hydrogen mobility schemes through relevant public-private partnerships (PPPs).<br><br>**Delphi Green Hydrogen Association** will be formed by public authorities, Special Management Authority of Regional Operational Plan of Continental Greece (regional policy maker entity), research institutes, universities and industry enterprises with knowledge in hydrogen applications.<br>The creation of this public/private network is a key action to ensure the launch of low-carbon energy production and mobility projects in the Phocis region. |

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| **PARTNER** | **PANNON BUSINESS NETWORK ASSOCIATION** |
| **POLICY INSTRUMENT** | **SZOMBATHELY 2030 STRATEGY**<br>Szombathely 2030 envisages several measures to be taken in the city of Szombathely in the following 10 years. The strategic document explicitly-in a dedicated session- enhances the promotion of green (low-carbon) mobility solutions. The overarching goal of the mobility related session is to make the city environmentally friendly with the promotion of green mobility solutions which might contribute to the decrease of own car usage. In order to reach this goal, the strategy recommends various solutions such as: attractive and competitive urban and suburban public transport, introduction of flexible transport in peripheral periods and peripheral districts, implementation of a coherent cycling system throughout the city, implementation of smart solutions in parking, implementation of vehicle sharing systems. Further measures are also proposed to popularise the Mobility as a Service concept.<br>Due to PBN's participation in the SMART-HY-AWARE project and our active role in the elaboration of the **Szombathely 2030 Strategy, the implementation of hydrogen in mobility appeared as one of the proposed actions** within the sub-session related to enhancement of green mobility. Our intention was to facilitate, and influence hydrogen related activities in the region. Since PBN was the main contributor of the document, these hydrogen measures were proposed, then discussed and then approved by the other contributors (stakeholders). **According to the city level policy document, one of the Hydrogen Refuelling Stations might be installed in the City of Szombathely by 2030.** Furthermore, the policy document is highlighting that **tourism might be the area in the county where a hydrogen-fuelled mobility project** might be implemented as a **pilot project** by the end of this decade. **In later steps- (following 2030)- the hydrogen-fuelled vehicles might also appear in everyday public transport** |
| **BEST PRACTICES SELECTED** | Lazio, South Holland and Aberdeen interregional stakeholder workshops were all very interesting and the lessons learnt were shared with regional experts and policy makers who might exploit the partners' good practices to improve the hydrogen-related measures appeared in the Szombathely 2030 Strategy.<br>Specific selected Good Practice: Hydrogen Trucks in Aberdeen City Council<br>Specific selected Good Practice: Hydrogen Refuelling Stations in Aberdeen |
| **AP GOALS** | **HYDROGEN FUEL CELL FORKLIFT DEMONSTRATION IN A REGIONAL COMPANY**<br>The AP goal is to implement a pilot project with Linde Gas Hungary Ltd. and other regional companies to test and demonstrate hydrogen fuel cell forklifts.<br>The goal of this action is to demonstrate how hydrogen, and in particular hydrogen fuel cell forklift might be utilizable and applicable in production. Due to the demonstration of hydrogen forklifts and their usage in production, experience and lessons learnt will be gained which might contribute to future activities in hydrogen application in industrial production and logistics. This action would have also a direct impact on the implementation of the SZOMBATHELY 2030 Strategy since it is going to be a new project financed in the framework of the Strategy. Moreover, due to the action, the increase of the hydrogen demand is also expected from industrial players. The foreseen increased demand on hydrogen shall be also influencing policy makers to apply hydrogen related projects, contributing to the overarching hydrogen objectives defined in the Strategy. |
| **HYDROGEN PRODUCTION AND STORAGE** | Linde Gas Hungary Ltd will provide their own hydrogen fuel cell forklift which will be tested in a regional company. They will also maintain the vehicles during the action |

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| **PARTNER** | **LAZIO REGION** |
| **POLICY INSTRUMENT** | Lazio Region attaches great importance to green hydrogen electric mobility but, also due to the very high green hydrogen costs, considers these technologies concretely applicable only in a long-term period which means not earlier than 10 years. Therefore it is not possible to improve through Project Best Practices concrete and short-period Policy Instruments like for example the ERDF Regional Operational Programme. The only possibility is trying to insert the Lesson Learnt from the Project in a very long-term Policy Instrument.<br>That's way Lazio Region selected Lazio Regional Energy Plan that contains strategic goals, guidelines and general suggestions to be concretely implemented within 2050 through more operative and short-term European Programs and regional laws.<br>The Regional Energy Plan (REP) is the tool with which the regional competences in energy planning are implemented, as regards the rational use of energy, energy saving and the use of renewable sources. It contains the study of the current regional energy system, trend scenarios, target scenarios for increasing energy efficiency and for developing renewable sources and the actions necessary to achieve them within the time limits established by national and European legislation. |
| **BEST PRACTICES SELECTED** | Smart-Hy-Aware Best Practices can not be concretely applied in Lazio Region through Regional Energy Plan but can be simply taken as a general reference and inspiration for the elaboration of the strategic goals, guidelines and suggestions contained in the Plan. All these BPs could be considered in the next years by other short-term European Programs and regional laws addressing hydrogen-electric mobility. That's why it is very relevant inserting in Regional Energy Plan the full list of Smart Hy Aware Best Practices. |
| **AP GOALS** | The last version of the Regional Energy Plan has been adopted with Regional Government Resolution N. 98 of 10 March 2020 and contains no reference to hydrogen sector and to hydrogen mobility.<br>It is structured in five Parts:<br>1. "Context of Reference"<br>2. "Strategic Objectives and Scenarios"<br>3. "Policies and Programming"<br>4. "Monitoring and Periodic Updating of REP"<br>5. "Technical Implementation Rules"<br>Chapter 3 "Policies and Programming" provides the framework of the intervention policies that will address the regional programming actions in the short, medium and long term period for the development of renewable energy sources (RES) and for the improvement of energy efficiency in each area of final use.<br>Lazio Region Action Plan aims at improving the Chapter 3 through insertion of priority guidelines, political goals and interventions addressing hydrogen sector and hydrogen mobility that are in some way influenced by the most interesting results and Best Practices of Smart Hy Aware Project. |

# Chapter 5 Concluding remarks and Outlook

## Proposed actions and targeting of specific barriers

Due to the implementation of a hydrogen value chain, several energy-intensive and hard to abate sectors can be decarbonised, notably if hydrogen production is supplied by renewable energy sources. Therefore, green hydrogen production via electrolysis powered by RES becomes a crucial component for the energy transition of national and international energy systems.

IRENA's 1.5°C scenario[37] states that hydrogen and its derivatives will account for up to 12% of final energy consumption by 2050.

Green hydrogen, coupled with renewable energy sources, can be integrated across energy sectors in different ways:

- Power-to-power: water electrolysis is adopted to produce hydrogen from renewable electricity; H2 is stored and then re-electrified using a Fuel Cells (FCs) or used to power Combined Cycle Gas Turbines.
- Power-to-gas: hydrogen produced by electricity is directly transported, distributed, and stored, allowing to use $H_2$ blended in natural gas grids and for the generation of synthetic methane.
- Power-to-fuel: green hydrogen is used in its pure form to power Fuel Cell Electric Vehicles (FCEVs) as fuel; $H_2$ can also be converted into ammonia ($NH_3$), to be used as fuel in the transport sector.
- Power-to-feedstock: hydrogen produced by electricity is used as feedstock and to synthetise chemical compounds and e-fuels.

Power-to-fuel use of hydrogen represents a crucial solution in the hard-to-decarbonise sectors in which direct electrification is difficult to be implemented, such as heavy industry (particularly steel manufacturing and chemical production), heavy-duty road transport, shipping and aviation. Through power-to-power use, hydrogen can also provide flexibility by managing the balance between electricity production and demand on seasonal basis, especially in case of significant rising shares of variable renewable energy generation.

Nowadays, the hydrogen value chain breakthrough faces some barriers that need to be removed. These include technological issues, lack of dedicated infrastructure, high costs and the need to plan common actions aiming at creating a secure market.

### Technological and Cost barriers

A limiting factor for the extensive deployment of hydrogen technologies is the cost, due to the process efficiency and life cycle and to the small-scale economy of hydrogen.

Electrolysers suffer from degradation of components; in this perspective, the technology development is needed to increase both process efficiency and system durability. According to IRENA scenarios[38], investment costs for electrolyser plants can be reduced by a significant percentage (40% in the short term and 80% in the long term) through strategies focusing on improved electrolyser design and

[37] World Energy Transitions Outlook 2022: 1.5°C Pathway: https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_World_Energy_Transitions_Outlook_2022.pdf

[38] Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

construction, scaling up, replacing scarce materials with abundant metals, increasing efficiency and flexibility of operations and high technology deployment.

As it is not viable to instantaneously balance the supply and the demand for hydrogen, storage technologies are expected to play a fundamental role. Presently, hydrogen storage and transport are realised mainly through compression. In the perspective of long-distance imports-exports, the liquefied form seems to be the easier solution, but the cost of liquefied storage represents the major constraint. Adequate research and economies of scale are required to develop innovative and/or niche technologies (LOHCs and Solid storage), to foster a cost reduction.

## Lack of dedicated infrastructure

Hydrogen has historically been produced close to the site of end-use, with limited dedicated transport infrastructure. The lack of hydrogen transmission pipelines, storage units and refuelling stations around the world represents a restricting factor.

In this perspective, gas system operators are required to have a leading role in gaseous hydrogen storage with various solutions (salt caverns, depleted gas fields, pipelines).

Furthermore, it would be worthwhile to incentivise the re-use of existing infrastructure, lowering costs of gaseous hydrogen storage.

Synthetic fuels made from green hydrogen, instead, may be stored and transported using existing infrastructure; consequently, the latter might be increased.

## Boost hydrogen demand and scale up $H_2$ plants

Many pilot projects around the world focused on green hydrogen production, storage and transport should be the starting point for scaling up $H_2$ plants. Lessons learned might provide the best practices for the implementation, operation and maintenance of hydrogen production, storage and transport technologies.

Furthermore, the standardisation of strategies and protocols can enhance the use of hydrogen in various sectors, facilitating the boost of hydrogen demand by end-user sectors.

## International Cooperation

The increasing demand for green hydrogen is expected to be a common issue in a growing number of countries striving to decarbonise their own energy systems.

Encouraging the definition of global standards and protocols can facilitate the implementation of a world hydrogen value chain.

Additionally, partnerships across countries might rise the share of green hydrogen imports and exports from one region to another. Collaborations for long distances transport and storage are, for example, those between Australia and Japan and Europe and Northern Africa.

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