Best practices in hydrogen electromobility with potential appliance in Phocis region

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Abbreviations

AEM	anion exchange membrane
ALK	Alkaline
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditure
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
FCEB	Fuel cell bus
FCEV	Fuel cell electric vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Greenhouse Gas
HRS	Hydrogen refueling stations
H_2	hydrogen
ICE	Internal Combustion Engine
IIT	Institut für Innovative Technologien Bozen
JIVE	Joint Initiative for hydrogen Vehicle across Europe
LH_2	Liquefied hydrogen
LNG	Liquefied Natural Gas
NH_3	Ammonia
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
SASA	SOCIETA' AUTOBUS SERVIZI D'AREA SPA
SMR	steam methane reforming
SOC	Standard Operating Conditions
SOE	solid oxide electrolysis
TCO	Total Cost of Ownership
ZEV	Zero Emission Vehicle
ZE	Zero Emission

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Executive Summary

The project aims to promote hydrogen electromobility by addressing its main obstacles, such as infrastructure, technology issues and the further penetration of hydrogen in the market. The aim of the project also concerns the market transition of Europe to the minimization of carbon footprint. The main objectives of the project are:

- Exploitation of various hydrogen technologies for electromobility, including its supply chain
- Improving regional and local strategies by creating measures to penetrate the use of hydrogen in the market
- Improving transport efficiency with the use of environmentally friendly vehicles
- Improvement of energy transmission networks and the integration of renewable energy sources in the production of hydrogen by electrolysis
- Enhancing the development and accessibility of hydrogen supply infrastructure in urban and rural areas through private and public sectors
- Formation of financial models for the implementation of environmentally friendly vehicles in public transport
- Strengthen the capacity of public authorities to create policies for public transport with a low carbon footprint.

The current work firstly introduces existing hydrogen applications in global and EU level with focus on commencing usage in the transportation sector. Following that, a detailed review on current state-of-the-art hydrogen refueling station (HRS) modules are presented. These modules consist the hydrogen production, storage, transportation/distribution and the dispensing units used to refuel hydrogen vehicles. In the same context, a thorough presentation of all commercially available hydrogen fuel cell vehicle (FCEV) types is included in this deliverable. Each vehicle is presented individually together with their technical specifications and usage capabilities. In this report, the vehicle types presented are: passenger cars, fuel cell buses/coaches, light-duty vehicles, heavy-duty vehicles, trucks and public duty service vehicles.

In the third section of this deliverable, a presentation of several best practices in the European region (EU-funded initiatives) which are demonstrated in small-medium scale cities and regions is held. The selected scenarios have demonstrated and implemented different state-of-the-art hydrogen applications in production, refueling and mobility sectors which could be potentially tested in the Phocis region and the Municipality of Delphi. In total, four (4) scenarios will be presented in this report. Scenarios are presented from a city-centered point of view although several cities have participated in several hydrogen-related projects. This holistic approach provides a clearer presentation of the hydrogen initiatives performed in a specific area and would help in the comparison of these regions/cities with the Phocis region (Delphi city) which will assist the formulation of their Regional Action Plan at a later stage.

Introduction to hydrogen

Hydrogen basics

Hydrogen is the lightest element in the periodic table – fourteen times lighter than air; 1 Nm^3 (normal cubic meter) of hydrogen gas weighs 90 grams; and is colorless, odorless, and non-toxic. Hydrogen does not exist naturally on Earth. Since it forms covalent compounds with most nonmetallic elements, most of the hydrogen on Earth exists in molecular forms such as water or organic compounds. Combined with oxygen, it is water (H_2O). Combined with carbon, it forms methane (CH_4), coal, and petroleum. It is found in all growing things (biomass).

Hydrogen has the highest energy content of any common fuel by weight, but the lowest energy content by volume. It is a high efficiency, low polluting fuel that can be used for transportation, heating, and power generation in places where it is difficult to use electricity. Once hydrogen is produced as molecular hydrogen, the energy present within the molecule can be released, by reacting with oxygen to produce water. This can be achieved by either traditional internal combustion engines, or by devices called fuel cells.

The most important primary energy source for hydrogen production currently is natural gas, at 70%, followed by oil, coal, and electricity (as a secondary energy resource). Steam reforming (from natural gas) is the most used method for hydrogen production. To date, only small amounts of hydrogen have been generated from renewable energies, although that amount is set to increase in future.

Electrolysis currently accounts for around 5 % of global hydrogen production If hydrogen is extracted from water using a machine called an electrolyser, which uses an electric current to split H_2O into its constituent parts and renewable or carbon free electricity is used, the gas has a zero-carbon footprint, and is known as green hydrogen.

Also, hydrogen-based chemistry could serve as a carbon sink and complement or decarbonize parts of the petrochemical value chain. Today, crude oil (derivatives) is used as feedstock in the production of industrial chemicals, fuels, plastics, and pharmaceutical goods. Almost all these products contain both carbon and hydrogen (hence their name hydrocarbons). If the application of carbon capture and utilization (CCU) technology takes off (as part of a circular economy or an alternative to carbon storage), the technology will need (green) hydrogen to convert the captured carbon into usable chemicals like methanol, methane, formic acid, or urea. This use of hydrogen would make CCU a viable alternative for other hard-to-decarbonize sectors like cement and steel production and would contribute to the decarbonization of part of the petrochemical value chain.

Since hydrogen's production translates into extracting it from its compound by using energy from other primary sources, it is an energy carrier, which is used to move, store, and deliver energy produced from these sources [5].

All these reasons provide a strong environmentally-friendly reason to use hydrogen products as fuel in the transportation sector and this will be shown in the chapters below. Nevertheless, hydrogen can be unharmful towards the environment if it is produced, stored, transported and used in a way that has zero carbon footprints. The various applications of hydrogen are shown in the following chapters.

Hydrogen applications

Hydrogen is versatile and can be utilized in various ways. These multiple uses can be grouped into two large categories:

1. Hydrogen as a feedstock. A role whose importance is being recognized for decades and will continue to grow and evolve.
2. Hydrogen as an energy vector enabling the energy transition. The usage of hydrogen in this context has started already and is gradually increasing. In the coming this field will grow dramatically. The versatility of hydrogen and its multiple utilization is why hydrogen can contribute to decarbonize existing economies.

Hydrogen's role in the decarbonization process can be summarized as shown in the graph below:

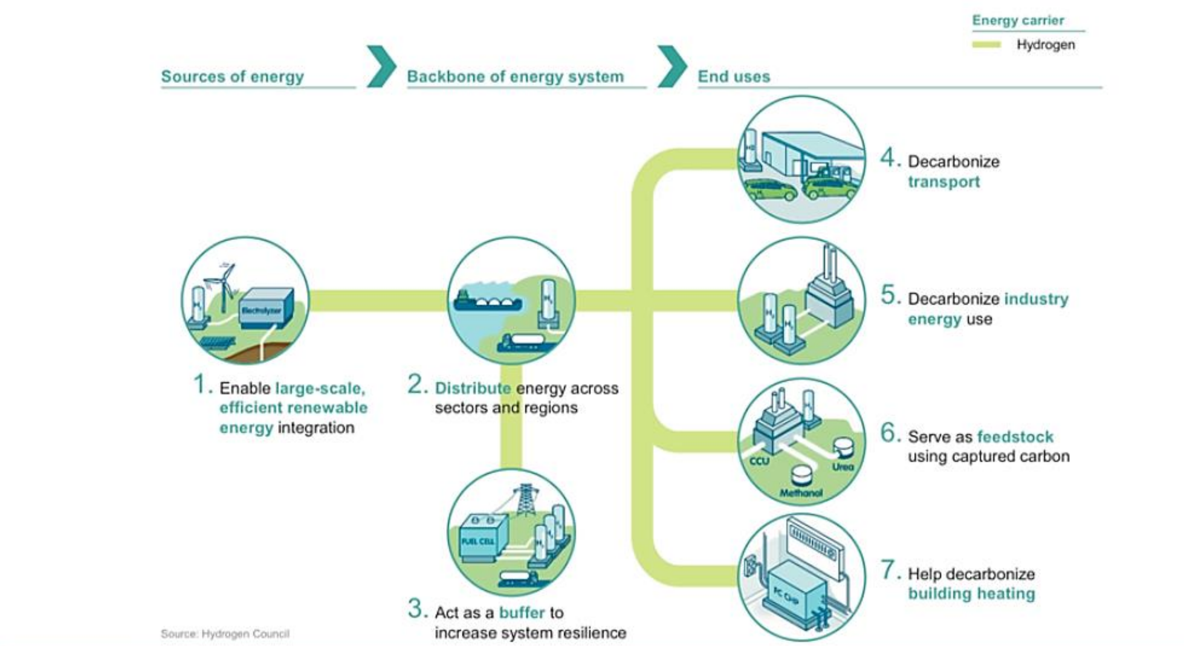


*Figure 1. **Hydrogen's several roles in decarbonization of major economic sectors** [5]*

Long established uses – Hydrogen as a feedstock

Nowadays, hydrogen is used in several industrial processes. Among other applications, it is important to point out its use as raw material in the chemical industry, and also as a redactor agent in the metallurgic industry. Hydrogen is a fundamental building block for the manufacture of ammonia, and hence fertilizers, and of methanol, used in the manufacture of many polymers. Refineries, where hydrogen is used for the processing of intermediate oil products, are another area of use. Thus, about 55 % of the hydrogen produced around the world is used for ammonia synthesis, 25 % in refineries and about 10 % for methanol production. The other applications worldwide account for only about 10 % of global hydrogen production.

Ammonia - Fertilizers

The most important hydrogen-nitrogen compound is ammonia (NH_3), also known as azane.

Technically, ammonia is obtained on a large scale by the Haber-Bosch process. This process combines hydrogen and nitrogen together directly by synthesis. To this end, the starting materials nitrogen and hydrogen must first be obtained. In the case of nitrogen this is achieved by low-temperature separation of air, while hydrogen originates today from natural gas steam reforming.

Almost 90 % of ammonia goes into fertilizer production. For this purpose, a large part of the ammonia is converted into solid fertilizer salts or, after catalytic oxidation, into nitric acid (HNO_3) and its salts (nitrates). Owing to its high energy of evaporation, ammonia is also used in refrigeration plants as an environmentally friendly and inexpensively produced refrigerant; its technical name is R-717.

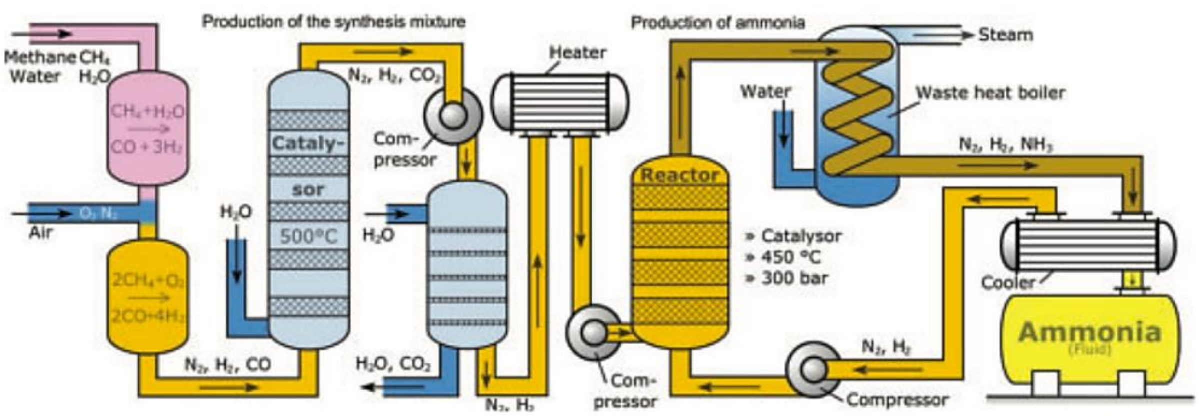


*Figure 2. **Ammonia production scheme** [5]*

Industrial Fields

Hydrogen is used in various in industrial applications; these include metalworking (primarily in metal alloying), flat glass production (hydrogen used as an inerting or protective gas), the electronics industry (used as a protective and carrier gas, in deposition processes, for cleaning, in etching, in reduction processes, etc.), and applications in electricity generation, for example for generator cooling or for corrosion prevention in power plant pipelines.

The direct reduction of iron ore – i.e. the separation of oxygen from the iron ore using hydrogen and synthesis gas – could develop into an important industrial process in steel manufacturing, because in the traditional blast furnace method large amounts of carbon are released. While direct reduction with natural gas is now well-established in steel production, corresponding production methods based on hydrogen so far exist only on a pilot scale.

Fuel Production

Hydrogen is used to process crude oil into refined fuels, such as gasoline and diesel, and also for removing contaminants, such as sulphur, from these fuels. Hydrogen is also an important basic substance for producing methanol. The production of methanol (methanol synthesis) takes place by means of the catalytic hydrogenation of carbon monoxide.

Methanol can be used directly as a fuel in internal combustion engines. It is also used in direct methanol fuel cells or, after reforming, in PEM fuel cells. Fuel additives are produced from methanol, and it is used to transesterify vegetable oils to form methyl esters (biodiesel).

Additionally, Electrofuels (e-fuels) are produced by the reaction of hydrogen with CO_2 into liquid products with gasoline, diesel, jet fuel or naphtha-like characteristics. Hydrogen-based e-fuels are considered attractive for multiple reasons:

- Easier storage than for hydrogen
- Easier integration with existing logistic infrastructure (e.g., use in gas pipelines, tankers, refuelling infrastructure)
- Ability to enter new markets (e.g., aviation, shipping, freight, building heating, petrochemical feedstocks)

Hydrogen can unleash the opportunity of new exports of energy-intensive commodities. The main feedstock produced from hydrogen today is ammonia. Ammonia is a global commodity with production volumes of around 175 Mt/year. However, the hydrogen used for ammonia production today is produced from natural gas or coal [7].

Because ammonia has an energy content of 18.6 GJ per ton, roughly half that of oil products and comparable to biomass, it can also be used as an energy carrier. It is also the only e-fuel that does not contain carbon, making it carbon-free like pure hydrogen, unlike most of the other e-fuels. On the downside, ammonia is highly toxic for humans as well as for aquatic life if leakages occur in water sources. It is also a potential source of nitrogen oxide emissions, if combustion is not perfectly optimized.

Another increasingly important chemical product is methanol. Methanol is currently produced from a mixture of hydrogen and carbon monoxide, which themselves are produced from natural gas or coal. However, methanol can also be produced from hydrogen and from CO / CO_2 gas [8].

Methanol also has the potential to be used as a drop-in fuel. For instance, it is used in China as a gasoline additive as well as in the maritime industry. It is relatively simple to extract hydrogen back from methanol, for instance through on-board reformers in transport, to allow the use of hydrogen in fuel cells rather than methanol in ICEs, greatly increasing the end-use efficiency. Methanol from renewables also has a limited cost-gap with its fossil-based counterpart and is experiencing a growth in demand. On the downside, it is toxic and water soluble and has been banned in several countries including the US.

Hydrogen gas can also be processed with CO_2 to yield synthetic methane or liquids. Synthetic liquid production from syngas (hydrogen / CO / CO_2 mixture) is a proven technology and is applied on a commercial scale in South Africa, where coal is used as feedstock.

Synthetic natural gas can benefit from natural gas infrastructure as well as from a strong and growing LNG industry. It can be used directly in existing infrastructure as well as in appliances, including for power generation and heating. Today the cost gap between synthetic methane and natural gas is the largest among the e-fuels (see Table 1). However, there is potential for improvement if the cost of the CO_2 DAC drops significantly [7].

*Table 1. **Power to X production cost** [7]*

	Formula	Hydrogen feedstock [t H2/t]	CO_2 feedstock [t CO2/t]	Feedstock cost [USD/t]	Total production cost [USD/t]	Fossil-based product price [USD/t]
Ammonia	NH_3	0.14	0	429	500-600	200-350
Methanol	CH_4O	0.13	1.38	513	675	300-350
Synthetic methane	CH_4	0.25	2.75	1025	1380	100-500
Synthetic oil products	$C\,H_2$	0.14	3.14	743	1000	500-800

Commencing uses - energy based uses

In the energy field, most hydrogen is used through Fuel Cells (FCs). A fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as byproducts. In its simplest form, a single fuel cell consists of two electrodes - an anode and a cathode - with an electrolyte between them. At the anode, hydrogen reacts with a catalyst, creating a positively charged ion and a negatively charged electron. The proton then passes through the electrolyte, while the electron travels through a circuit, creating a current. At the cathode, oxygen reacts with the ion and electron, forming water and useful heat.

Hydrogen in transport

Hydrogen fuel is considered a good candidate to contribute to the decarbonisation of the road transport sector if it is produced from renewable energy sources through the process of electrolysis. In this case, the main advantages of fuel cell electric vehicles (FCEV) are [10]:

- Efficiency: higher efficiency of fuel cells compared with internal combustion engines.

- Ecology: low emissions, low noise;
- Energy: it is not a fossil fuel;
- Innovation high-tech development;
- Economy: new industry;
- Autonomy: less dependent on oil cartel countries

Passenger cars and urban buses, among other vehicles, as material handling equipment, etc., are good examples of the new technology ready for mass commercialization in the coming years. The application options for hydrogen as a fuel for mobility can be differentiated firstly by the chemical form or bonding of hydrogen and secondly by the energy converter by means of which the energy stored in the hydrogen is made available.

- In direct use, (pure) molecular hydrogen (H_2) is used by the transportation means directly, i.e., without further conversion, as an energy source. In this case hydrogen can be used both in internal combustion engines and in fuel cells (fuel cell systems).
- In indirect use, hydrogen is used to produce final energy sources or is converted by means of additional conversion steps into gaseous or liquid hydrogen-containing fuels. Such PtG (Power-to-Gas) and PtL (Power-to-Liquids) fuels can then in turn be used in heat engines. Use in fuel cells would also be possible (in some cases), using a reformer, but it is not economically viable.

Currently, hydrogen is used in different transport sectors [7]:

- **Aviation**: In civil aviation, hydrogen-powered fuel cells are regarded as potential energy providers for aircraft as they have been in space travel for some time now. Thus, fuel cell modules can supply electricity to the aircraft electrical system as emergency generator sets or as an auxiliary power unit. More advanced concepts include starting of the main engine and the nose wheel drive for airfield movements by commercial aircraft.
- **Maritime**: The use of hydrogen-powered fuel cells for ship propulsion, by contrast, is still at an early design or trial phase – with applications in smaller passenger ships, ferries or recreational craft. The low- and high-temperature fuel cell (PEMFC) and the solid oxide fuel cell (SOFC) are seen as the most promising fuel cell types for nautical applications. As yet, however, no fuel cells have been scaled for and used on large merchant vessels.
- **Trains**: Rail vehicles that use hydrogen as an energy store and energy source can offer an additional alternative. Fuel cell-powered rail vehicles combine the advantage of pollutant-free operation with the advantage of low infrastructure costs, comparable with those for diesel operation. This option is ideal for train lines with a low transport volume that the high up-front investment that is needed for electrification of the lines cannot always be justified

- **Material Handling Vehicles**: Fuel cell industrial trucks, like forklifts or towing trucks (airports) are especially suitable for indoor operation, because they produce no local pollutant emissions and only low noise emissions. Fuel cell vehicles have advantages over battery-operated industrial trucks in terms of refueling. Instead of having to replace the battery, the trucks can be refueled within two to three minutes. They take up less space and are cheaper to maintain and repair. Fuel cell industrial trucks allow for uninterrupted use and are therefore particularly suitable for multi-shift fleet operation in material handling. In the case of larger industrial truck fleets in multi-shift operation, (moderate) cost reductions can be achieved in comparison to battery technology, and productivity in material handling can also be increased.

- **Buses**: In terms of road transport, buses in the public transport network are the most thoroughly tested area of application for hydrogen and fuel cells. Although hydrogen was initially still used in buses with internal combustion engines, bus developers are now concentrating almost entirely on fuel cell electric buses (FCEB). The use of small FCEB fleets is being promoted in urban areas as a way of contributing to technological development and to clean air policy. Fuel cell buses now have a range of 300 to 450 km and so offer almost the same flexibility as diesel buses in day-to-day operation. While some older municipal buses still consume well over 20 kg of hydrogen (rather than 40 liters of diesel) per 100 km, newer fuel cell buses now use only 8 to 9 kg per 100 km, giving FCEBs an energy efficiency advantage of around 40 % as compared with diesel buses. The FCEB fleet in Europe is expected to expand from 90 to between 300 and 400 vehicles by 2020.

- **Passenger cars**: Along with battery electric vehicles, hydrogen-powered fuel cell passenger cars are the only zero emission alternative drive option for motorized private transport. Although hydrogen is a clean fuel with excellent physicochemical properties, it has been unable to gain acceptance as a fuel for motorized road transport. For passenger cars the focus is now almost entirely on hydrogen-powered fuel cells as a source of drive energy. The prices for medium-sized vehicles fitted with fuel cells are still well above those for passenger cars with internal combustion engines – at around 60,000 EUR/USD. With the launch of FCEV series production, vehicle cost and prices are expected to fall substantially. The fuel cell stacks in the latest fuel cell models have an output of 100 kW or more. As compared with battery electric cars they have a greater range – of around 400 to 500 kilometers today – with a lower vehicle weight and much shorter refueling times of three to five minutes. They usually carry 4 to 7 kg of hydrogen on board, stored in pressure tanks at 700 bar.

During this report, a focus is given on the exploitation of hydrogen for road passenger and commercial vehicles. Hydrogen technologies and applications in each vehicle type will be shown separately in the following chapters.

Current hydrogen techno-economic status in EU

The EU has set ambitious Greenhouse Gas (GHG) emission reduction targets, aiming at carbon neutrality by 2050, with an ambitious milestone of -55% by 2030 compared to 1990 levels. With the road transportation sector responsible for 21.8% of EU CO2eq emissions, part of the European Union's answer to the emission reduction challenge is an irreversible shift to decarbonated mobility, with the clear objective to stay competitive while responding to the increasing mobility needs. Buses are the cornerstone of every country's public transportation system, enabling non-motorized individuals to gain affordable access to medium and long-distance mobility while emitting ~40% less GHG than if using a personal vehicle. However, with 100-130 gCO2/(pax.km), the traditional diesel-powered bus solution that proved effective thus far is showing limitations in a low-emissions world. While there is no well-to-wheels zero emission solution, public transportation players are testing alternative powertrain technologies through specific pilot projects, in order to understand their techno-economic implications and devise the optimal way forward [17].

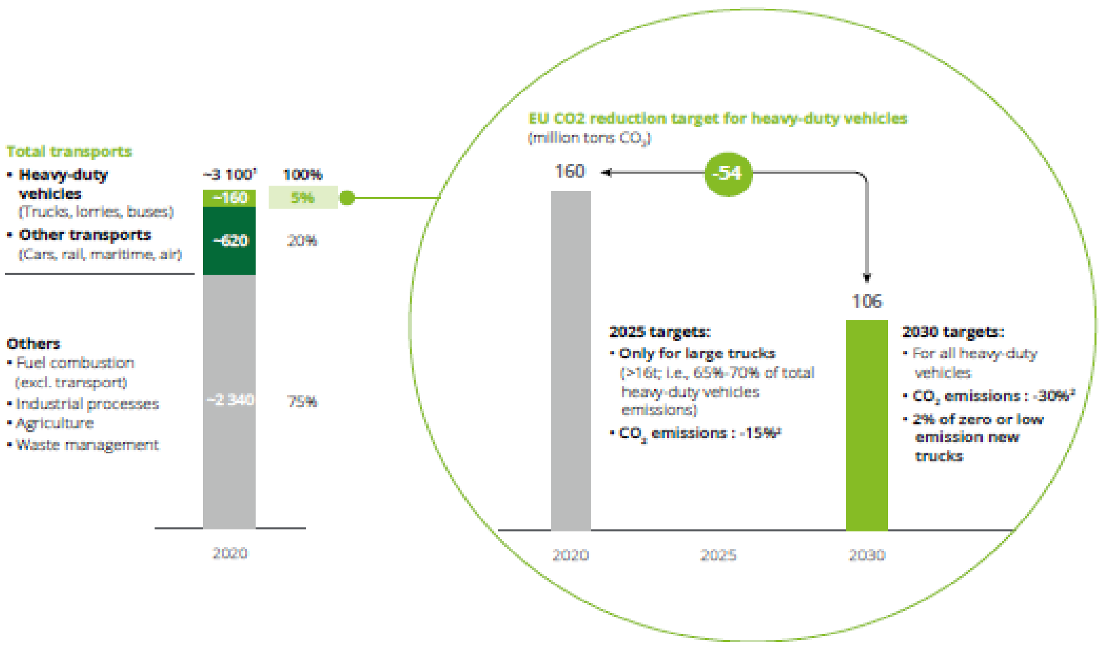


*Figure 3. **EU CO2 emission reduction targets for transport sector** [17]*

Until 2020, approximately 2300 FCEVs are operating in the EU (Figure 4). The graph contains all types of available vehicle categories; light duty vehicles (LDV), passenger cars, two or three-wheeled vehicles (i.e. bikes, motorcycles), buses & coaches and heavy-duty vehicles (HDV) or trucks. As it can be seen, the first hydrogen mobility applications were focused on LDVs and buses/coaches and since 2015 hydrogen passenger cars share has been significantly increasing along with the share of FCEB or coaches. The majority of these vehicles are located in the US or Asia (Japan, South Korea) flowed by EU countries [14].

Though, our focus on this report is mainly on the EU countries. In detail, we can see in Figure 5 that the highest hydrogen market share is located in Germany, Netherlands, UK, France, Norway, Denmark and Switzerland. Most importantly, FCEB have been exploited primarily in Germany, UK and Switzerland. Germany has also the highest share in hydrogen passenger cars together with Netherlands and France. These countries have more than 150 hydrogen vehicles registered cumulatively in each country. Only France, has significant focus on implementing hydrogen mobility in LDVs and light duty public service vehicles (almost 40% of country's hydrogen vehicles). Last but not least, it can be seen in Figure 5 that only 17 EU countries have purchased at least one hydrogen vehicle which shows the immaturity of EU hydrogen market and there is still a long way to go. Nevertheless, EU Commission due to its environmental targets set by 2050 will continue to support and invest in hydrogen and green mobility.

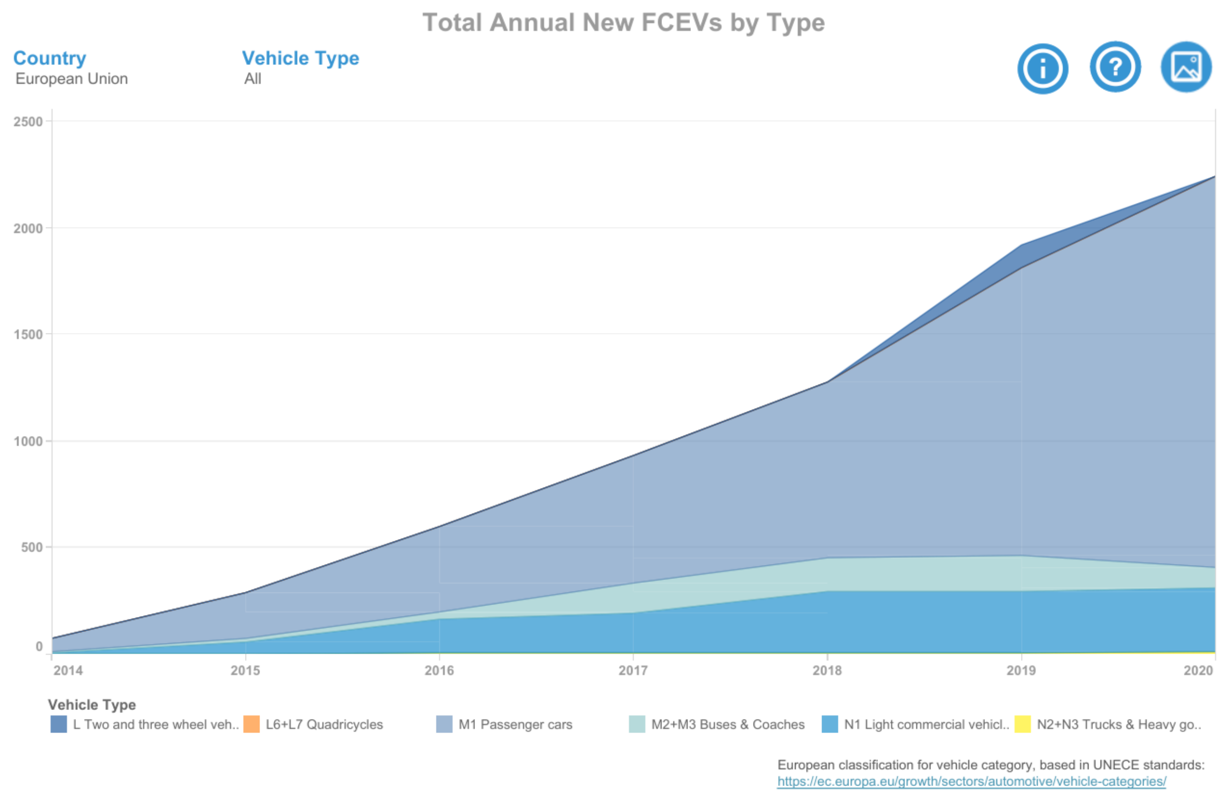


*Figure 4. **Total Annual new FCEVs by Type in EU** [14]*

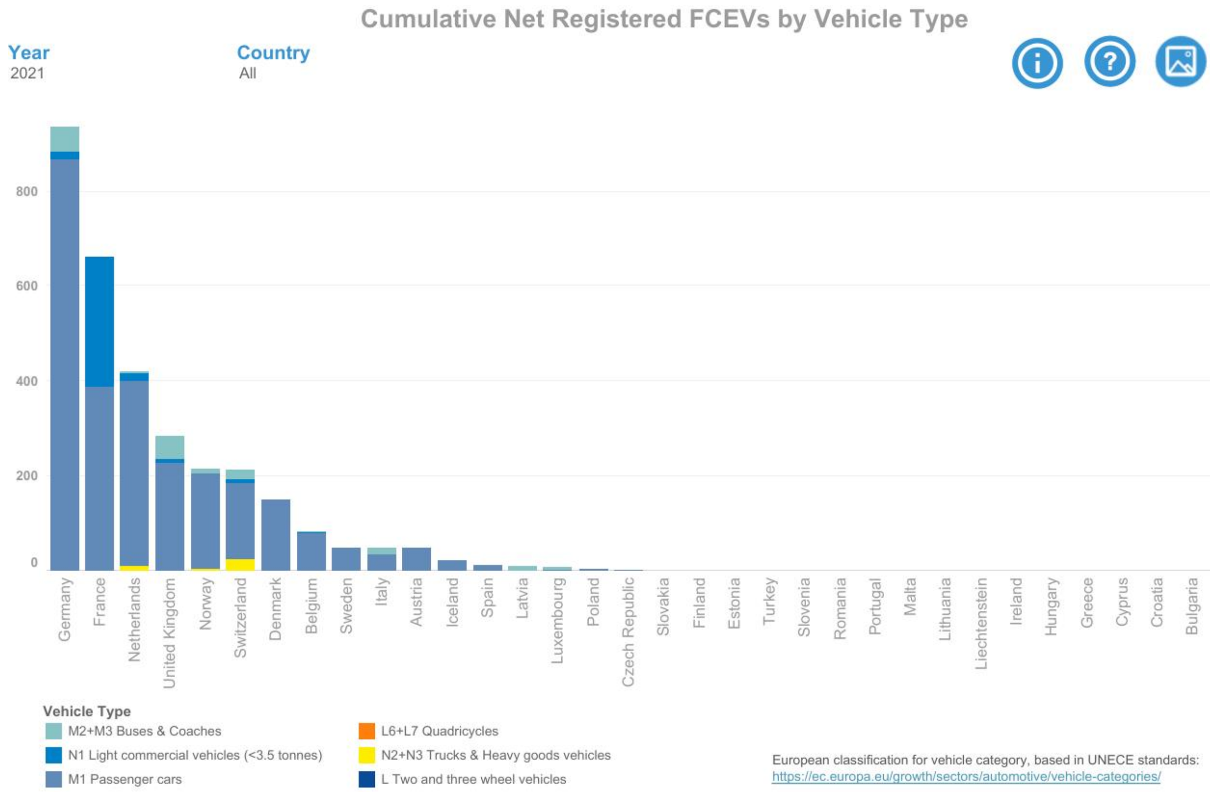
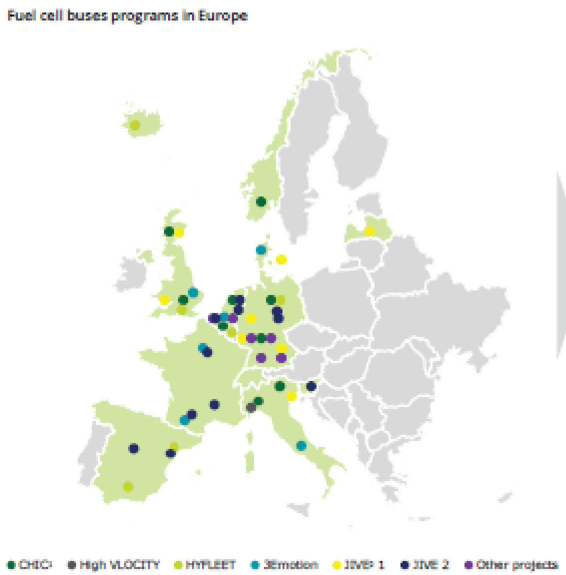


*Figure 5. **Cumulative Net Registered FCEVs by vehicle type in EU** [14]*

The EU Commission together with Fuel Cells and Hydrogen Joint Undertaking (FCHJU), Hydrogen Europe and other relevant funding schemes have launched 88 projects since 2007. Some indicative projects concerning FCEB are displayed in Figure 6.



Project	Cities	# buses	Timeline
CHIC	Bolzano, London, Milan, Oslo, Cologne, Hamburg	~29	2010-2016
High VLOCITY	Antwerp, Aberdeen, Groningen, San Remo,	~14	2012-2019
HyFLEET: CUTE	10 cities (e.g., London, Madrid, Barcelona, Reykjavik, Berlin)	~47	2006-2009
3Emotion	Aalborg, London, Pau, Rome, South Rotterdam, South Holland, Versailles	~26	2015-2022
Other projects	Karlsruhe, Stuttgart, Frankfurt, Arnhem, North Brabant	~13	2013-2017
JIVE 1	Aberdeen, Birmingham, Bozen, Cologne, London, Rhein, Riga, Sagelse, Wuppertal	~300	2017-2022
Jive 2	Auxerre, Brighton, Dundee, Emmen, Pau, Toulouse, Velenj		2018-2023

*Figure 6. **Map of FCEV programs in EU** [17]*

During these projects in order to better monitor and coordinate current and future hydrogen initiatives funded by EU and private-public partnerships (PPPs), hydrogen regional clusters have been created as depicted in Figure 7 below. These clusters will help EU countries who haven't yet adopted hydrogen mobility solutions to engage pioneering companies and cities from their respective regional clusters [1].

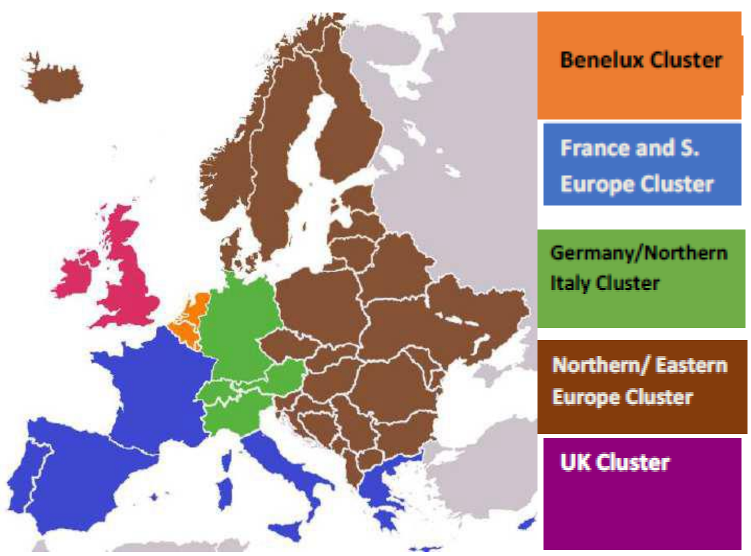


*Figure 7. **EU Hydrogen initiatives cluster division for procurements/tenders and funding procedures** [1]*

State-of-the-art hydrogen refueling station modules

Hydrogen Refueling Stations (HRS)

A hydrogen refueling station (HRS) is a storage or filling station for hydrogen. The hydrogen is dispensed by weight. There are two filling pressures in common use. H70 or 700 bar, and the older standard H35 or 350 bar. These stations are usually considered small scale with a production capacity 15-50 kg/hour (0.5-2 MW H_2 capacity).

A large variety of HRS concepts exists. The following paragraphs explain the most important ones. Figure 8 shows a scheme of typical HRS concepts in which **four different modules** can be differentiated. These are the **H_2 production** or **delivery unit** (for external supply), the **compression unit**, the **hydrogen storage and the dispensing unit**. Since compression and storage are strongly related to each other, they are illustrated together within Figure 8 and will be addressed together within this section.

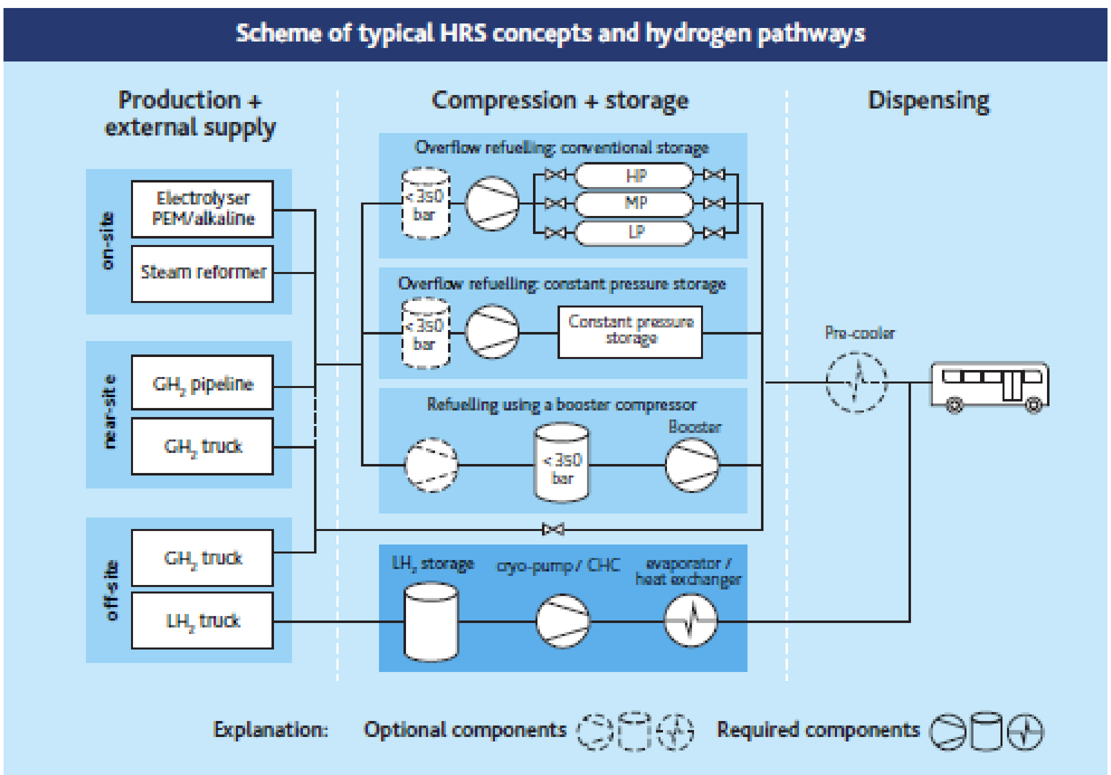


*Figure 8. **Scheme of typical HRS concepts and hydrogen pathways [12]***

An essential differentiation of HRS concepts is the origin of the hydrogen. If the required hydrogen is produced directly at the HRS, this is called **on-site production.** In contrast, some HRS only refuel the hydrogen to the vehicles and use hydrogen that is delivered from a different facility. This could be a specialized facility for large-scale hydrogen production, or one that produces hydrogen as a by-product.

Both cases are examples of the **off-site production of hydrogen**. If the production of hydrogen does not take place at the HRS but close to it, this is called **near-site production** and a truck trailer delivery or pipeline is usually used for the transport of the hydrogen to the HRS. On-site hydrogen production generally uses one of the two following technologies: **electrolysis or steam reforming (SMR)**.

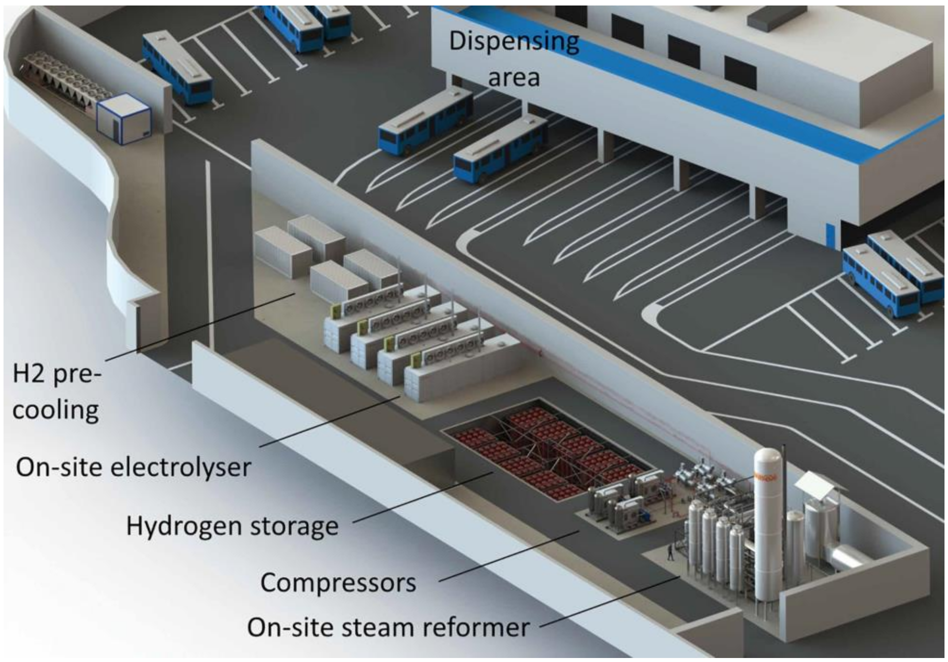


*Figure 9. **Example of an HRS with on-site electrolysis and steam reforming [12]***

As of 2021, there are 145 hydrogen refueling stations (HRS) in operation in the EU, the majority in Germany, France, Denmark, the Netherlands, and Belgium. They offer hydrogen compressed to either 700 or 350 bar. As yet there are no liquid refueling stations in the EU. The bulk of these 145 HRS service passenger cars, with only 16 delivering 350 bar H_2 to HDVs, mainly city buses (Figure 10 & Figure 11).

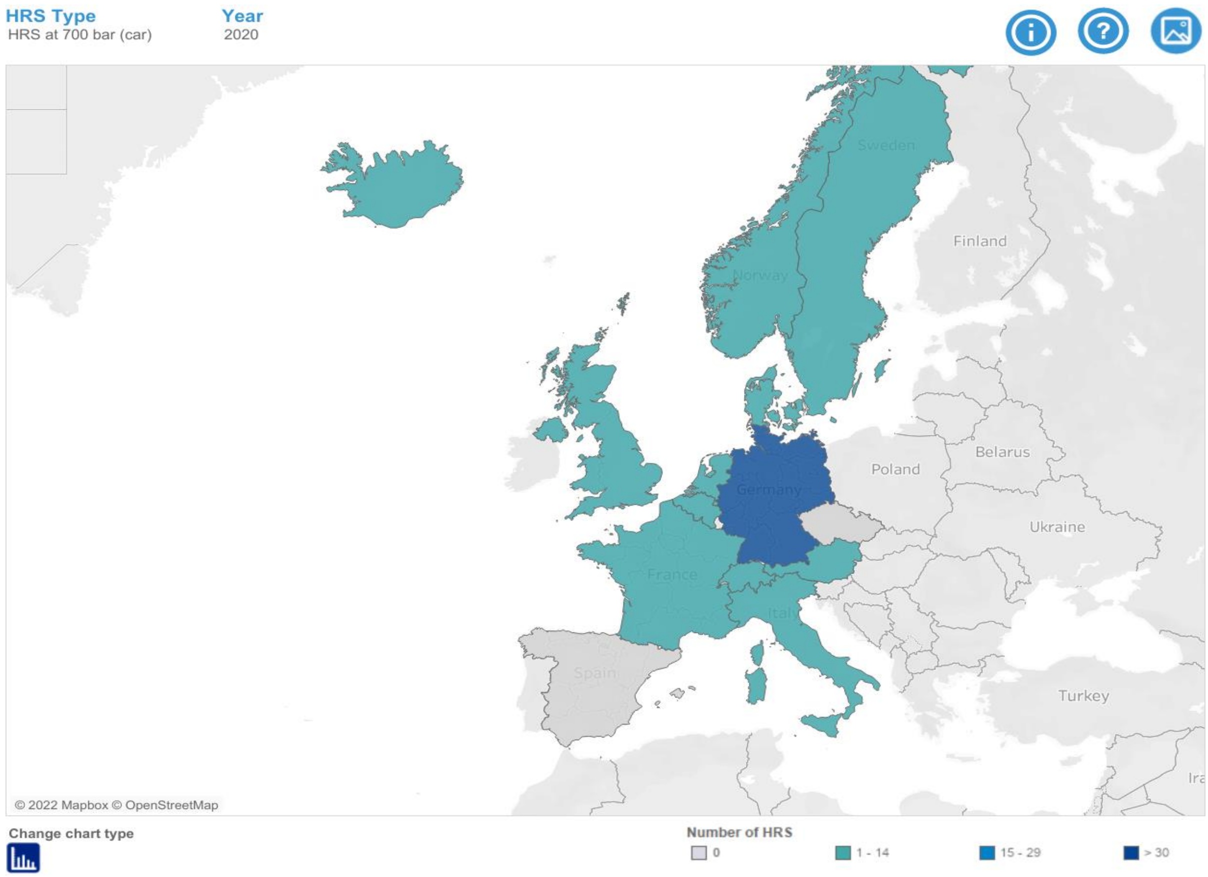


Figure 10. ***Number of HRS @700bar (cars) in EU [13]***

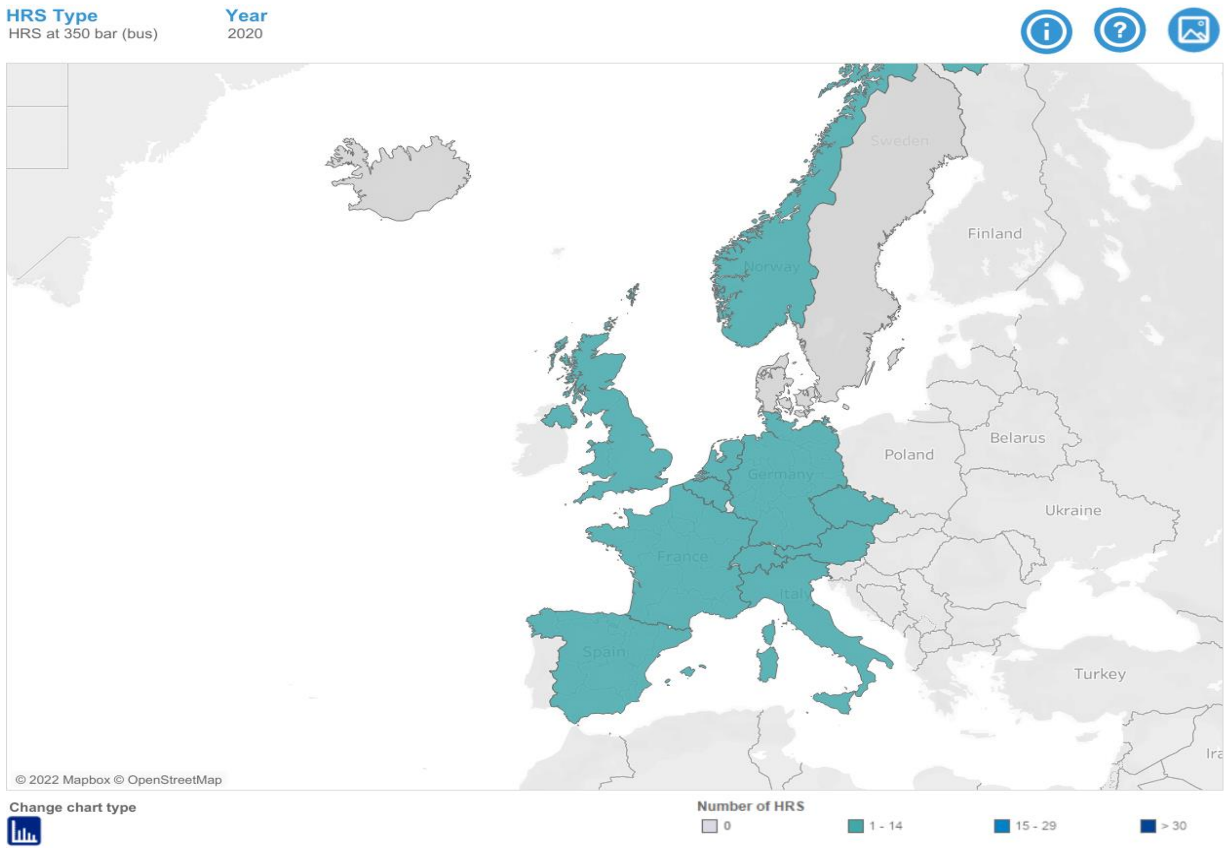


*Figure 11***. Number of HRS @350bar (buses/trucks) in EU [13]**

Development of bus refueling infrastructure is currently vulnerable to limited investment security and lack of a stable long-term policy framework, including binding targets, making investment in alternative infrastructure more attractive to investors. Though, the important point here is to highlight to potential investors the significant environmental benefits (i.e. very low carbon footprints) that hydrogen mobility and subsequently HRS could provide. Since bus depots are often located within urban areas and surrounded by commercial or residential areas, the constraints on the HRS footprint are usually very strict and challenging.

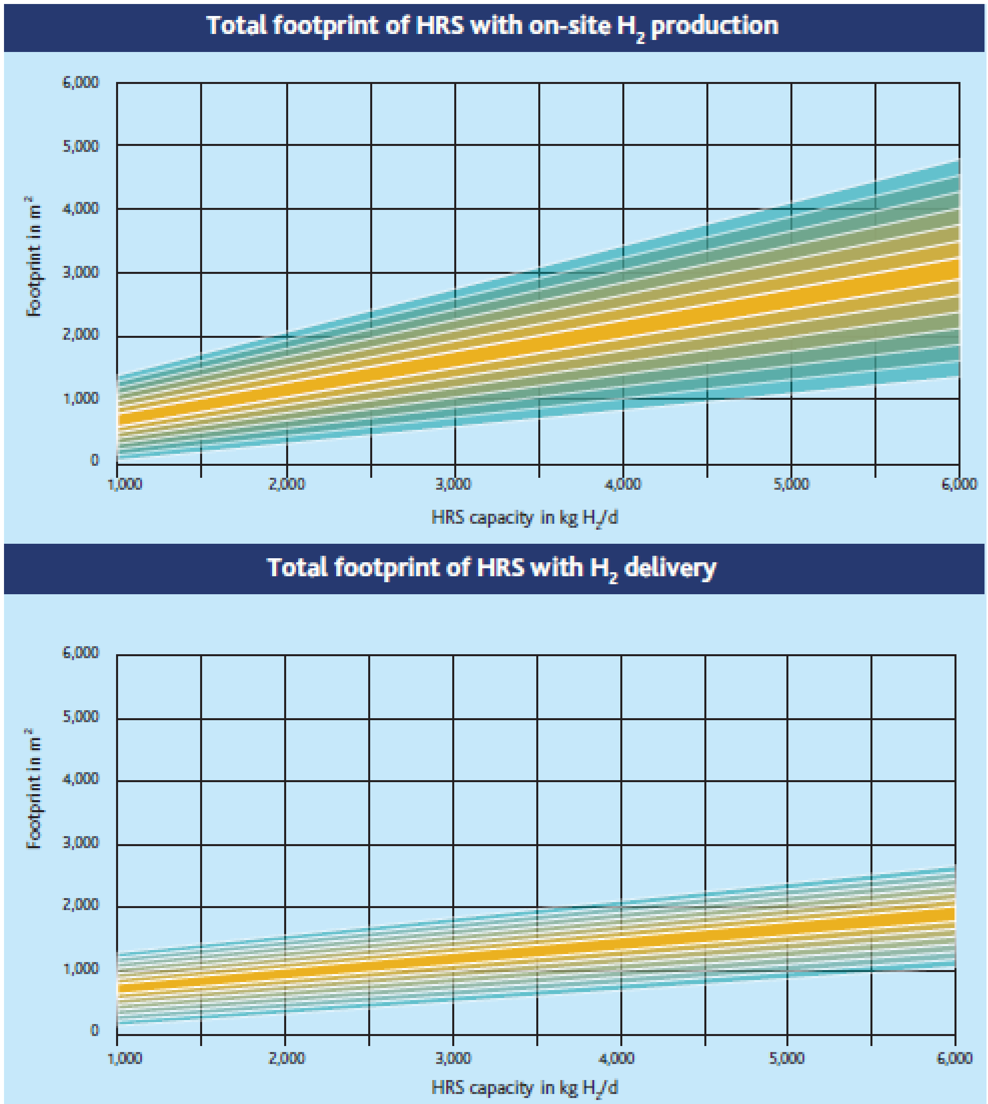


*Figure 12. **Total footprint of HRS with on-site hydrogen production & hydrogen delivery [12]***

Currently, there is a total of 152 HRS, distributed over 14 European countries. With 60 hydrogen stations, Germany is the leading country in Europe. Several global companies have participated in the aforementioned funded initiatives or invested to in-house pilot programs for HRS exploitation in an international/national level. An indicative list of HRS suppliers and manufacturers is presented below (Table 2).

Table 2. Non exhaustive list of hydrogen supplier and HRS manufacturer

	Relevant experiences/ Facts	Places where HRS are installed
INTERNATIONAL LEVEL		
AIR LIQUIDE Creative Oxygen **(FR)**	Designed and installed over 100 H_2 stations around the world. Part of the H_2 mobility consortium, SWARM consortium	Saga, Aalborg, Dubai, Copenhagen, Düsseldorf, Rotterdam, Aargau Paris, Oslo, Kawasaki, Tokyo, Los Angeles, Whistler in Canada
AIR PRODUCTS **(BE)**	Offer an extensive patent portfolio in hydrogen dispensing technology and involved in over 200 hydrogen fueling projects in the United States and 20 countries worldwide, including China (SmartFuel station)	London, Cologne, California, Texas, Pennsylvania, Florida, Missouri, Illinois, Washington, Tennessee, Beijing (chosen to support China's first, commercial-scale liquid hydrogen-based fuelling station)
THE LINDE GROUP Linde **(DE)**	Build the largest HRS in the UK (Abeerdeen) and one of the most powerful HRS with a capacity of up to 200kg/h in Berlin	Aberdeen, Milan, Bolzano, Arlanda Airport in Stockholm, Hamburg, Berlin and Munich, Vienna, Amagasaki City in Japan, Shanghai Anting in China + USA
Shell **(UK-NE)**	In Germany, Shell is part of a joint venture with industrial gas manufacturers Air Liquide and Linde, car manufacturer Daimler and energy companies Total and OMV, to develop a nationwide network of 400 hydrogen refueling stations for new hydrogen car models by 2023.	Cobham, Beaconsfield (Southeast of England) The Netherlands, Germany (Frankfurt, Berlin), Los Angeles, Citrus Heights (California), Vancouver
LUXFER **(UK)**	Luxfer's G-Stor H_2 products are the leading line of lightweight high-pressure hydrogen-storage cylinders used by OEMs to manufacture compressed hydrogen-storage systems for fuel- cell electric vehicles.	Europe, Australia, India, Russia, New Zealand
HYDROGENICS SHIFT POWER | ENERGIZE YOUR WORLD **(Canada)**	Global provider of H_2 fuelling stations (HySTAT™) and fuel cell systems. Participated in the CUTE program, deliver first green Hydrogen production station to New Zealand, and world's largest Hydrogen electrolysis plant in Canada.	Dunkerque, Hamburg, Stuttgart, Brussels, Istanbul, Oslo, Brügg (Switzerland), Los Angeles, Barcelona, Stockholm and Amsterdam
NATIONAL LEVEL		
PITPOINT CLEAN FUELS **(NE)**	International provider of clean fuels. Design, build, and operate service public or private fuelling stations for LNG, CNG, bio-methane, hydrogen, as well as electric charging points.	Chemie Park Delfzijl in the Netherlands
McPhy Driving clean energy forward **(FR)**	Designed, manufactured and integrated the first hydrogen system in France, combining an innovative high energy-efficient electrolyser with a hydrogen station with a capacity of 40 kg per day.	Sarreguemines, Rovaltain (France) Ivry-sur-Seine (inaugurated during the COP21) Berlin Airport
engie **(FR)**	Will supervise through its subsidiary GNVERT the construction and exploitation of HRS for the first hydrogen bus line in France (Pau). Founder member of the hydrogen Council. Inaugurated the first multi-fuel station in France.	Pau, Rungis International Market, Member of the Rhône Alpes H_2 plan
Everfuel **(DK)**	Establishes green hydrogen distribution – and production operations, installs and operates HRS directly at bus depots. Member of the consortium H2bus.	

(NO)	hydrogen company delivering technologies to produce (electrolysers), store and distribute energy. Member of the consortium H2bus.	

Hydrogen production

Hydrogen might be the most abundant element on earth but it can be found rarely in its pure form. Practically, this fact means that in order to produce hydrogen, it needs to be extracted from its compound. This extraction process needs energy but hydrogen can be produced or extracted using virtually any primary source of energy, be it fossil or renewable. Characteristically, hydrogen can be produced using diverse resources including fossil fuels, such as natural gas and coal, biomass, nonfood crops, nuclear energy and renewable energy sources, such as wind, solar, geothermal, and hydroelectric power to split water. This diversity of potential supply sources is the most important reason why hydrogen is such a promising energy carrier [7].

Although most of the world's hydrogen production today is being produced through a more CO_2 intensive process called Steam Methane Reforming (SMR), hydrogen can also be produced through a process that makes use of renewable electricity, leading to the production of "green" or CO_2 neutral hydrogen. The current most widely used hydrogen production methods are shown (Figure 13) and described below [7].

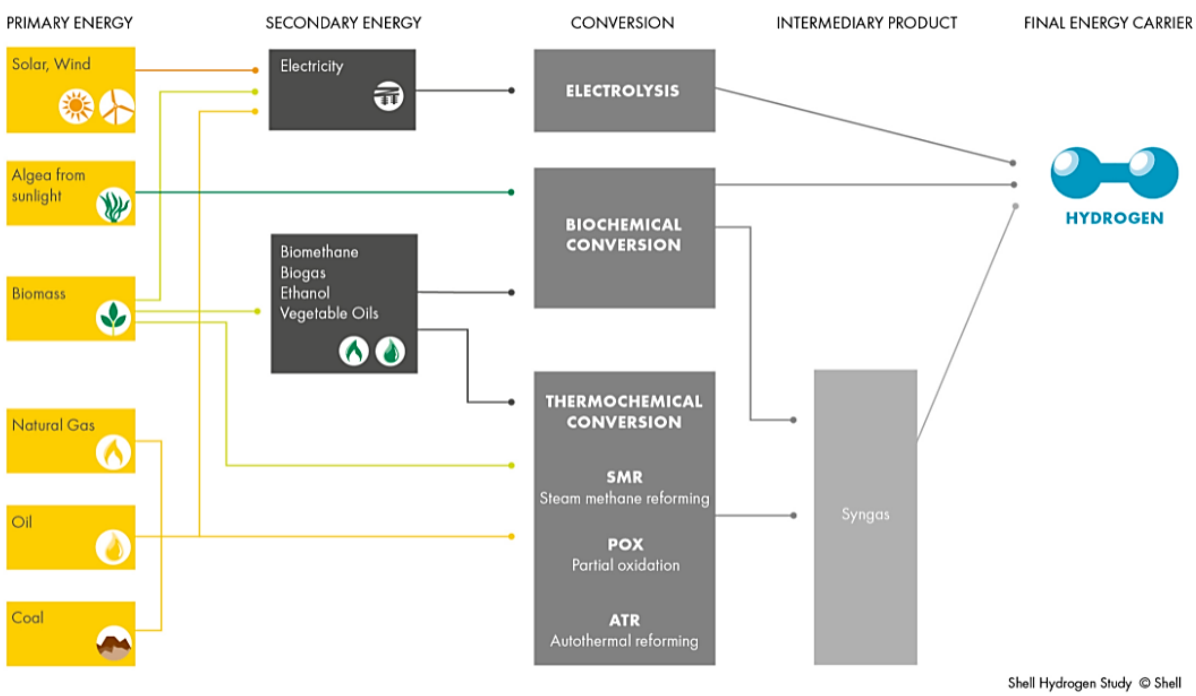


*Figure 13. **Hydrogen production methods** [7]*

The costs of each hydrogen production method differentiates according to the primary energy source used to produce hydrogen products. According to the latest IRENA's study [7], SMR produced hydrogen from fossil fuels or biogas are the cheapest options nowadays followed by the exploitation of on-shore wind energy infrastructure (Table 3). Solar energy is a very suitable primary energy source but only if its production cost is low (i.e. in Mediterranean countries).

Table 3. ***Comparison of the Technology Readiness Level (TRL), CAPEX and H_2 production costs of different processes*** *[11]*

Comparison of the Technology Readiness Level (TRL), CAPEX and H_2 production costs of different processes.

Process	TRL	Production scale	CAPEX	H_2 production cost ($/kg)[12]
FOSSIL RESOURCES				
SMR	9	Large/Available	170.95–240.20 M€[1]	0.77
Coal Gasification	9	Large/Available	257.60 M€[2]	0.92–2.83
WATER				
Water Electrolysis	9	Small/Available	4.0 M€[9] 8.9 M€[10]	2.35–4.80 (Nuclear) 5.00–10.00 (RSE[13])
Vegetal/algal biomass				
Gasification	7	Mid-size/Available	11 M€[3] 215.3 M$[4]	1.21–3.5
Steam Reforming	8	Small/Available	9.9 M€[5]	1.83–2.35
Pyrolysis	7	Mid-size/Available	210–287 M$[4]	1.21–2.57
ScWG	4	Pilot plant	57.44 M€[6] 277.8 M$[4]	1.51–3.89
APR	4–5	Pilot plant	12.85 M$[7]	4.00
Dark fermentation	5	Pilot plant	/	2.57–2.80
Photo-fermentation	4	Under research	115.6 M$[8]	2.83–3.89
MEC	2–4	Under research	2.8 M€[11]	1.7–4.51[14]

Steam methane reforming (SMR)

As already described above, currently, most of the hydrogen produced today is being produced through the CO_2 intensive process called Steam Methane Reforming. High-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic—that is, heat must be supplied to the process for the reaction to proceed.

Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. Steam reforming can also be used to produce hydrogen from other fuels, such as ethanol, propane, or even gasoline.

In partial oxidation, the methane and other hydrocarbons in natural gas react with a limited amount of oxygen (typically from air) that is not enough to completely oxidize the hydrocarbons to carbon dioxide and water. With less than the stoichiometric amount of oxygen available, the reaction products contain primarily hydrogen and carbon monoxide (and nitrogen, if the reaction is carried out with air rather than pure oxygen), and a relatively small amount of carbon dioxide and other compounds. Subsequently, in a water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and more hydrogen [7].

Biomass gasification

Gasification is the thermochemical conversion of a carbonaceous solid fuel into a product gas (also referred to as producer gas, or in the case of wooden feedstock referred to as wood gas) in the presence of a specific gasification agent. Figure 14 shows a general process layout for hydrogen production via gasification.

*Figure 14. **General process layout for hydrogen production via gasification** [15]*

In a recent review study made by J.F.G.M et al. [16], the thermochemical process, particularly gasification, partial oxidation, and steam reforming, presented the best yield for H_2 production. Steam gasification is the best compromise because it is suitable for wet and dry biomass, and it does not require an oxidizing agent. As for biological conversion, dark fermentation is more worthwhile than photo-fermentation due to its lower energy consumption. Additionally, the electrochemical process is feasible for biomass.

Electrolysis

In this process, the electrolysis breaks down water into hydrogen and oxygen by using electricity. If the electricity used, springs from renewable energy sources like wind or solar and the hydrogen produced is used in a fuel cell, then the entire energy process would create no net emissions. In this case, we would be talking about "green hydrogen" [7].

The electrolyser consists of a DC source and two noble metal-coated electrodes, which are separated by an electrolyte. The electrolyte or ionic conductor can be a liquid, for example conductive caustic potash solution (potassium hydroxide, KOH) for alkaline electrolysis.

In an alkaline electrolyser the cathode (negative pole) loses electrons to the aqueous solution. The water is dissociated, leading to the formation of hydrogen (H_2) and hydroxide ions (OH –) The charge carriers move in the electrolyte towards the anode. At the anode (positive pole) the electrons are absorbed by the negative OH – anions. The OH – anions are oxidised to form water and oxygen. Oxygen rises at the anode. A membrane prevents the product gases H_2 and O_2 from mixing but allows the passage of OH – ions. Electrolysers consist of individual cells and central system units (balance of plant). By combining electrolytic cells and stacks, hydrogen production can be adapted to individual needs.

Electrolysers are differentiated by the electrolyte materials and the temperature at which they are operated: **(i) low-temperature electrolysis (LTE), including alkaline electrolysis (ALK)**, **(ii) proton**

exchange membrane (PEM) electrolysis, **(iii) anion exchange membrane (AEM) electrolysis** (also known as alkaline PEM), and **(iv) solid oxide electrolysis (SOE)**. The choice of a given electrolysis technology depends on the use needs and the local context.

Table 4 summarizes the operating conditions and the most important components for the four types of electrolysers. The coloured cells represent conditions or components with significant variation from different manufacturers or R&D institutions. In this respect, it also gives a sense of the less mature technologies, which is clear for the AEM and solid oxide types.

*Table 4. **Challenges and characteristics faced by each storage/transport pathway** [7]*

	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or NaHCO3 $1molL^{-1}$	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (e.g. LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Note: Coloured cells represent conditions or components with significant variation among different companies.
PFSA = Perfluoroacidsulfonic; PTFE = Polytetrafluoroethylene; ETFE = Ethylene Tetrafluorethylene; PSF = poly (bisphenol-A sulfone); PSU = Polysulfone; YSZ = yttriastabilized zirconia; DVB = divinylbenzene; PPS = Polyphenylene sulphide; LSCF = $La_{0.58}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$-δ; LSM = $(La_{1-x}Sr_x)_{1-y}MnO_3$; § = Crofer22APU with co-containing protective coating.

Based on IRENA analysis.

Hydrogen types based on their production/extraction method

Hydrogen types are categorized in colors that depict the differentiations in hydrogen production pathways. These distinctions are no official definitions, though represent a common industry nomenclature [6].

- **Green Hydrogen**

Green hydrogen is mainly produced by splitting water (i.e., water electrolysis) using electricity generated from renewable energy sources (RES). The reason it is called green is that there is no CO_2 emission associated with the hydrogen production nor with its usage. When used in a fuel cell, the only by-product of its use is the pure water that was originally used in its production. Renewable hydrogen is generally more expensive than blue hydrogen, though prices are becoming more competitive. Although "green" hydrogen often refers to electrolytic hydrogen produced using electricity generated from renewable energy sources, it can also refer to hydrogen produced via different methods using other renewable sources such as biogas, biomethane, bio-waste and other renewable sources, these methods are less common than water electrolysis but also result in either very low or zero emissions.

- **Blue Hydrogen**

Blue hydrogen refers to hydrogen derived from natural gas, which is a fossil fuel, however, most (albeit not all) the CO_2 emitted during the process would be captured and stored underground (carbon sequestration) or bound in a solid product (such as bricks) and utilized. This is called carbon capture, storage and utilisation (CCSU).

One process for achieving this is called steam methane reforming (SMR). This mixes natural gas with very hot steam, in the presence of a catalyst, where a chemical reaction creates hydrogen and carbon dioxide and carbon monoxide. An improvement of this process, auto-thermal reforming (ATR) combines the steam reforming reaction and fuel oxidation into a single unit. This process is more efficient and is able to capture more of the CO_2 emitted in course of production. When considering the CO_2 emission reduction potential of "blue" hydrogen, it is important to acknowledge the importance of tackling methane leakage upstream of the hydrogen production plant. This should be done by applying a strict life-cycle assessment when determining the CO_2 emissions associated with its production.

Due to the differences in CO_2 emissions that can occur in the production of "blue" hydrogen (depending on upstream methane emissions and the production technology used), the term itself can be considered too broad. Instead, when referring to hydrogen produced from natural gas, it is more accurate to refer to it using the actual GHG footprint associated to its production.

- **Black /Gray**

Gray hydrogen is produced from fossil fuel and commonly uses steam methane reforming (SMR) method. During this process, CO_2 is produced and eventually released to the atmosphere.

- **Turquoise**

Extracted by using the thermal splitting of methane via methane pyrolysis, this process (though at the experimental stage) removes carbon in a solid form instead of CO_2 gas.

- **Yellow**

Yellow hydrogen refers to hydrogen produced by electrolysis using the electricity grid.

- **White**

White hydrogen refers to naturally occurring hydrogen in its most natural state.

- **Brown**

Produced from coal, the black and brown colours refer to the type of bituminous (black) and lignite (brown) coal. The gasification of coal is a method used to produce hydrogen. However, it is a very polluting process, and CO_2 and carbon monoxide are produced as by-products and released into the atmosphere.

- **Red**

Red hydrogen is produced through the high-temperature catalytic splitting of water using nuclear power thermal as an energy source.

- **Pink**

Pink hydrogen is generated through electrolysis of water by using electricity from a nuclear power plant.

- **Purple**

Purple hydrogen is made though using nuclear power and heat through combined chemo-thermal electrolysis splitting of water.

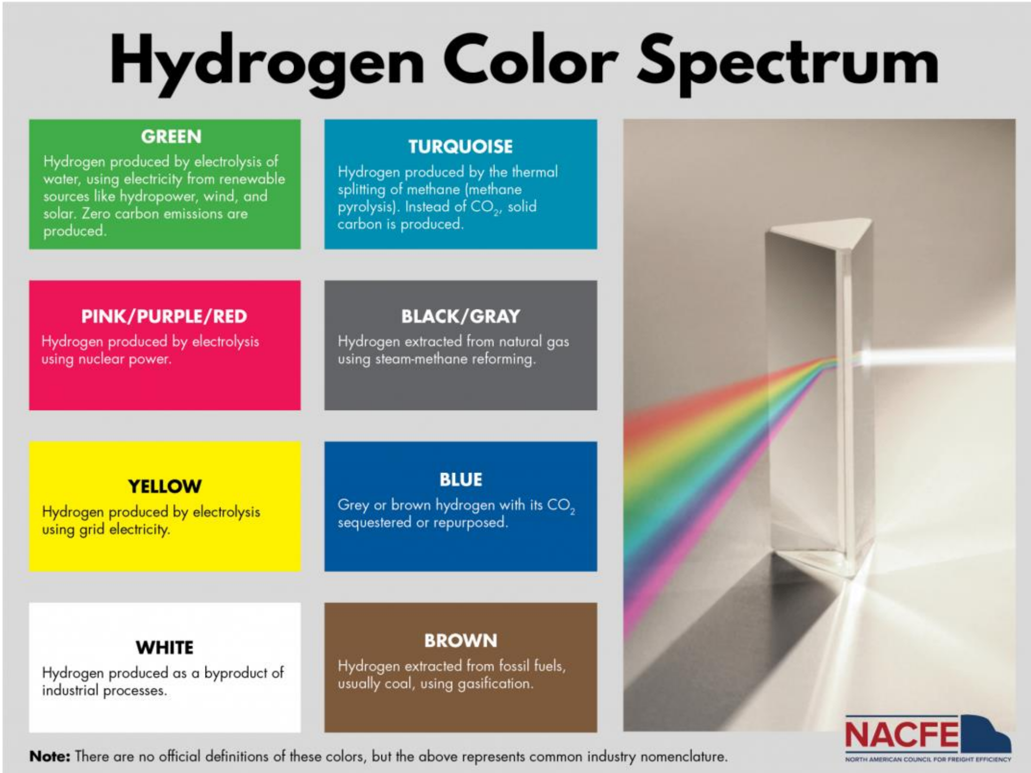
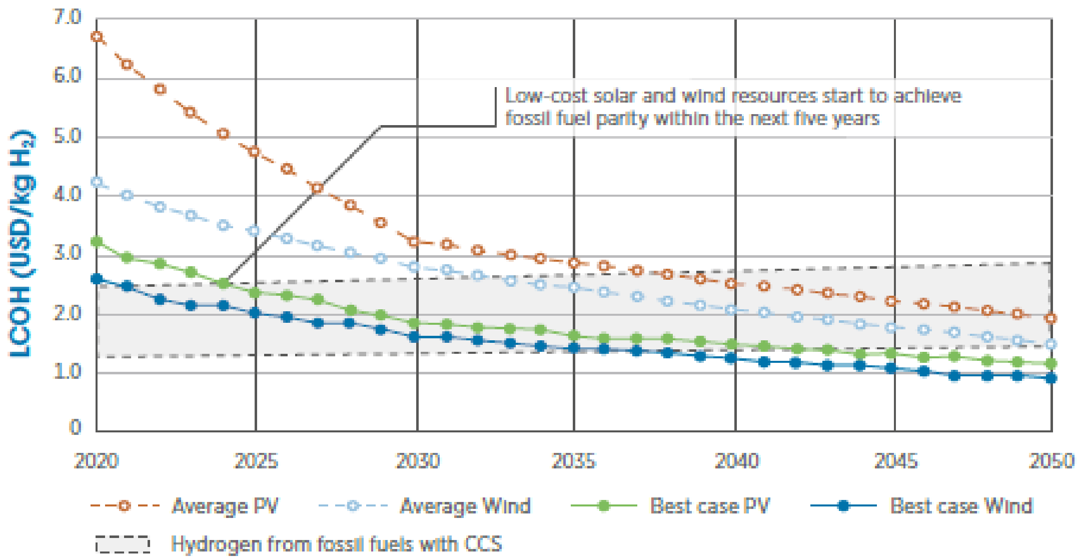


*Figure 15. **Types of hydrogen according to its production source and extraction methods** [2]*

Future costs of green hydrogen will be below those for blue hydrogen fossil fuels. By 2035, average-cost renewables also start to become competitive. Pricing of CO_2 emissions from fossil fuels further improves the competitiveness of green hydrogen. In the best locations, renewable hydrogen is competitive in the next 3-5 years compared to fossil fuels [7].



Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

*Figure 16. **Projection of hydrogen production costs from solar and wind power vs. fossil fuels** [7].*

Hydrogen storage

Batteries are not suitable for storing large amounts of electricity over time. A major advantage of hydrogen is that it can be produced from (surplus) renewable energies, and unlike electricity it can also be stored in large amounts for extended periods of time. For that reason, hydrogen produced on an industrial scale could play an important part in the energy transition.

However, hydrogen can complement batteries in the transport sector. The optimal energy storage system for vehicles lies in hydrogen and battery systems. The hydrogen system would provide the bulk energy storage, while a relatively small energy capacity battery would allow regenerative braking, meet peak power demands, and generally buffer the fuel cell against load changes to extend its lifetime.

Alongside other demand and supply measures, energy storage can play an important part in improved system integration. Short-term electricity storage in batteries for small plants is developing dynamically, however, longer-term storage of larger surplus amounts of electricity requires new types of storage, such as chemical storage in the form of hydrogen [7].

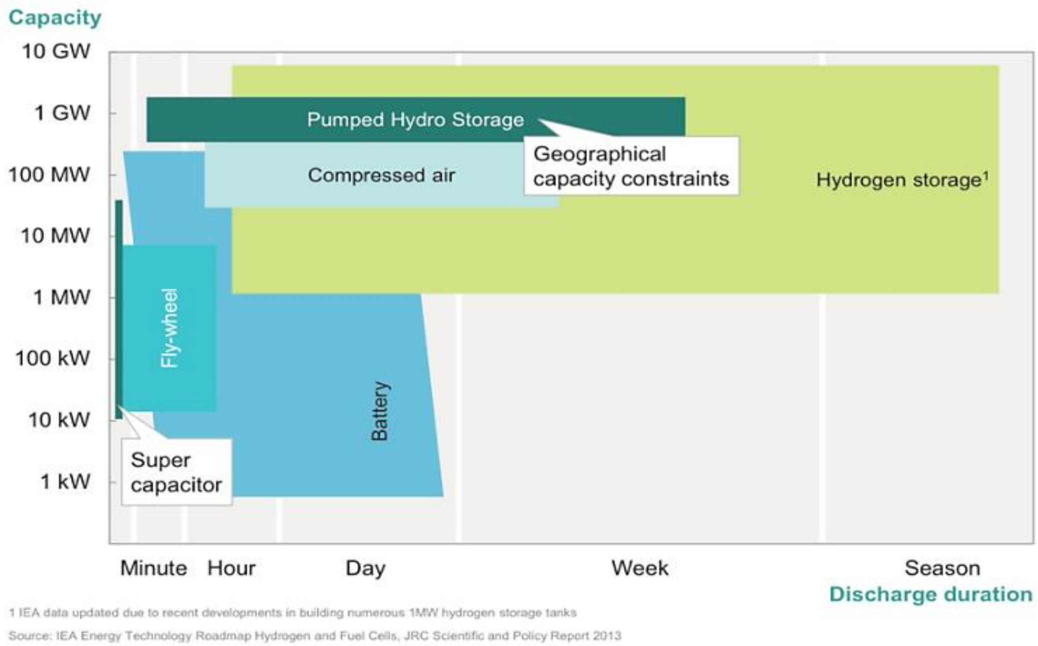


*Figure 17. **Energy storage technologies summary graph** [7].*

Hydrogen can be obtained by electrolysis from electricity produced with surplus renewables. If there is a corresponding energy demand, the hydrogen can fulfill it directly. However, it can also be stored in bulk tanks as pressurized gas and retrieved when supplies are low.

Hydrogen can be utilized several ways as an energy carrier, such as feeding it in small amounts into the natural gas network, converting it to methane and introducing the obtained methane into the natural gas network, or the stored hydrogen can be directly converted back into electricity via fuel cells.

Hydrogen as an energy carrier has by far the highest gravimetric energy density. The mass-based energy density of hydrogen is thus almost three times higher than that of liquid hydrocarbons, however, the volumetric energy density of hydrogen is comparatively low. Therefore, for practical handling purposes, the density of hydrogen must be increased significantly for storage purposes.

The most important hydrogen storage methods, which have been tried and tested over lengthy periods of time, include physical storage methods based on either compression or cooling or a combination of the two (hybrid storage). In addition, a large number of other new hydrogen storage technologies are being pursued or investigated. These technologies can be grouped together under the name materials-based storage technologies. These can include solids, liquids, or surfaces [7].

In the **transportation sector,** hydrogen is stored usually in a physical-based method, either as compressed or liquified gas in order to be directly transported to the nearest fuel depot to service all hydrogen vehicles. These methods are described below (Figure 18).

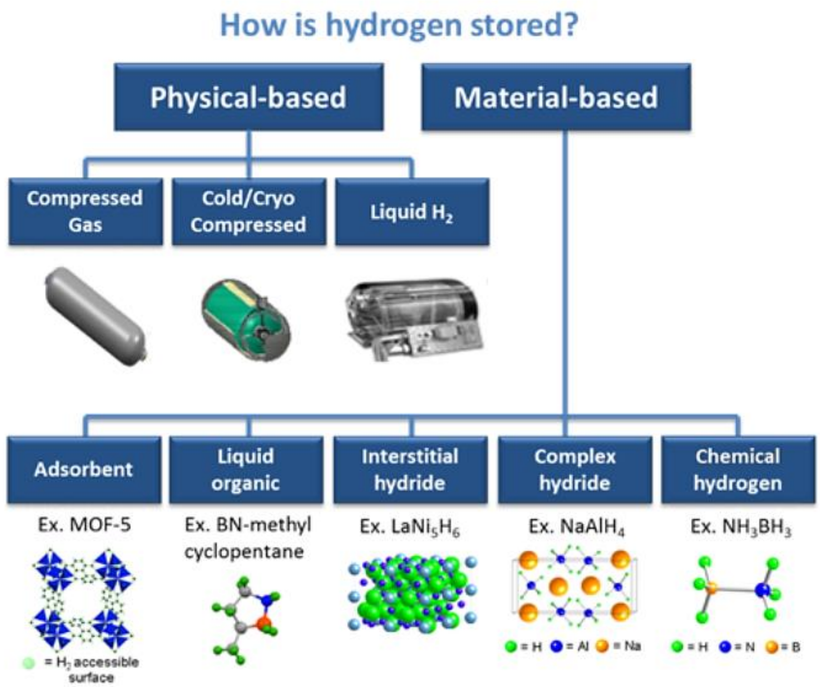


*Figure 18. **Scheme of different hydrogen storage technologies** [7].*

*Table 5. **Hydrogen storage standards by pressure** [17]*

Category	Features	Max pressure
Type I	All-metal cylinders (steel or aluminum), low-cost and commonly used in CNG vehicles	200 bars
Type II	Load-bearing steel or aluminum liner hoop wrapped with continuous glass-fiber composite filament	300 bars
Type III	Non-load-bearing metal liner axial and hoop wrapped with continuous full composite filament	300-700 bars
Type IV	Non-load-bearing non-metal liner wrapped with continuous filament (all composite with carbon or carbon/ glass fiber)	700 bars

Liquified hydrogen

As well as storing gaseous hydrogen under pressure, it is also possible to store cryogenic hydrogen in the liquid state. Liquid hydrogen (LH_2) is in demand today in applications requiring high levels of purity, such as in the chip industry for example. As an energy carrier, LH_2 has a higher energy density than gaseous hydrogen, but it requires liquefaction at –253 °C, which involves a complex technical plant and an extra economic cost. When storing liquid hydrogen, the tanks and storage facilities have to be insulated in order to keep in check the evaporation that occurs if heat is carried over into the stored content, due to conduction, radiation or convection. Tanks for LH_2 are used today primarily in space travel [7].

Cold- and cryo-compressed hydrogen

In addition to separate compression or cooling, the two storage methods can be combined. The cooled hydrogen is then compressed, which results in a further development of hydrogen storage for mobility purposes. The first field installations are already in operation. The advantage of cold or cryogenic compression is a higher energy density in comparison to compressed hydrogen. However, cooling requires an additional energy input.

Currently it takes in the region of 9 to 12 % of the final energy made available in the form of H_2 to compress hydrogen from 1 to 350 or 700 bar. By contrast, the energy input for liquefaction (cooling) is much higher, currently around 30 %. The energy input is subject to large spreads, depending on the method, quantity and external conditions. Work is currently in progress to find more economic methods with a significantly lower energy input [7].

Hydrogen transport and distribution

Hydrogen is ideal for long-distance transportation and can be transported in different formats. Today, the transport of compressed gaseous or liquid hydrogen by lorry and of compressed gaseous hydrogen by pipeline to selected locations are the main transport options used. The most common hydrogen transportation means, covering the needs of the different hydrogen markets, are [7]:

- Compressed gas cylinders or cryogenic liquid tankers
- Pipelines
- Blending with natural gas

Compressed gas cylinders or cryogenic liquid tankers

Compressed Gas Containers

Gaseous hydrogen can be transported in small to medium quantities in compressed gas containers by lorry. For transporting larger volumes, several pressurized gas cylinders or tubes are bundled together on so-called CGH_2 tube trailers. The large tubes are bundled together inside a protective frame. The tubes are usually made of steel and have a high net weight. This can lead to mass-related transport restrictions. The newest pressurized storage systems use lighter composite storage containers for lorry transport.

The low density of hydrogen also has an impact on its transport: under standard conditions (1.013 bar and 0°C), hydrogen has a density of 0.0899 kg per cubic meter (m^3), also called normal cubic meter (Nm^3). If hydrogen is compressed to 200 bars, the density under standard conditions increases to 15.6 kg hydrogen per cubic meter, and at 500 bar it would reach 33 kg H_2 /m^3.

A tube trailer cannot store compressed gas as compactly as a tanker for liquid fuels (petrol or diesel fuel). This means that the available tank volume for hydrogen per tanker is lower. Single tube trailers carry approximately 500 kg of hydrogen, depending on the pressure and container material. The largest tank volumes for gaseous hydrogen transport are currently 26 cubic meters. Taking account of the low hydrogen density factor at 500 bars, this results in a load of around 1,100 kg hydrogen per lorry. This figure extrapolates to approximately 12,000 normal cubic meters of hydrogen. At 250 bars both the weight of hydrogen and its transport volume in Nm 3 would be roughly halved [7].

Liquid Transport

As an alternative, hydrogen can be transported in liquid form in lorries or other means of transport. In comparison to pressure gas vessels, more hydrogen can be carried with an LH_2 trailer, as the density of liquid hydrogen is higher than that of gaseous hydrogen. Since the density even of liquid hydrogen is well below that of liquid fuels, at approx. 800 kg/m^3, in this case too only relatively moderate masses of hydrogen are transported. At a density of 70.8 kg/m^3, around 3,500 kg of liquid hydrogen or almost 40,000 Nm^3 can be carried at a loading volume of 50 m^3. Over longer distances it is usually more cost-effective to transport hydrogen in liquid form, since a liquid hydrogen tank can hold substantially more hydrogen than a pressurized gas tank. For the purposes of liquid transport, the hydrogen is loaded into insulated cryogenic tanks. LH_2 trailers have a range of approximately 4,000 km. Over the journey time the cryogenic hydrogen heats up, causing the pressure in the container to rise. Similarly, to lorry transport, LH_2 can also be transported by ship or by rail, provided that suitable waterways, railway lines and loading terminals are available [7].

Pipelines

A pipeline network would be the best option for the comprehensive and large scale use of hydrogen as an energy source. However, pipelines require high levels of initial investment, which may pay off, but only with correspondingly large volumes of hydrogen. Nevertheless, one possibility for developing pipeline networks for hydrogen distribution is local or regional networks, known as micronetworks. These could subsequently be combined into transregional networks [7].

Worldwide there are already (since 2016) more than 4,500 km of hydrogen pipelines in total, the vast majority of which are operated by hydrogen producers. The longest pipelines are operated in the USA, in the states of Louisiana and Texas, followed by Belgium and Germany (Figure 19**)**.

Figure 19. ***Countries with the longest hydrogen pipeline network since 2016*** *[7].*

Blending with natural gas

Blending hydrogen into natural gas pipeline networks has also been proposed as a means of delivering pure hydrogen to markets, using separation and purification technologies downstream to extract hydrogen from the natural gas blend close to the point of end use. As a hydrogen delivery method, blending can defray the cost of building dedicated hydrogen pipelines or other costly delivery infrastructure during the early market development phase. However, a number of components have been listed that are still considered to be critical and to be generally unsuitable for operation with these hydrogen concentrations. For CNG vehicles, the currently authorized limit value for the proportion of hydrogen used is only 2 vol%, depending on the materials built in.

It can be assumed that many of the gas transport network distribution lines and storage facilities that were operated in the past are still in use today. In Leeds (UK), for instance, the possibility has been explored of converting the existing natural gas network in the region (used primarily for municipal heating supply) entirely to hydrogen. Given their length, the large gas networks in many industrial countries could store considerable amounts of hydrogen[7].

Hydrogen supply chain schemes

The transportation method mentioned previously must be selected according to the existing hydrogen production facilities and the overall national or regional strategic hydrogen supply chain approach. From a logistics perspective, four development stages can be envisaged (Figure 20):

- The **first stage** involves multi-megawatt-capacity hydrogen facilities to directly feed large consumers, such as medium- to large-scale industries and specific transport fleets leveraging on the use of existent gas grids, and eventually their conversion to hydrogen grids. This approach would ensure long-term off-take for hydrogen system developers.

- In the **second and third stages**, these and other new facilities can supply smaller, local consumers through trailer trucks. For this, investments in conditioning and filling centres would be needed.
- Once hydrogen from renewables applications achieves mass markets, regional hydrogen imbalances may result in regions with surplus hydrogen exporting to regions with deficits. This may lead to the creation of a continent-wide or even intercontinental hydrogen market between countries with large renewables potential and hence export capacities (for example, Australia, Chile, Africa, the Middle East and the North Sea region), and countries with large hydrogen demand and costlier or limited renewables potential.

The hydrogen form to be chosen depends on the quantities and distance involved, typically gas cylinders (small quantities), gas trailers (large quantities, shorter distances) or in liquid rather than gaseous form (large quantities, longer distances). Whereas hydrogen transport by gas grids generally occurs by compressing it, the most promising and studied pathways for international shipping are liquid forms either through hydrogen liquefaction or its transformation into ammonia, converted back to hydrogen at the local of destination if required [7].

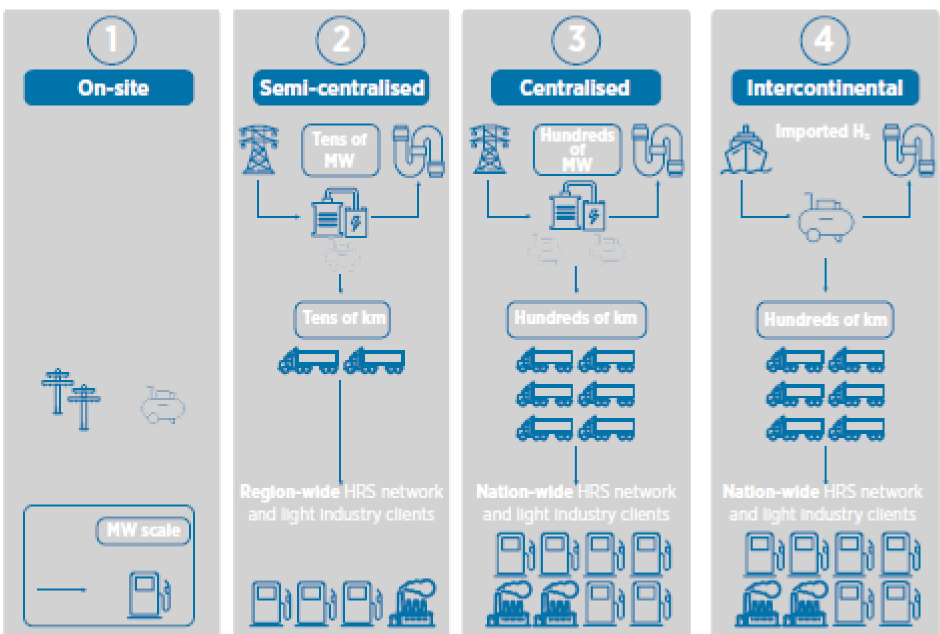


*Figure 20. **Potential future ramp-up pattern of the hydrogen supply chain** [7].*

Hydrogen trade and the use of surplus renewable electricity for local production close to centers of demand can co-exist. Logistics of imported hydrogen account for 30-40% of supply cost [7]. Each of these approaches and transported fuels have various characteristics, all presented below (Table 6).

*Table 6. **Challenges and characteristics faced by each storage/transport pathway** [9]*

CHARACTERISTICS	LIQUID	TOLUENE-MCH	AMMONIA (NH_3)
Challenges	• Requires very low temperature (about −250 °C) • High energy requirement for cooling/liquefaction • Demands cost reduction for liquefaction • Liquefaction currently consumes about 45% of the energy brought by H_2 • Difficult for long-term storage • Requires boil-off control (0.2%–0.3% d^{-1} in truck) • Risk of leakage	• Requires high-temperature heat source for dehydrogenation (higher than 300 °C, up to 300 kilopascal) • The heat required for dehydrogenation is about 30% of the total H_2 brought by MCH • As MCH with molecular weight of 98.19 gram per mol^{-1} only carries three molecules of H_2 from toluene hydrogenation, the handling infrastructure tends to be large • Durability (number of cycles)	• Lower reactivity compared to hydrocarbons • Requires treatment due to toxicity and pungent smell • Treatment and management by certified engineers • Consumes very high energy input in case of dehydrogenation (about 13% of H_2 energy) and purification
Advantages	• High purity • Requires no dehydrogenation and purification	• Can be stored in liquid condition without cooling (minimum loss during transport) • Existing storing infrastructure • Existing regulations • No loss	• Possible for direct use • Potentially be the cheapest energy carrier • Existing NH_3 infrastructure and regulation
Development stage	• Small scale: application stage • Large scale: infrastructure development is being carried out	• Demonstration stage	• Research and development stage • Partly has entered demonstration stage
Required development/ actions	• Regulation for transport loading/ unloading system • Development in H_2 engines • Improvement of energy efficiency in liquefaction	• Catalysts for both hydrogenation and dehydrogenation • Energy-efficient dehydrogenation	• High energy efficiency in synthesis • Fuel cell with direct NH_3

Source: Wijayanta *et al.* (2019)

Dispensing unit

The buses are connected to the HRS using the dispensing unit. Different standards and protocols exist for the refueling of different vehicles, such as passenger vehicles, buses or forklifts. An important parameter is the refueling speed which can be considered in three clusters: slow-fuelling (up to 30 g/s or 1.8 kg/min), normal-fuelling (up to 60 g/s or 3.6 kg/min), and fastfuelling (up to 120 g/s or 7.2 kg/min). These clusters indicate the maximum refueling speed, and the average during an entire refueling process may be well below these limits. Depending on the refueling protocol, pre-cooling of hydrogen may be required, e.g. when using fast-fuelling, especially for passenger vehicles due to the higher pressure (700 bar), leading to additional installations and higher dispensing cost.

Standardization efforts, as laid out by international standard ISO 17268:2012 and SAE J2600, ensure compatibility with vehicles from different manufacturers, which is crucial for the future deployment at scale of public refueling stations. The dispensing process for heavy-duty vehicles is also subject to standardization (SAE J2601-2), providing guidance on the safe conditions under which FCEBs can achieve high SOC in terms of rate, pressure and temperature, enabling fast-refueling rates of up to 7.2 kg/min. Additionally, accurate flow metering for proper accounting of volumes dispensed is currently lacking, due to the absence of methodologies for calibrating hydrogen flow meters at the operating pressures and temperatures. This issue can be addressed by measuring the FCEB bus weight [17].

*Figure 21***. Groningen's Hydrogen Refueling Station (HRS) with a car dispensing unit @700 bar** *[56]*

Description & Technical specifications of hydrogen fuel cell electric vehicles (FCEV) types

Hydrogen fuel cell cars

As of 2021, there are two models of hydrogen cars publicly available in select markets: The Toyota Mirai (2014–), which is the world's first mass-produced dedicated fuel cell electric vehicle (FCEV), and the Hyundai Nexo (2018–). The Honda Clarity was produced from 2016 to 2021. Most companies that had been testing hydrogen cars have switched to battery electric cars; Volkswagen has expressed that the technology has no future in the automotive space, mainly because a fuel cell electric vehicle consumes about three times more energy than a battery electric car for each mile driven. As of December 2020, there were 31,225 passenger FCEVs powered with hydrogen on the world's roads.

The benefits of hydrogen technology are fast refueling time (comparable to gasoline) and long driving range on a single tank. The drawbacks of hydrogen use are high carbon emissions when hydrogen is produced from natural gas, capital cost burden, low energy content per unit volume at ambient conditions, production and compression of hydrogen, the investment required to build filling stations around the world to dispense hydrogen, transportation of hydrogen to filling stations, and lack of ability to produce or dispense hydrogen at home [29].

H2ME EU-funded project [30] has tested during its implementation all existing hydrogen FCEVs available on the commercial market in order to quantify and evaluate hydrogen vehicles and infrastructure performances. Key statistics on the kilometers driven, the utilization rate of refueling stations and the amount of hydrogen refueled are presented in this report. By March 2021 there were:

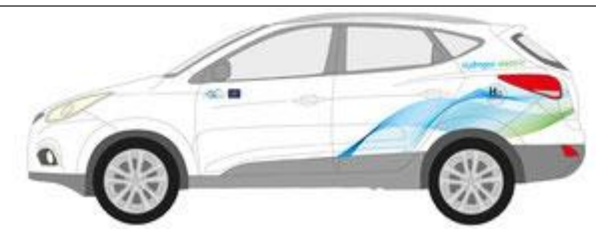
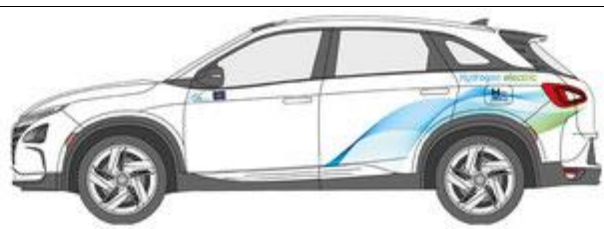
- **330 fuel cell electric vehicles** (FCEVs) made by Daimler, Honda, Hyundai and Toyota;
- **237 fuel cell range-extended electric vehicles** (FC REEVs) from Symbio and;
- **39 hydrogen refueling stations** (HRS) supplied by Air Liquide, ITM Power, Linde (including its subsidiaries AGA and BOC), McPhy and NEL Hydrogen Fueling deployed.

By the end of May 2021, a total of 17.2 million kilometers had been traveled (FCEV & REEV) within the project. In 84.866 refuels, 193.000 kg of hydrogen were refueled. A summarized table with all available hydrogen FCEVs and their usage characteristics in the H2ME project is shown in Table 7. In addition, in Table 8 the technical specifications of the three most widely-used FCEVs during EU-funded pilot projects [31]; Hyundai ix35 Fuel Cell, Hyundai Nexo and Toyota Mirai.

*Table 7. **Vehicles reporting data to H2ME project [30]***

	Daimler B-Class F-CELL FCEV	Daimler GLC F-CELL FCEV/PHEV	Honda Clarity FCEV	Hyundai ix35 FCEV	Hyundai Nexo FCEV	Toyota Mirai FCEV	Symbio ZE H2 FC REEV
							
Project and dates reporting data	H2ME-1 2015-2018 (retired)	H2ME-1 & 2 2019-	H2ME-2 2017-	H2ME-2 2017-	H2ME-2 2019-	H2ME-1 & 2 2017-	H2ME-1 & 2 2015-
H2ME use-cases	Passenger and fleet car	Passenger and fleet car	Passenger and fleet car	Passenger and fleet car, taxi	Passenger and fleet car	Passenger and fleet car, police car, taxi	Light van in company fleets
NEDC range	380 km	478 km	650 km	590 km	756 km	605 km	300 km
H_2 tank capacity and pressure	3.7 kg (700 bar)	4.4 kg (700 bar)	5.5 kg (700 bar)	5.6 kg (700 bar)	6.3 kg (700 bar)	5.0 kg (700 bar)	1.8 kg (350 bar version)
Battery capacity	1.4 kWh	13.5 kWh (9.3kWh usable)	1.7 kWh	0.95 kWh	1.6 kWh	1.6 kWh	22 kWh

*Table 8. **Indicative list and technical specifications – Hydrogen cars [31]***

	**Hyundai ix35 Fuel Cell** *Maximum power motor: 100kw (~136PS)* *Maximum torque: 300NM* *Maximum speed: 160 km/h* *Range: up to 594km (NEDC)* *Duration refuelling: 3-4 min.* *At the moment there are 5 Hyundai ix35 Fuel Cell in our fleet.*
	**Hyundai Nexo** *Maximum power motor: 120kw (~163PS)* *Maximum torque: 395NM* *Maximum speed: 177 km/h* *Range: up to 666km (WLTP)* *Duration refuelling: 4-5 min.* *At the moment there are 10 Hyundai Nexo in our fleet.*

	**Toyota Mirai** *Maximum power motor: 113kw (~154PS)* *Maximum torque: 335NM* *Maximum speed: 175 km/h* *Range: up to 500km (NEDC)* *Duration refuelling: 4-5 min.* *At the moment there are 3 Toyota Mirai in our fleet.*

Hydrogen fuel cell electric urban/inter-city buses (FCEB) and coaches

Description and technical specifications

Fuel Cell Electric Buses offer a very promising option for low-emission public transportation. FCEBs have a level of service equivalent to that of diesel-fueled buses, with similar operating range (up to 400 km), service duration (up to 22 hours a day), and fast refueling time (~10 minutes), while boasting zero tailpipe emissions and reduced noise9. If fueled with green hydrogen, FCEBs offer a better zero-emissions mode of transportation than Battery Electric Buses, which suffer from long charging times and the additional weight of batteries. Even though FCEB design and technology are still evolving, its structural components are well defined. Hybridized powertrains, in which fuel cells continuously charge electric batteries, have demonstrated superior performance compared to fuel cells alone, as the batteries can provide the peak power required for acceleration and store brake energy from deceleration, thereby extending vehicle range. Waste heat generated by the fuel stack can also be used to heat up the cabin and/or the batteries for increased energy efficiency (especially in colder environments) [17].

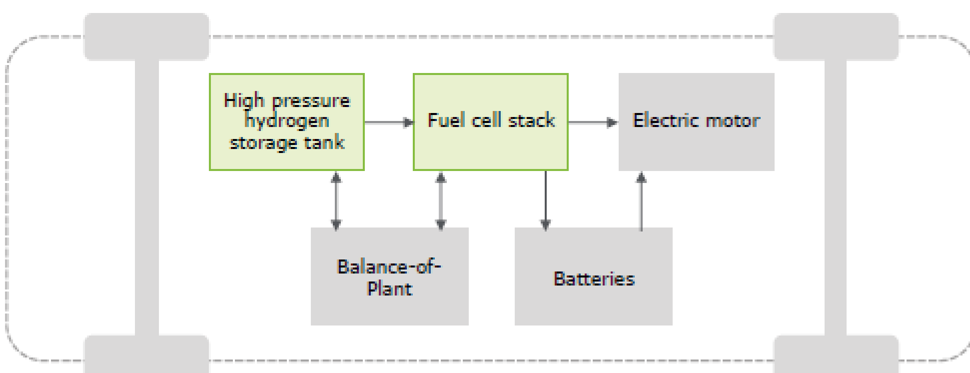


*Figure 22. **Typical FCEB hybrid powertrain elements** [17]*

Hydrogen is stored at high pressure (350 bar) in gaseous form in cylindrical tanks, usually located on the roof of the FCEB. Typical storage capacity range for an individual bus is 35-50 kg. Buses have lower storage pressure than in Passenger Cars (700 bars) as they have enough space to accommodate large storage equipment. Hydrogen tanks' design, construction, operations and maintenance requirements are subject to standards specific to on-road vehicles as laid out in SAE J2579. Future technological developments focus on increasing energy density for the same storage footprint, either by lowering the temperature (and therefore requiring advanced insulating material), or through the reversible adsorption of hydrogen onto the surface of porous solids such as metal alloys or complex hydrides. FCEB power is generated from hydrogen using heavy-duty PEM fuel cells supported by all the auxiliary equipment, such as coolant and air sub-systems or data acquisition systems for performance monitoring and diagnostics [17]. During the implementation of several FCEB projects globally, a summary of key performance indicators and learnings are shown in Table 9 below.

*Table 9. **Summary of major KPIs across major FCEB pilot programs** [17]*

	HyFLEET: CUTE	CHIC	V.LO-City	Sunline Transit	Stark Area Regional Transit (Ohio)	Orange County (California)	3Emotion	JIVE 1	JIVE 2
Region	EU	EU	EU	USA	USA	USA	EU	EU	EU
Duration of the project	2006-2009	2010-2016	2012-2019	2014-2019	2018-2019	2017-2018	2015-2022	2017-2022	2018-2023
Bus average availability	>92%	69%	85%	73%	68%	70%	<80%	>90%	>90%
FC Bus Cost	Not communicated	2012: 1.3 m€ 2015: 650k€	1.3 m€	1.8 m€	1.7 m€	1.1 m€	850k€	650k€	625k€
Maintenance Cost	Not communicated	Between 0.40 & 1.73 €/km	Not communicated	0.29 €/km	0.17 €/km	0.24 €/km	N/A	N/A	N/A
FC consumption (kg/100km)	21.9	Between 7.9 & 16 Average 12.1	Not communicated	11.3	12.5	9.7	<9	N/A	N/A

Source: National Renewable Energy Laboratory (NREL), FCH

Targets figures

Components

Bus Chassis

The body style of FCEBs are very similar to traditional buses. The composition of the bus frame often depends on the proposed application and route for the bus being manufactured. Generally, frames are a mixture of stainless steel, carbon steel, and various aluminum alloys. Bus manufacturers are responsible for designing, building and servicing the buses based on the contract with operators.

Electric Drive System

An electric drive system converts electrical energy into mechanical motion. Within a fuel cell hybrid bus, the principal aim of the electric drive system is to control the energy transfer from the fuel cell and battery with maximum efficiency. The electric motor, as well as all other electric accessories contained in the vehicle (the communication and computer systems, the lighting, etc.) operate with electricity delivered by the fuel cell. Sensors and software monitor the drive system to ensure that it properly integrates fuel cell and battery operation, that it functions efficiently and that it relays safety information to the driver. The software system and the inverter coupled to the electric motor are particularly fundamental devices in the FCEB layout. The software system plays a central role as it communicates within the electric drive system and manages the electrical load to respond to the changing power requirements of the electric motor. In the fuel cell hybrid bus industry, the two most prominent electric drive system integrators are Siemens and BAE.

Proton Exchange Membrane Fuel Cell

The leading fuel cell type for automotive applications is the Proton Exchange Membrane (PEM), also called Polymer Electrolyte Membrane fuel cell (PEMFC), because it deploys a solid polymer membrane sandwiched between an anode and a cathode. Its quick startup time, low operating temperature and good power-to-weight ratio make it an appropriate fuel cell for transportation. Moreover, PEM fuel cells only require a supply of pure hydrogen, ambient air and a method to remove the waste heat generated by the cells' electrochemical reactions. The PEM fuel cell has many subcomponents, including bipolar plates, catalysts, gas diffusion layers and membrane electrode assemblies (MEA) which is its most critical component.

FCEB suppliers & key stakeholders

As the FCEB market is the most mature one amongst the other potential hydrogen vehicle markets, numerous stakeholders joined this industry either as FCEBs manufacturers or fuel cell utilities manufacturers. The indicative lists below (Table 10 & Table 11 & Table 12) demonstrate the plurality of stakeholders in this sector and can be used as a useful list for further exploitation in global level once more hydrogen transport-related projects will be exploited.

Table 10. Non exhaustive list of European FCEB manufacturers

European OEMs	Production sites	Relevant experience/ product	Clients for FCEB (non-exhaustive)
INTERNATIONAL LEVEL			
ALEXANDER DENNIS **(UK)**	UK, Germany, Hong- Kong, Singapore, Malaysia, New Zealand, Mexico, USA, Canada	hydrogen-powered Enviro400 double deck	
EvoBus **(DE)**	Germany, France, Spain, Czech Republic	Demonstrated 17 FCEB in the CHIC project, tens of FC bus produced to date.	Aargau, Bolzano, Hamburg, Milan
VANHOOL **(BE)**	Belgium	Market Leader, more than 40 FCEB operating in Europe (since 2007) and the US (since 2005). About to deliver 30 buses for Köln and 10 for Wuppertal (largest order for FCEB in Europe). New A330 FC hydrogen bus + Van Hool Exqui.City 18 FC bus, which will be on the	Köln, Wuppertal (JIVE 2),Pau, Aalborg (Denmark), RET in Rotterdam, Oslo

		road from the end of 2019 in Pau, France => the first BRT system in Europe running on hydrogen.	
(NE)	The Netherlands	Delivered the first 18-metre FCEB, named Phileas, to Köln and Amsterdam	Amsterdam, RVK in Köln, Eindhoven, Riga
NATIONAL LEVEL			
(IT)	Italy	Built the "H80" FC Bus in 2007. Plans to produce tens of FCEB over the coming years	
(DE)	Germany	"Blue City Bus" (10, 12 and 18 m)	ÖPNV Deutschland (Wiesbaden, Mainz and Frankfurt am Main)
(FR)	France	Developing an FC version of plug-in hybrid electric buses of the "businova" platform (10.5 – 12 m)	Arthois-en-Gohelle
(PL)	Poland	Solaris Urbino 12 H_2, the continuation and development of two articulated electric buses (Solaris Urbino 18,75) powered with H_2 fuel cells as range extenders, should be released in 2019	Hamburg (CHIC project)
(PL)	Poland	First FCEB delivered to Syntus (Dutch bus operator) in mid-2016	Syntus
(UK)	Northern Ireland	Single and double deck FCEB available for order from 2017: StreetDeck FCEV. Order of 20 buses from TfL	London (CHIC project & JIVE), Brighton, Birmingham, Aberdeen (JIVE)
(PT)	Portugal	Received fuel cell systems from Toyota with the aim to become the first company in Europe to implement the Toyota technology. First FCEB will deploy in autumn 2019	

Table 11. Non exhaustive list of European FCEB manufacturers

Non-European OEMs	**(Canada)** **(Japan)** **(South korea)** **(India)** **(China)**

Table 12. Non exhaustive list of key fuel cell utilities suppliers

	International Position	Relevant experience/ product	Clients
BALLARD® (UK)	Canada, USA, China, Mexico, Europe (UK, Denmark, Norway, Belgium, Germany)	Leading global provider of fuel cell solutions through Heavy-Duty Modules (FCveloCity), Fuel Cell Stack (FCgen, FCvelocity)	Daimler, Solaris, Van Hool, Wrightbus in Europe, New Flyer, ElDorado in the USA, King Long, Yinlong & Feichi in China, Toyota in Japan,etc.
elringklinger (DE)	Germany, France, India, South Korea, Spain, Turkey	produces metallic bipolar plates, casings, end and media modules for PEM	
SIEMENS (DE)	Canada, China, India, USA, Europe (Germany, Denmark, Austria, Romania, France)	Developed the SILYZER portfolio, a PEM electrolysis using wind and solar energy + part of Hydrogen Mobility Europe	Leading 3 projects: H2Future in Austria, HY4LL in France and NEWBUSFUEL in the UK
PM Fuel Cells · Power Systems (DE)	Germany	Produces HyRange®-extender for battery electric commercial vehicles and buses. Committed with Skoda Electric to develop at least ten FCEBs (using the HyRange system) per year from 2020.	

*Table 13. **Indicative list and technical specifications – Hydrogen fuel cell buses/coaches (FCEB) [52] [71]***

	**EvoBus Mercedes-Benz** *quantity of hydrogen: 35 kg with 350 bar* *Travel range with one charge: up to 250 km* *consumption: 9-12 kg / 100 km* *maximum power to the drive wheels: 2 x 120 kW* *maximum torque to the drive wheels: 2 x 10,500 Nm* *Km traveled:> 300,000 / bus (data updated to December 2020)*
	**Solaris Urbino 12 buses/coaches** *quantity of hydrogen: 37 kg with 350 bar* *Travel range with one charge: up to 350 km* *consumption: 7-11 kg / 100 km* *maximum power to the drive wheels: 2 x 110 kW* *maximum torque to the drive wheels: 2 x 10,500 Nm* *Km traveled:> 300,000 / bus (data updated to December 2020)*

	**Van Hool Exqui.City FC** *bus length: 18m* *a 200 kW electric motor* *240km/day autonomy – 10-12kg H_2/100km* *capacity: 145 passengers* *31,000 liters of diesel saved (per year/per bus)*

Hydrogen light-duty vehicles (LDV)

Commercial/Cargo vehicles - Vans

Light-vehicle vehicles (vans) fueled with hydrogen are looking as a very attractive option in the global and EU market. Currently, several car manufacturers such as Citroen, Renault, etc. and fuel cell manufacturers such as Ballard and Stellantis, are looking to extend their market share in this sector. According to a latest press kit form Stellantis (Figure 23), hydrogen LDV can have a range up to 400 km with a single refueling charge, which takes a maximum of 4 minutes.

In this context, Renault Group has launched their respective hydrogen fuelled LDV. Since the end of 2019, Renault has been producing battery-electric light commercial vehicles with a hydrogen-powered range extender, the heart of which is a low-power fuel cell (5 kW, 20% to 25% of what would be needed for normal vehicle propulsion). The range extender allows the battery to be recharged even when the vehicle is stationary. The Kangoo extends its range from 230 km for the battery electric version to 370 km for the hydrogen version. The Master achieves a range of 350 km compared to 120 km without hydrogen. The hydrogen chain for these vehicles is currently being produced in an artisanal way, to test the market before industrial production.

In response to new environmental and social challenges, Citroën in 2021 is implementing new energies with ë-Jumpy Hydrogen. An electric van with a fuel cell and rechargeable batteries, is the first Citroën powered by this form of energy. Citroën ë-Jumpy Hydrogen has a range of over 400 km. Its three 700 bar carbon-fiber hydrogen tanks, which sit next to the battery under the front seats, can be filled in just three minutes. Citroën ë-Jumpy Hydrogen is fully electric. It benefits from a 45 kW fuel cell that produces electricity by consuming hydrogen and a 10.5 kWh battery that takes over automatically when the hydrogen tank is empty. The battery is automatically charged using electricity generated by the hydrogen or using a cable at electric-vehicle charging stations [25].

Several hydrogen LDVs are presented along with their technical specifications in the Table 14 below.

*Table 14. **Indicative list and technical specifications – Hydrogen fuel LDV [18] [25]***

	**Renault Z.E. 33 H_2 Hydrogène** *low-power fuel cell: 5 Kw* *range extender allows the battery to be recharged even when the vehicle is stationary* *Travel range with one charge: up to 370 km*
	**Citroën ë-Jumpy** *quantity of hydrogen: 35 kg with 700 bar* *Travel range with one charge: over 400 km* *consumption: 7-11 kg / 100 km* *three 700 bar carbon-fiber hydrogen tanks* *a 45 kW fuel cell*

Hydrogen Fuel Cell Zero Emission by Stellantis:
PROVISIONAL TECHNICAL DATA

Dimensions:	
Length	
L2 version / L3 version	4959 mm / 5306 mm
Height	
L2 version / L3 version	1965 mm / 1975 mm
Width	2204 mm (with external mirrors)
Wheelbase	3275 mm
Trunk space	
L2 version / L3 version	5.3 m3 / 6.1 m3
Load length	
L2 version / L3 version	2512 mm / 2862 mm
Load width	1628 mm
Load height	1397 mm
Curb Weight	
L2 version / L3 version	1952 kg / 1975 kg
Turning circle	12.4 m
Payload	
L2 version / L3 version	1100 kg / 1100 kg
Towing capacity	1000 kg
Hydrogen storage system:	
Type	3 type IV CGH2 vessels
Operating pressure	70 MPa
Capacity	4.4 kg
Refueling time	3 minutes

Fuel cell stack:	
Type	Proton Exchange Membrane (PEM)
Power	45 kW
Battery system:	
Type	Lithium-ion
Power	90 kW
Energy content	10.5 kWh
Possible charging power	11kW maximum
Charging time (empty --> full)	~ 60 minutes
Electric propulsion system:	
Type	3-phase permanent magnet synchronous motor
Power (Eco Mode)	60 kW
Maximal Power	100 kW
Maximal Torque	260 Nm
Performance:	
Top speed	130 km/h
Acceleration (0-100km/h)	15 seconds
Range (WLTP)	> 400 km (certification pending)
Operating temperature	-20°C / + 45°C

16

HYDROGEN FUEL CELL ZERO EMISSION PRESS KIT STELLANTIS

*Figure 23**. Technical specifications of Stellantis Group FCEV light-duty vehicles' fuel cell utilities [24]***

Agricultural activities

Hydrogen technologies have not been yet introduced to agricultural vehicles, such as tractors and similar vehicles. So far it has been introduced in pilot-testing and prototype levels and is not combined with batteries, but they rely on ICE blended with hydrogen.

For instance, the H_2 Dual Power runs on a combination of hydrogen and diesel, producing much lower CO_2 and NO_X emissions with no loss of torque or power. The H_2 Dual Power is based on the renowned New Holland T5.140 Auto Command™ tractor, a model developed for a whole range of agricultural applications from field, loader and yard work through to high-speed transport. With CVT transmission, the tractor is also a perfect all-rounder in urban areas and public green spaces. The tractor is built in Italy but converted to dual fuel here in the Netherlands. This involves mixing hydrogen into the already highly economical Stage V diesel engine. The hydrogen is stored in 5 cylinders, which are placed above the tractor cab for increased safety without compromising functionality. Each cylinder contains 11.5kg of hydrogen pressurized at 350 bar [26].

*Figure 24. **First hydrogen tractor deployed in Netherlands by H_2 Dual Power**[26].*

Public service duties (i.e. forklifts, ambulance)

Hydrogen technologies have limited usage in public service vehicles, such as light-weight carriers, ambulances or police cars. So far it has been introduced in prototype levels or through national pilot testing programs.

Recently in London, the first hydrogen-powered ambulance is set to take to the road later on 2021, carrying an NPROXX hydrogen storage tank system that is capable of storing up to 8kg of compressed gas at a nominal pressure of 350 bar. The prototype vehicle is currently being built as an example of what the future can hold for high-tech ambulances will be delivered to The London NHS Trust service this autumn by UK hydrogen conversion specialists ULEMCo and partners. NPROXX has worked closely with ULEMCo to assist in the design of the conversion, deriving a design solution that places the hydrogen storage tank in the roof space of the ambulance, which will give a payload of up to 900kg while offering a low-floor chassis for easy patient access. Named ZERRO (short for Zero Emission Rapid Response Operations), the prototype ambulance will be powered by a combination of a 30kW fuel cell, with NPROXX's type IV pressure vessel and a 400V 92kWh battery. The fuel cell will act as a range-extender to charge the battery when needed. This will give the ZERRO an expected average daily range of 200 miles (320 kilometers) and a top speed of 90mph (145kph). [27].

In the same context, Japanese Red Cross Kumamoto Hospital and Toyota Motor Corporation begin demonstration testing of the world's first fuel cell electric mobile clinic. The organizations aim to use this demonstration testing to confirm the effectiveness of a commercial fuel cell electric vehicle in areas of medicine and disaster response, and to achieve carbon neutrality. In consultation with the International Medical Relief Department of Japanese Red Cross Kumamoto Hospital, Toyota has developed the mobile clinic based on its Coaster minibus, with the power source using the Toyota fuel cell system that uses hydrogen, employed by the “Mirai” Fuel Cell Vehicle. On the road, it exhibits superior environmental performance with no CO2 emissions or substances of concern, while offering a low-noise, low-vibration driving experience.

With multiple 100 VAC accessory power outlets supplied not only inside the vehicle but also outside the cabin, the vehicle is able to supply electricity to a variety of electrical products. It is also equipped with an external DC electric power supply system that delivers a high-output, large-capacity supply of power (9 kW max output, approx. 90 kWh supply capacity). Inside, the vehicle combines air conditioning with an exhaust system and HEPA filter to improve infection control for occupants when working [28].

Several hydrogen-fueled ambulances are presented along with their technical specifications in the Table 15 below.

*Table 15. **Indicative list and technical specifications – Hydrogen public service duty vehicles [27] [28]***

	**NPROXX Hydrogen ambulance** *Maximum speed Approx. 100 km/h* *Cruising range Approx. 210 km* *FC stack Quantity 1; Maximum output: 114 kW/155 PS* *3 high pressure hydrogen tanks with each storage @7.2kg*
	**Toyota Mirai alternate Hydrogen ambulance** *Maximum speed Approx. 100 km/h* *Cruising range Approx. 210 km* *FC stack Quantity 1; Maximum output: 114 kW/155 PS* *3 high pressure hydrogen tanks with each storage @7.2kg*

Hydrogen heavy-duty vehicles (HDV) & trucks

A comparison of today's alternative powertrain technologies options for the HD road transportation sector – namely FCH, battery-electric vehicles (BEV), lower-carbon fuels, e-fuels and catenary – shows that FCH heavy-duty trucks offer a zero-emission alternative with high operational flexibility allowing for long-haul operation, while featuring a relatively short refueling time. The comparison considers three indicators for a comprehensive overview of the technology state of the art [21]:

- Technology Readiness Level of each technology measured on a scale from ideation to full commercial utilization;
- Availability of refueling and charging infrastructure;
- Emission reduction potential on a well-to-wheel basis.

FCH HDT prototype trucks are beginning on-road demonstrations, however a market ready vehicle offering, fully proven in an operational environment, is yet to be established in the market. Commercialization is still at an early stage with relatively high vehicle and H_2 supply costs as well as a lack of sufficient HDT refueling infrastructure. Similarly, BEV heavy-duty trucks face constraints regarding battery weight and price, which limits their range and payload for operations as well as charging time requirements and utilization flexibility. However, BEV development benefits from industry experience in the passenger car and light-duty vehicle segments. As a result, battery heavy-duty trucks are already more established in operational environments. Overall, the emission reduction potential of vehicles with alternative powertrains depends on the source of energy or fuel. If the electricity used for vehicle charging or the energy used for H_2 or e-fuel production does not stem from renewable energy, these alternatives cannot be counted towards a full CO_2 reduction. Comparing alternative powertrains is complex and inherent uncertainties should be considered. Technology adoption depends on different requirements in infrastructure, regional differences in regulations and incentives, varying customer preferences as well as the total cost of ownership. Overall, zero-emission powertrains for trucks have yet to reach full commercial readiness. Considering the lack of available truck products in the market, the key challenge remains the development of commercially competitive zero emission heavy-duty trucks [21].

Refuse trucks

Heavy duty vehicles (such as buses and trucks) account for roughly 20% of Europe's road transport CO_2 emissions. The challenges which will be faced in decarbonising heavy duty vehicles are becoming increasingly apparent. There are very few technical solutions to removing either the carbon dioxide or air pollutant emissions from heavy duty vehicles.

Several commentators have noted that hydrogen and fuel cell platforms are one of the very few options that can plausibly offer a zero (or even ultra-low) emission heavy duty vehicle. Refuse trucks are a particularly attractive application for early heavy duty hydrogen fuel cell platforms for many reasons, such as [10]:

- **Captive fleets**: refuse vehicles are likely to operate within a confined area. At this early stage of hydrogen roll-out, such operation is useful because they can provide a steady fuel demand at stations.
- **Large hydrogen consumption**: because of the heavier duty cycles these vehicles operate and the substantial energy used by the compaction equipment, they are expected to result in larger hydrogen demand at the pump.
- **Urban air quality**: a key advantage of fuel cell refuse vehicles over diesel equivalents is that fuel cell options result in zero tailpipe emissions. Air quality is currently an issue of key political, and public health importance in Europe, and so the necessity for zero-emission options for urban vehicles is expected to increase significantly over the coming years.
- **Vehicles are operated by municipalities**: The vehicles also tend to be operated either by municipal authorities, or large subcontractors, who are sensitive to environmental issues and hence prepared to assign a considerable economic value to the zero emissions which are available from a hydrogen refuse vehicle.
- **Vehicles are highly visible**: almost all households in European cities are served by refuse collection vehicles, which are highly polluting and noisy. A demonstration of fuel cell refuse trucks will allow residents to see first-hand the benefits of fuel cell technologies, which in turn will increase their awareness and acceptance of hydrogen mobility.

Garbage trucks on hydrogen are a promising solution to meet this challenge. They are zero emission, largely silent and at the same time they provide the equivalent flexibility of diesel fueled vehicles, as battery vehicles struggle to meet the range requirements. So garbage trucks on hydrogen are meeting the requirements of as well municipalities, waste collection institutions as the local residents [20] [21].

*Table 16. **Refuse trucks types' technical specifications [21]***

Fuel cell garbage trucks	FCH range extender	FCH power-box
Key components	Fuel cell stack and system module, hydrogen tank, battery, electric engine	"Power-box" for loader and compactor (truck power-train typically conventional diesel combustion)
Output	40 kW (extender)	32-68 kW (power box)
Range (full truck)	360 km (45-50kg H_2 tank)	200 km
Fuel	Electricity, hydrogen	Diesel, hydrogen
Consumption	6-9 kg H_2 /100 km	tbc
OEMs & vehicle integrators	E-Trucks Europe, FAUN Kirchhoff, ULEMCo, Navistar, Heliocentrics	
Fuel cell suppliers	Hydrogenics, Symbio Fcell, Nedstack	
Typical customers	Offices of municipal sanitation, city cleaning companies	
Competing technologies	Battery electric, diesel combustion	

There are several EU-funded projects executed in different urban and rural areas, developing hydrogen FCEV garbage trucks. Some of these projects are REVIVE [10], HECTOR[19] and Life 'N Grab Hy [20]. During the REVIVE project, "Waste-to-Wheels" circular economy waste disposal plan is introduced [4][10] and is shown in Figure 25.

One of the largest refuse trucks manufacturers, E-Trucks Europe, has joined these projects as a hydrogen vehicle provider and operator. Technical specifications of two E-Trucks Europe refuse trucks are presented (Table 17) and some indicative photos.

*Table 17**. Indicative list and technical specifications – Hydrogen refuse trucks [27] [28]***

	**E-Trucks Groningen** *Brand: E-Trucks Europe* *G.V.W. 27000kg* *Hydrogen Range extender:* *Hydrogen storage: 20kg* *Fuel Cell power: 30kW* *Motor:* *Power: 188kw (256pk) Nominal* *Type: 3 phase electric motor (PEM)* *Battery Pack:* *Energy capacity: 136kWh* *Powertrain:* *Axle configuration: 6x2* *Transmission: E-Drive*
	**E-Trucks Baetsen Cure** *Max. Gross Vehicle Weight 26 Ton 26 Ton* *Battery capacity 154 kWh 154 kWh* *Range (depending on* *operation mode) 400 km 400 km* *Power Fuelcell 40 kW 40 kW* *Power electric motor 150 kW – 210 hp 150 kW – 210hp* *Torque 2000 Nm 2000 Nm* *Hydrogen tank content 30 kgs 20 kgs* *Chassis DAF CF 6x2 DAF CF 6x2* *Compactor Haller-Zöller Translift* *Type of pick-up system Backloader Sideloader*

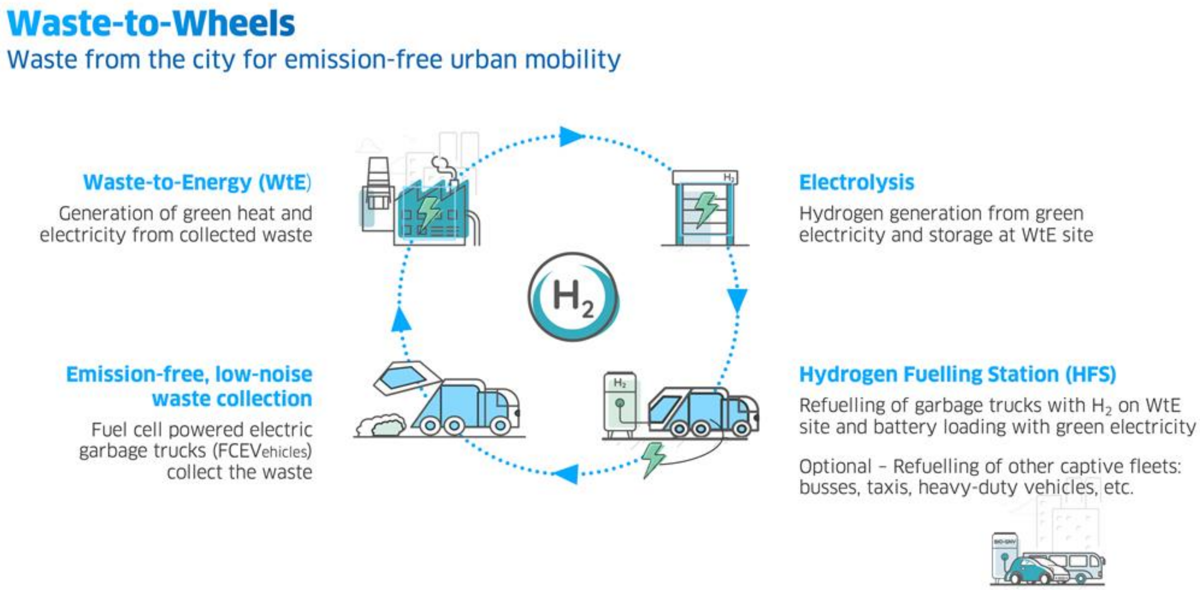


Figure 25. Waste-to-Wheel framework diagram [4]

Since today, hydrogen trucks are considered an expensive solution compared to the diesel-side garbage loaders according to the latest FCH JU's study [21]. More specifically, although fuel costs and consumption is significantly lower, FCEV truck purchase cost and HRS operational costs increase the overall expenditures; and thus, funding support is required from alternative sources in order to make this option more persuasive to cities to invest on.

Table 18. Refuse trucks types' technical specifications [21]

	FCH side-loader	Diesel side-loader
Technical specifications	Full FCH vehicle Weight: ~24 t Lifetime: 12 years Availability: 85%	Full diesel vehicle Weight: ~20 t Lifetime: 12 years Availability: 95%
CAPEX		
> Purchase price	~ EUR 400-450k	~ EUR 200-220k
> Initial HRS	~ EUR 2.4 m	-
Fuel		
> Fuel type	Hydrogen (350 bar)	Diesel
> Consumption (/km)	~0.120-130 kg	0.6 litre
> Consumption (/day)	~20-25 kg	110 litre
Maintenance costs		
> Trucks	0.40-0.50 EUR/km	0.5 EUR/km
> Ref. station p.a.	EUR 70-75k	EUR 10,350
Labour costs p.a.	EUR 64,000	EUR 64,000

Commercial/Cargo trucks

Fuel cell technology is particularly well-suited to commercial shipping and logistics due to long ranges and short refueling times. The dual-mounted fuel cell system provides enough energy to drive the heavy-duty trucks up and down the mountainous terrain in the region [22]. A typical scheme showing how hydrogen FCEV trucks operate is shown in Figure 26 below.

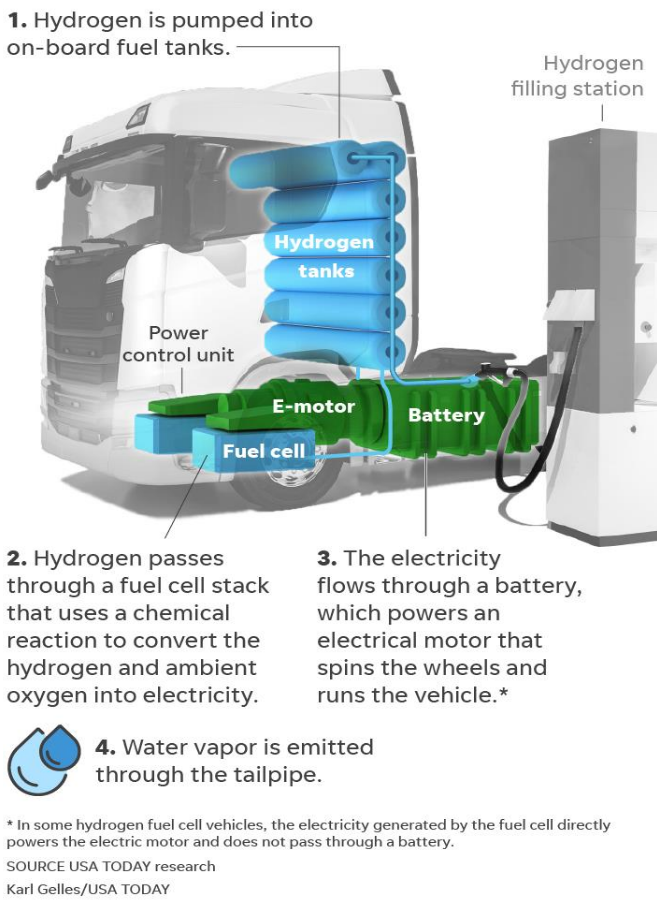


Figure 26. Hydrogen truck fuel cells indicative structure [3]

Many truck manufacturers, such as DAF, target to switch to zero-emission trucks by 2050. Together with Toyota and Shell, DAF's parent company PACCAR has started extensive trials with hydrogen-powered trucks with sophisticated fuel cell technology in the port of Los Angeles. Using hydrogen as a fuel means that in many areas use can be made of an existing distribution network: from green electric power generation to the location where it is needed. In addition, one should not forget that we in Europe have extensive knowledge and a comprehensive manufacturing footprint in combustion engine technology. The European truck industry has commonly expressed the aim to refrain from using fossil fuels for their commercial vehicles as from 2040. Despite, thanks to for instance hydrogen technology, the internal combustion engine still offers huge potential for the further future, especially in the heavy duty long haul transport segment [23].

In a similar context, Hyundai Motor Company today shipped the first 10 units of the Hyundai XCIENT Fuel Cell, the world's first mass-produced fuel cell heavy-duty truck, to Switzerland. The company plans to ship a total of 50 XCIENT Fuel Cells to Switzerland this year, with handover to commercial fleet customers starting in September. Hyundai plans to roll out a total of 1,600 XCIENT Fuel Cell trucks by 2025, reflecting the company's environmental commitment and technological prowess as it works toward reducing carbon emissions through zero-emission solutions [22].

Figure 27. Hyundai XCIENT Fuel Cell truck [22]

Table 19.Hyundai XCIENT Fuel Cell trucks technical specifications [22]

XCIENT Fuel Cell Specifications

Chassis	
Vehicle Type	Cargo (Chassis Cab)
Cab Type	Day Cab
Drive System	LHD / 4X2
Dimensions [mm]	
Wheel Base	5,130
Overall (Chassis Cab)	
Length	9,745
Width	2,515 (2,550 with side protector) Maximum allowable width 2,600
Height	3,730
Weight [kg]	
Max. Gross Combination Weight	36,000 as pull-cargo
Max. Gross Vehicle Weight	19,000 as rigid truck
Front / Rear	8,000 / 11,500
Empty Vehicle Weight (Chassis Cab)	9,795
Calculated Performance	
Drive Range	Accurate range to be confirmed later
Max. Speed	85km/h

Powertrain	
Fuel Cell Stack	190 kW (95 kW x 2 EA)
Battery	661 V / 73.2 kWh – by Akasol
Motor / Inverter	350 kW / 3,400 Nm – by Siemens
Transmission	ATM S4500 – by Allison / 6 forward speeds and 1 reverse speed
Rear Axle ratio	4.875
Hydrogen Tank	
Filling Pressure	350 bar
Capacity	32.09 kg H2 (available hydrogen amount at SOF 100%)
Brake	
Service Brake	Disc
Auxiliary Brake	Retarder (4-Speed)
Suspension	
Type (Front / Rear)	Air (2-bag) / Air (4-bag)
Tires (Front / Rear)	315/70R22.5 / 315/70R22.5
Safety	
Front Collision-avoidance Assist (FCA)	Standard
Smart Cruise Control (SCC)	Standard
Electronic Braking System (EBS) + Vehicle Dynamic Control (VDC)	Standard (ABS is included in VDC)
Lane Departure Warning (LDW)	Standard
Air Bag	Option

Best practices in hydrogen mobility

In total, four (4) scenarios will be presented in this report. Scenarios are presented from a city-centered point of view although several cities have participated in several hydrogen-related projects. These scenarios are:

(a) Case A – Bolzano city & South Tyrol region in Northern Italy
(b) Case B – Pau city in Southwestern France
(c) Case C – Groningen city in Northern Netherlands
(d) Case D – Arnhem city & Gelderland region in Central Netherlands

Each scenario-city is presented separately in the following chapters.

Case A – Bolzano city, Italy

Bolzano area presentation

Bolzano is the capital city of the “South Tyrol” province in northern Italy. With a population of 108,245 inhabitants, Bolzano is also the largest city in South Tyrol and the third largest in historical Tyrol. South Tyrol province covers an area of 7,400 square kilometers and has a total population of 531,178 inhabitants as of 2019[40]. The greater metropolitan area of Bolzano has about 250,000 inhabitants and is one of the urban centers within the Alps. In the 2020 version of the annual ranking of quality of life in Italian cities, Bolzano was ranked joint first for quality of life alongside Bologna [39]. The area of the city of Bolzano is 52.3 km^2, of which 28 km^2 is used as a settlement area. The city is located in the basin where the Sarntal, Eisacktal, and the Adige Valley with their rivers (Talfer, Eisack, and Adige) meet.

The climate of the area differs depending on the altitude as the city is being located at multiple climate borders, Bolzano is characterized by hot summers (reaching up to maximum 40°C) and very cold winters (the absolute minimum temperature reaches -18.5°C) by Italian standards.

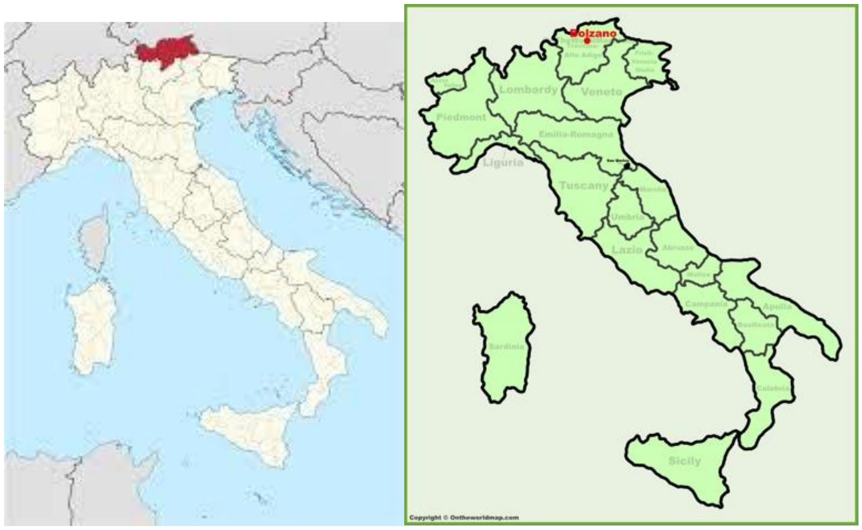


Figure 28. South Tyrol province & Bolzano city location

The region is, together with northern and eastern Tyrol, an important transit point between southern Germany and Northern Italy. Freights by road and rail pass through here. One of the most important highways is the A22, also called the Autostrada del Brennero. It connects to the Brenner Autobahn in Austria. Public transportation is coordinated by the South **Tyrolean Transport Association,** which unites urban and intercity lines, city buses, regional trains and the Trenitalia Italian Railway (between Innsbruck and Trento) as well as the trains of the South Tyrolean Railway. Moreover, Bolzano offers for touristic activities and towards the local community car sharing opportunities. In recent years, the car-sharing fleet in South Tyrol has been enhanced with electric or hydrogen-fuel based vehicles.

Objectives on hydrogen exploitation & mobility

Bolzano is considered one of the most important hydrogen valleys (hydrogen applications in energy production, mobility, etc.). The selection of hydrogen mobility applications in the South Tyrol's region was made in order to reach the following regional/national objectives [35] [36] [38]:

1. Decarbonization of South Tyrol region's light and heavy commercial mobility (public transport & public-use vehicles) according to national and European energy and green transport goals.

2. Introduction of new green mobility technologies to regional society by creating more environmental and societal benefits; ensuring higher life quality in the city and improved comfort of public transport providing boost to the regional economy.

3. Provide clear evidence that viable zero emissions solutions will exist for all vehicle types in the medium term.

4. Bolzano city's long-term strategy focuses on the conversion of a large part of SASA bus fleet to sustainable vehicles, i.e. battery and hydrogen buses, by 2030.

5. Create a sustainability regional mobility scheme with greater efficiency and safety for our staff and citizens.

6. aims at developing zero emission services which will benefit the local population and touristic activities in the area.

7. Establish and enhance hydrogen production and refueling infrastructure and facilitate the production of locally and regionally available sustainable transport energy for urban public transport.

8. create a Brenner Green Corridor that connects southern and northern Europe in a sustainable way and based on three fundamental pillars: transfer to rail, digitalization and low-emission vehicles.

Detailed description of the best practice

Bolzano is considered a major freight and transportation corridor due to one of the most important highways crossing the region (A22 highway), also called the Autostrada del Brennero. The impact on economic and societal scale of these activities is significant and preserves the competitiveness of this region in the mobility sector. However, these activities could have major negative environmental impacts in the near future.

These impacts along with the European green mobility initiatives forced Bolzano city authorities to alter their energy and mobility schemes. In order to address that, Bolzano city authorities, IIT - Institut für Innovative Technologien Bozen and South Tyrol region targeted in the creation of a green, zero emission competitive urban, public and freight transportation strategy and to connect the region with the main Italian and European economic areas along the Brenner Corridor [42].

In addition to that, as the demographic and labor force in Bolzano city was decreasing, regional transportation stakeholders (IIT, SASA, Municipality of Bolzano, etc.) decided to use "zero-emission mobility" as a tool to efficiently increase the green activities in freight and touristic sector. Due to unknown benchmarks for the new hydrogen technology applications, Bolzano city started as a pilot city (Phase 1) for adapting hydrogen mobility vehicles and refueling stations (HRS) with their participation in the EU-funded CHIC project [43]. With the eagerness of local authorities to step forward and the highly experienced team of researchers in IIT preparing large scale demonstration projects in the renewable energy sector, an initial trust and minimum funding from the local funding administration was achieved.

This led to the current involvement of Bolzano and Merano cities along with the South Tyrol region to participate in four major EU-funded projects (CHIC, JIVE, MEHRLIN & REVIVE [41],[43],[44]), which were funded from three different EU sources: FCH JU (Horizon 2020), Connecting Europe Facility (CEF) and LIFE-Program. In parallel, a major test, that took a lot of time and resources, was to obtain co-funding at the national/regional level after receiving the commitment for European funding. Although having that commitment substantially eases the search for local co-funding. In total **"Hydrogen Valley South Tyrol" initiatives** will invest approximately €55 million. A short description of each project is presented in the table (Table 20) and involved stakeholders (Table 21) are shown below:

Table 20. EU Hydrogen projects constituting the "Hydrogen Valley South Tyrol" framework

Project Title	**Small description**	**Project duration**	**Outcome of the project in the Bolzano regional area**	**Total funding amount of the project**
CHIC	The Clean Hydrogen in European Cities project (CHIC) was a flagship zero emission bus project that deployed a fleet of fuel cell electric buses and hydrogen refueling stations in cities across Europe and at one site in Canada. The project successfully demonstrated that fuel cell buses can offer a functional solution for cities to decarbonize their public transport fleets, improve their air quality and lower their noise levels. The buses can operate with the same flexibility as a diesel bus without compromising the productivity of public transport.	April 2010 – December 2017	5 FCEV EvoBus Mercedes-Benz buses & 1 Hydrogen Refueling Station with on-site Water electrolysis with ALK electrolyser with daily production capacity of 390 kg/day	the total project budget was €81.8 million, of which €25.88 million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
JIVE	The JIVE (Joint Initiative for Hydrogen Vehicles across Europe) project seeks to deploy 139 new zero emission fuel cell buses and associated refueling infrastructure across five countries.	January 2017 – December 2022	● 12 FCEV Solaris Urbino 12 buses/coaches & exploitation of the existing (1) Hydrogen Refueling Station to capacity of 500 kg/day ● Foster joint procurement	the total project budget was €102.5 million, of which €32

			processes, encourage manufacturers to develop and refine their fuel cell bus offers	million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
MEHRLIN	The MEHRLIN project will deploy seven hydrogen refueling stations serving bus fleets in cities across Europe, in the UK, the Netherlands, Italy and Germany.	July 2017 – December 2020	● create an additional (1) Hydrogen Refueling Station with on-site Water electrolysis with PEM electrolyser with daily production capacity of 370 kg/day ● add extra dispenser for hydrogen fuel-cars (700 bar)	co-funded by the European Commission's Connecting Europe Facility (€5.5M)
REVIVE	REVIVE will significantly advance the state of development of fuel cell refuse trucks, by integrating fuel cell powertrains into 15 vehicles and deploying them across 8 sites in Europe. REVIVE's overall objective is to be the largest demonstration of fuel cell-range extender trucks to date, one of very few options for the decarbonization of heavy duty vehicles. For urban trucks, there is an increasing need for zero emission solutions to comply with upcoming access restrictions imposed by cities as part of pollution reduction strategies.	January 2018 – June 2024	Bolzano and Merano will deploy one hydrogen DAF garbage truck. It will operate on waste collection routes in the municipalities of Bolzano and Merano (residual waste collection and cardboard collection). It will refuel at a HRS in Bolzano.	the total project budget was €9 million, of which €5 million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

Table 21. Stakeholders' list involved in Bolzano's hydrogen mobility initiatives

LEAD DEVELOPER IIT - Institut für Innovative Technologien Bozen

PROJECT PARTNERS IIT - Institut für Innovative Technologien Bozen, Autostrada del Brennero SpA, Alperia AG, SASA AG, Südtiroler Transportstrukturen AG, Vinschger Energiekonsortium, Stadtwerke Bruneck, EURAC, Neogy GmbH, Stadtwerke Meran, SEAB AG
MAIN POLITICAL SPONSORS Autonomous Province of South Tyrol, Euregio, MISE Ministry of Economic Development
SYSTEM INTEGRATORS (VEHICLES, FUEL CELLS) E-Trucks Europe/Renova, Proton Motor Fuel Cell, PowerCell, EvoBus GmbH, Air Liquide Hydrogen Energy, SHELL Downstream Service International BV, hySOLUTIONS GmbH

SOCIETA' AUTOBUS SERVIZI D'AREA SPA (SASA) [71] **South Tyrol's public bus & inter-city coaches' operator**, currently has **300 buses, including diesel and hybrid buses, as well as 5 battery electric buses (e-buses) and 17 hydrogen buses**. Moreover, 8 e-buses are expected to be commissioned by 2022 in order to achieve its ambitious goal; by 2030, the entire fleet must be modernized and a large part will be converted to zero-emission buses.

In line with the EU "Clean Hydrogen in European Cities" CHIC project, five EvoBus Mercedes-Benz Fuell-CELL hydrogen buses have been operating on the SASA scheduled service since the end of 2013. As part of this EU project, 56 hydrogen buses were tested in Oslo, London, Aargau, Milan and Bolzano. In 2021 the SASA bus fleet was supplemented by another 12 hydrogen buses. The purchase of the buses took place within the EU JIVE project. Building on the experience gained from the CHIC project, JIVE (Joint Initiative for Hydrogen Vehicles across Europe) is the first fuel cell bus marketing project in Europe. 142 FC buses will be distributed in nine European cities with the aim of replacing traditional fossil fuel buses with zero emission buses. Fleets of 10-30 buses will be distributed in the cities of Dundee, Birmingham, London, Bolzano, Slagelse, Riga, Wuppertal, Cologne and Rhein-Main. Specifications and pictures of the EvoBus and Solaris fuel cell (FCEV) buses are shown below.

Table 22. EvoBus Mercedes-Benz Technical characteristics

quantity of hydrogen	35 kg with 350 bar
Travel range with one charge	up to 250 km
consumption	9-12 kg / 100 km

maximum power to the drive wheels	2 x 120 kW
maximum torque to the drive wheels	2 x 10,500 Nm
Km traveled	More than 300,000 / bus (data updated to December 2020)

Figure 29. FCEV bus in Bolzano city

Table 23. Solaris Urbino 12 buses/coaches Technical characteristics

quantity of hydrogen	37 kg with 350 bar
Travel range with one charge	up to 350 km
consumption	7-11 kg / 100 km
maximum power to the drive wheels	2 x 110 kW
maximum torque to the drive wheels	2 x 10,500 Nm
Km traveled	More than 300,000 / bus (data updated to December 2020)

At the moment buses only run in Bolzano; SASA Bolzano has inaugurated its batch of 12 new Solaris Urbino hydrogen, that will be powered thanks to a hydrogen filling station installed within the public transport company's depot. Hydrogen will be supplied by IIT as an associate partner of the project [37].

The Autonomous Province of Bolzano, which together with the EU has contributed **10.2 million euros** to the financing of the new buses, is thus continuing to invest in the decarbonization of transportation. The Province of Bolzano has also decided to co-finance, as part of the MEHRLIN project, the construction of a hydrogen filling station directly at the SASA bus depot in Bolzano [38]. Specifications and picture regarding the hydrogen refueling station (HRS) deployed outside Bolzano city is shown below.

Figure 30. Bolzano's Hydrogen Refueling Station (HRS)

Table 24. Bolzano HRS key characteristics

Key information	**Details**
HRS Supply type	• on-site Water electrolysis with PEM electrolyser with daily production capacity of 370 kg/day • on-site Water electrolysis with ALK electrolyser with daily production capacity of 500 kg/day
Power supply	Offsite Renewables (hydropower, wind & solar)
HRS Availability during operation time	99%
H_2 Refueling capacity (kg H_2/day)	350 & 420 kg H_2/day respectively
High SOC Refueling time	<10 min
HRS Available dispensers	• 350bar for bus/coaches • 700bar for cars

As the implementation of JIVE and MEHRLIN projects continued and the installation of HRSs took place, Bolzano city also decided to decarbonize several vehicles used for the city's waste collection and light-duty services. This led to the involvement of Bolzano city in the EU-funded REVIVE project and more specifically the deployment of one hydrogen DAF garbage truck. It will operate on waste collection routes in the municipalities of Bolzano and Merano (residual waste collection and cardboard collection) and It will refuel at a HRS in Bolzano. Plus, Seab Bolzano and Stadtwerke Meran as the managers of environmental services in the municipalities of Bolzano and Merano, including the selective collection of waste proceeded to the purchase of a total of 120 SEAB vehicles used to carry out urban hygiene services circulate in the territory of Bolzano and Laives. To these are added 25 vehicles for the management of the aqueduct, sewage and gas networks, 25 and 38 light service vehicles [36][41].

Figure 31. FCEV waste collector truck in Bolzano & Merano cities

Key outcomes of best practice

Currently, Bolzano is still actively participating in several EU-funded projects (JIVE, REVIVE) for which key results have not been published yet. In parallel, the **"Hydrogen Valley South Tyrol" initiative** is considering a highly important and huge investment in the area and as it will be completed during 2025, the results presented below highlight published data and information gathered during the implementation of CHIC & MEHRLIN EU-funded projects. Although, going step-by-step from a local demonstration project to a regional Hydrogen Valley with European funding is a promising path for future projects as well. It pays off to break down your project/Valley into stages or phases – and proceed from one to another learning-by-doing-mode.

Furthermore, the results presented in each scenario- best practice highlight important key performance indicators (KPIs) which are set by the EU-funded projects' stakeholders enhanced with the regional objectives of each area (presented in subchapter above). These KPIs highlight significant, environmental, financial and technological measures resulted by these initiatives.

For **Bolzano city & South Tyrol region**, CHIC & MEHRLIN projects provided important information on the installation costs (CAPEX) and operational/maintenance costs (OPEX) of both HRS facilities established and FCEV buses deployed. More specifically, these projects shown that the maximum FCEV bus purchase price is approximately €650 thousand euros [45] and the maximum waste truck purchase price is approximately €1-1,1 million euros respectively [46]. This shows the high CAPEX costs of these vehicles, which are still significantly higher than the relevant ICE (diesel) ones. At the same time, operational costs should be less than 10€/kg H_2 in order to remain a competitive fuel against oil-byproducts. Again, in this case OPEX costs were between 12-28€/kg H_2 as reported in the CHIC project [17]; and thus did not meet targets of 5-10€/kg due to the low utilization of the units for on-site generation.

Additional important KPIs are shown in following table (Table *25*):

Table 25. KPI outcomes table from CHIC project

Key information	**Details**
HRS Availability during operation time	99%
H_2 Refueling capacity (kg H_2/day)	350 & 420 kg H_2/day respectively
OPEX cost (€/kg H_2)	12-28€/kg
Replacement of Diesel Fuel	239,672 liters
Dispensing speed	2.8 kg H_2/min
High SOC Refueling time	<10 min
HRS Available dispensers	● 350bar for bus/coaches ● 700bar for cars
FC lifetime per bus [h]	6,186
FC bus availability during operation time	89%

Average Fuel consumption [kg/100 km]	8.7
Project total hours of operation [thousands h]	33.5

Case B – Pau city, Italy

Pau area presentation

Pau is a prefecture of the department of Pyrénées-Atlantiques, region of Nouvelle-Aquitaine, France. Pau lies on the Gave de Pau, and is located 100 kilometers from the Atlantic Ocean and 50 kilometers from Spain. The city, located at an average altitude of 200 meters, is crossed by the Gave de Pau, where a ford gave passage to the Pyrenees. With a population of 76,275 inhabitants (recorded in January 2018), Pau is also the largest city in the Pyrénées-Atlantiques department and covers an area of 31.51 square kilometers. Pau is the most populous city of the Department of Pyrénées-Atlantiques, and the fourth of the Nouvelle-Aquitaine region after Bordeaux, Limoges and Poitiers.

With the decline of tourism during the 20th century, Pau's economy gradually shifted towards the aviation industry and then to petrochemicals with the discovery of the Lacq gas field in 1951. The Université de Pau et des Pays de l'Adour, founded in 1972, accounts for a large student population.

Pau features wet mild winters, with warm, mild summers that are drier. Its geographical location, not far from the Pyrenees, gives the city a contrasting, warm oceanic climate. Temperatures colder than −10 °C are rare and during summertime the maximum temperatures are between 20 to 30 °C. Furthermore, the city of Pau is characterized by its frequent rainfalls (average rainfall is 1,100 millimeters per year) and lack of wind [47].

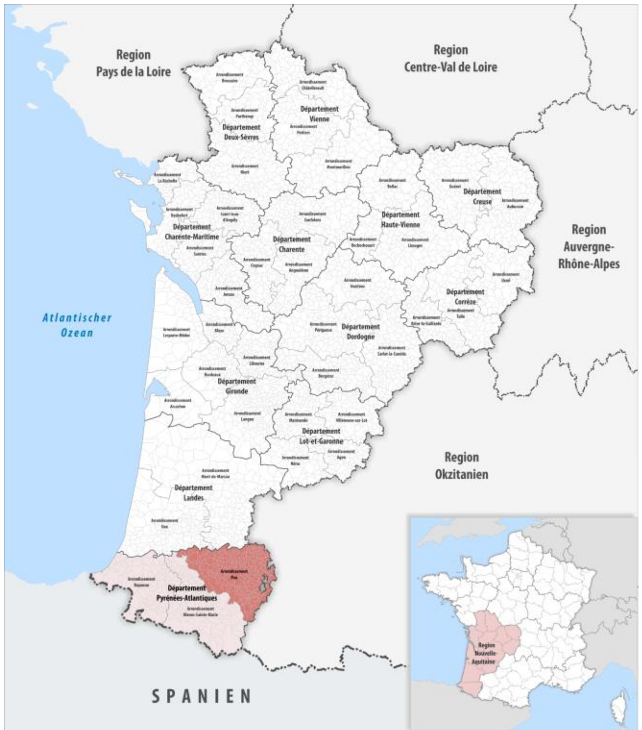


Figure 32. Pau city location

The Société des Transports de agglomération Paloise (STAP) or **IDELIS bus network as Pau's public bus operator**, currently has 23 regular lines, 60 school lines with 106 regular bus fleet, more specifically:

- 97 standard (12m &18m length) with 8 buses (18m length) being FCEV manufactured by VanHool,
- 5 electric minibus,
- 4 minibus for disabled.
- 8,5 M travelers/year
- 323 employees including 246 drivers

Objectives on hydrogen exploitation & mobility

Pau is considered one of the hydrogen pioneering cities in the Southwestern EU region (hydrogen applications in energy urban mobility). The selection of hydrogen mobility applications in the city is an outcome of **Pau 2030 urban initiative** region in order to reach the following regional/national objectives [48] [49]:

- Capitalize Pau 2030's urban project; through six major sectors, the city of tomorrow will be built, respectful of environmental and social issues.
- creating a sustainable mobility scheme for city's urban transport providing a frequent, autonomous, flexible and large capacity urban transport network.
- Facilitate day-to-day travel (by creating an efficient and reliable public transit network)
- Preserve the environment (thanks to air pollution reduction and limitation of greenhouse gas emissions).
- Enhance sustainable urban development and economic growth
- Anticipate/apply french regulation (« loi de transition énergétique »)
- Demonstrate technical feasibility and financially sustainability of an innovative mobility solution

Detailed description of the best practice

The choice to produce hydrogen on-site via electrolysis is part of the sustainable development policy of the Pau Béarn Pyrénées urban area. Hydrogen, recognized as a strategic vector of the energy transition, will contribute to the development of renewable energies in the territory. Europe has been supporting major funding programs for this technology for ten years. In 2014, it ratified an "alternative fuels" directive, requiring member states to deploy hydrogen charging infrastructure.

In France, the Energy Transition Law includes a section dedicated to public transport and categorizes low-emission vehicles by mentioning "electric vehicles powered by a hydrogen fuel cell" by decree of January 15, 2017. The Pau Béarn Pyrénées collaboration is developing a genuine Energy-Climate policy. It was recognized as a "Positive Energy Territory for Green Growth" by the Ministry of the Environment in 2015, and it decided to set up a Territory Air Energy Climate Plan. The Agglomeration's new strategy is structured in particular around the reduction of greenhouse gases, through the production of new and renewable energies and the development of an intermunicipal Local Urban Plan. As part of the National Call for Project "Hydrogen Territories", Pau Béarn Pyrénées Mobilités (the Joint Union of Urban Transport), in partnership with the company Teréga and the University of Pau and Pays de l'Adour, has developed a project entitled "Integrated electromobility: hydrogen as a vector for the development of clean mobility and the integration of energy networks". This project was labeled by the government in October 2016.

Pau involved stakeholders have chosen hydrogen as the preferred urban mobility option as it has been widely used for decades in industry and its use is very well mastered by the in-depth knowledge of its properties and its risks. The prospects for application in the field of transport benefit from this long experience feedback. All the precautionary principles are implemented and framed by strict regulations. Fébus, High Level Hydrogen Service Bus, is a program supported by regional and European funding which reinforces the relevance of this choice [51] [48]. A list of involved stakeholders for the execution of FEBUS project and Pau 2030 initiative is shown below (Table 26).

Table 26. Stakeholders' list involved in Pauo's hydrogen mobility initiatives

LEAD DEVELOPER Pau Béarn Pyrenees Mobilities
PROJECT PARTNERS Pau Béarn Pyrenees Mobilities, European programs FCH-JU (through JIVE2 & 3Emotion EU-funded projects), New Aquitaine Region equity, Department of Pyrénées Atlantiques.
MAIN POLITICAL SPONSORS French Transport Infrastructure Financing Agency (AFITF), Pau Béarn Pyrénées Agglomeration Community, City of Pau, European Regional Development Funds (ERDF).
SYSTEM INTEGRATORS (VEHICLES, FUEL CELLS) **Keolis** is providing technical assistance for the operation of the eight Fébus hydrogen BRTs. **The ENGIE consortium** (station operation), the **Van Hool companies** (vehicles), **ITM Power** (green hydrogen production unit) were selected following a public consultation launched in 2016 for the acquisition of rolling stock and its energy supply. **ENGIE , via its subsidiary GNVERT**, has been distributing and marketing Natural Gas for Vehicles since 1998. It thus offers clean mobility solutions to companies and local authorities wishing to reduce their environmental impact. It is the market leader of most alternative fuels. **Van Hool** is an independent Belgian manufacturer of buses, coaches and industrial vehicles. For 70 years, Van Hool has been renowned for designing and building bespoke high-tech products. It is the European leader in hydrogen fuel cell buses and has marketed around fifty hydrogen-powered vehicles: 32 in Europe and 21 in North America. Van Hool has introduced just over 200 High Service Level Bus vehicles in 13 European countries and Martinique. **ITM POWER** designs, manufactures and markets hydrogen production systems by electrolysis. Created in June 2001, the company is the first in the field of hydrogen and fuel cells to be listed on the London Stock Exchange (AIM) in 2004. ITM Power relies on its proprietary PEM electrolyser technology to offer integrated, turnkey solutions for hydrogen mobility, energy storage (Power to Gas), renewable heat production and industrial processes.

The **Fébus (FEBUS) project** represents an investment of 74.5 million euros: 50 million euros for the works, 10 million euros for the buses, 4.5 million euros for the hydrogen station. This is one of the largest investments in the department and allows several hundred jobs to be occupied. This project is mainly financed by Versement Transport, a tax paid by employers with more than 10 employees, which must be allocated to the public service of urban transport. Thus Fébus weighs nothing on Pau households while 50 million euros are invested in the living environment. [52]

In more detail, the implementation steps for FEBUS project and its corresponding timeline were:

- 2015 – market survey

- Oct 2016- July 2017 = tender procedure
- July 2017 – August 2019 = Design and Production both HRS & FCB
- August – November 2019 = Commissioning, testing, training
- November 2019 – ongoing = beginning of commercial operation

Some specifications about the FEBUS project is the creation of a brand new bus route with 14 bus stops (commercial length of 6 km with a 5,1 km dedicated bus lane). Each bus route operates in a 7-10 minutes' frequency and the total travel time of the bus line is 17 minutes. This bus route operates from 5:30 am to midnight.

A long-standing partner of Pau transport operator SPL STAP (Société de Transport de l'Agglomération Paloise), in charge of operating Pau Béarn Pyrénées Mobilités' city public transport network for 20 years, Keolis has worked on the launch of the 100% hydrogen BRT service called Fébus, that runs in the centre of Pau. This launch represents the culmination of the overhaul of the city transport network IDELIS, aimed at modernizing and developing the transport offer to increase the region's appeal.

Accessible to people with reduced mobility, these 18 meter vehicles have a 145-person capacity and include 32 leather-covered seats and large bay windows that provide passengers with plenty of light. The line's 14 stations are equipped with complete real-time passenger information, free Wi-Fi connection, automatic ticket vending machines and video protection cameras. Specifications and pictures of the Van Hool Exqui.City fuel cell (FCEV) buses are shown below.

Table 27. Van Hool Exqui.City FC Technical characteristics

bus length	*18m*
Electric motor power	*200 kW*
Fuel autonomy (fully charged)	*240km/day autonomy*
Hydrogen consumption	*10-12kg H_2/100km*
capacity	*145 passengers*
Diesel equivalent saved	*31,000 liters of diesel saved (per year/per bus)*

Figure 33. FCEV bus in Pau city

The 8 Van Hool Exqui.City FCEV trambuses are powered Ballard FCveloCity-HD 100-kW fuel cell modules. The vehicles use fuel cells for primary power and lithium batteries for additional power when needed, with the only emission being water vapor.

The hydrogen used to supply energy to the Van Hool buses is produced in the station built near the IDELIS bus depot in Pau. The trambuses are refueled overnight (outside operational hours) in an on-site HRS custom made by ITM Power. Hydrogen is produced by electrolysis of water and the station is powered by solar panels. [50]

At first, one transformer (1600kVA) imports the electricity from the grid (more specifically from renewable energy - solar panels) and one power supply unit allocates the required energy towards the electrolysers (max. output 670kW). Less than 60kWh are used to produce 1kg of green hydrogen.

An on-site Water electrolysis with PEM (Proton Exchange Membrane) technology with **daily production capacity of 174-268 kg/day**. Back-up hydrogen supply is ensured by a CHG tube-trailer. Every kg of H_2 produced requires 20 liters of water.

After hydrogen is produced, it is stored in gas form in tube-trailers with the help of two compressors (compression range 20-600 bar). In detail, storage pressure volumes are 230 kg @20 bar, 630 kg @600 bar; and 330 kg @200 bar in trailer-optional. These tube-trailers can store enough hydrogen for a 3-day refueling demand period. Finally, 8 dispensers (refueling points) are placed in the IDELIS bus depot in Pau and they refuel all buses during the night (non-operating hours). The buses refuel 36kg of Hydrogen per bus per 350bar dispenser. The refueling time is approx. 45 minutes during night for all buses and, if necessary, during operation hours it takes 15 minutes to fully refuel a bus [54].

Figure 34. Pau's Hydrogen Refueling Station (HRS) [53]

Key outcomes of best practice

Currently, Pau is still actively participating in two EU-funded projects (JIVE2, 3Emotion) for which key results have not been published yet. In parallel, the **FEBUS initiative** is completed (2019) and the results presented below highlight published data and information gathered during the implementation of this project.

FEBUS project was launched in one public tender for an "all-inclusive package" (18m articulated buses, energy system if required, maintenance) was published by the Municipality of Pau in close collaboration with the regional stakeholders.

The **Fébus project represents an investment of 74.5 million euros €** (50 M€ for the works; 10 M€ for the buses and 4.5 M€ for the hydrogen station), which makes it one of the largest investments in the Department, and makes it possible to occupy several hundred local jobs. The overall net cost of the project for the Syndicat Mixte Pau Béarn Pyrénées Mobilités is currently estimated at €58,765,520, after deduction of the following €15,734,480 in subsidies and contributions:

1. State: €5,410,000, via the French Transport Infrastructure Financing Agency (AFITF), as part of the second TCSPsuite call for projects at the Grenelle de l'Environnement.
2. Pau Béarn Pyrénées Agglomeration Community: €1,722,000
3. City of Pau: €1,400,000

4. European programs FCH-JU: €4,376,480 distributed as follows:
    - JIVE 2 project: €776,480
    - Project 3 Emotion: €3,600,000
5. ERDF funds: €1,600,000
6. New Aquitaine Region equity: €900,000
7. Department of Pyrénées Atlantiques: €326,000 under the territory contract.

Furthermore, the results presented in each scenario-best practice highlight important key performance indicators (KPIs) which are set by the EU-funded projects' stakeholders enhanced with the regional objectives of each area (presented in subchapter above). These KPIs highlight significant, environmental, financial and technological measures resulted by these initiatives.

For **Pau city**, important information on the installation costs (CAPEX), operational/maintenance costs (OPEX) of both HRS facilities established and FCEV buses deployed; and environmental impacts are highlighted. More specifically:

- One hundred employees were trained in this new rolling stock (50 for driving and 50 for maintenance and control).
- A ticket costs €1, with a one-time fee of €0.20 added to the first purchase to fund responsible disposal of the buses at the end of their working life. Tickets are sold at self-service machines in Fébus stations, in participating shops and on line [53].
- 1,000 litres of water (in the form of vapour) are released by Fébus every day
- 2 tonnes of oxygen are released per day—as much as a 62-ha forest releases in a year [53]
- On-site producing HRSs (Pau, Aalborg) present a stronger contribution of the CAPEX (25-30% of the annualized cost), although the LCOH in the long term is still driven by the OPEX (in this case, especially by electricity price). Producing hydrogen on-site is still not convenient for the analyzed HRS sizes (up to 400 kg/day) since significant scale economies cannot be obtained in terms of electrolyzer cost. [55]
- 174 kg of hydrogen per day are necessary for the circulation in complete autonomy of the six Buses with High Level of Service planned on the axis Station - Hospital of Pau.
- *HRS detailed cost list*:
    - HRS installation costs - CAPEX (k€): 2 million
    - HRS operational costs - OPEX (k€/year): 544
    - Average Levelized cost of fuel/H_2 - LCOH (€/kg): 12.02
    - Average Levelized CAPEX cost per Kg H_2 - $LCOH_{CAPEX}$ (€/kg): 3.46
    - Average Levelized OPEX cost per Kg H_2 - $LCOH_{OPEX}$ (€/kg): 8.56
    - Average CAPEX cost of HRS - $C_{HRS,CAPEX}$ (k€/(kg/day)): 18.97
    - HRS Availability: 98%
    - Dispensing speed: 2.4 kg H_2/min
    - High SOC Refueling time: 15 minutes

Case C – Groningen city, Netherlands

Groningen area presentation

Groningen is the capital city and main municipality of Groningen province in the Netherlands. It is the largest city in the north of the Netherlands. As of December 2020, it had 233,218 inhabitants. It has a land area of 168.93 km^2, and a total area, including water, of 180.21 km^2. Its population density is 1,367 residents per km^2.

Hotel and catering industries constitute a significant part of the economy in Groningen. Focus on business services has increased over time and areas such as IT, life sciences, tourism, energy, and environment have developed.

Groningen has an oceanic temperate climate, like all of the Netherlands, although slightly colder in winter than other major cities in the Netherlands due to its northeasterly position. Weather is influenced by the North Sea to the north-west and its prevailing north-western winds and gales.

Summers are somewhat warm and humid. Temperatures of 30 °C or higher occur sporadically; the average daytime high is around 22 °C. Very rainy periods are common, especially in spring and summer. Average annual precipitation is about 800 mm. Winters are cool; on average above freezing, although frosts are common during spells of easterly winds. Night-time temperatures of −10 °C or lower are not uncommon during cold winter periods [57].

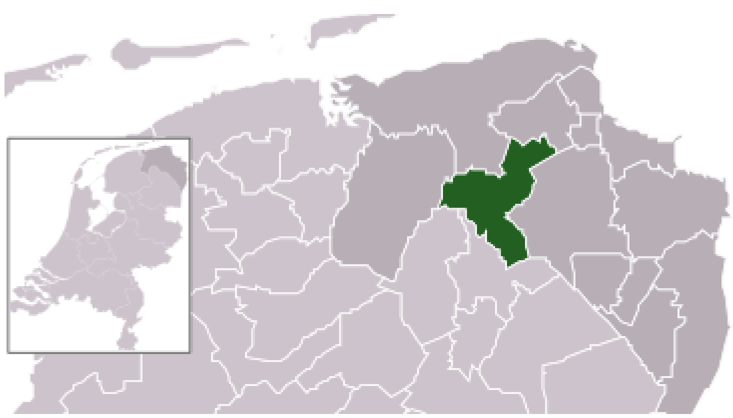


Figure 35. Groningen city location

Objectives on hydrogen exploitation & mobility

Groningen is considered one of the hydrogen pioneering cities in the EU (green hydrogen applications in energy production, mobility, etc.). The selection of hydrogen mobility applications in the city is an outcome of **"HEAVENN - Hydrogen Energy Applications in Valley Environments for Northern Netherlands" initiative** region in order to reach the following regional/national objectives [59] [65]:

- Northern Netherlands to become a green hydrogen economy
- Roadmap Groningen Carbon Neutral 2035
- Zero Emission City Logistics in 2025; City center to be zero-emission by 2025
- Zero Emission public transport in 2020
- Capitalize the Regional hydrogen strategy – The Green Hydrogen Economy + investment plan
- Foster joint procurement processes, encourage manufacturers to develop and refine their fuel cell bus offers
- Create a sustainability regional mobility scheme with greater efficiency and safety for our staff and citizens.
- Establish and enhance hydrogen production and refueling infrastructure and facilitate the production of locally and regionally available sustainable transport energy for urban public transport
- Enhance sustainable urban development and economic growth

Detailed description of the best practice

Groningen, in the North of the Netherlands has large ambitions with setting up a hydrogen economy in the Northern Provinces of the Netherlands. Beside the fact that current gas extraction is scaling down, a move to renewables is getting stronger and they also want to presort on the changing environment and the political ambitions in zero-emission transport (From 2025 onwards, all buses should be zero emission), made them to choose to enter the project, which was already running. This led the city of Groningen to initiate the **"HEAVENN - Hydrogen Energy Applications in Valley Environments for Northern Netherlands"** initiative, creating the necessary framework that will establish North Netherlands as the biggest green hydrogen player in Europe.

This led to the current involvement of Groningen to participate in four major EU-funded projects (JIVE 2, REVIVE, HyTrEc and HECTOR [61],[62],[63],[19]), which were funded from three different EU sources: FCH JU (Horizon 2020), Connecting Europe Facility (CEF) and LIFE-Program. In parallel, a major test, that took a lot of time and resources, was to obtain co-funding at the national/regional level after receiving the commitment for European funding. Although having that commitment substantially eases the search for local co-funding. In total **"HEAVENN - Hydrogen Energy Applications in Valley Environments for Northern**

Netherlands” initiatives will invest approximately €88 million. A short description of each project is presented in the table (Table 28) and involved stakeholders (Table 29) are shown below:

Table 28. EU Hydrogen projects constituting the “HEAVENN - Hydrogen Energy Applications in Valley Environments for Northern Netherlands” framework

Project Title	Small description	Project duration	Outcome of the project in the Bolzano regional area	Total funding amount of the project
High V.LO-City	The High V.LO-City project (https://www.fuelcellbuses.eu/projects/high-vlo-city) accelerated the integration of a new generation of FCH buses (14 FC buses were operated in Scotland (UK), Liguria (IT), Flanders (BE) and Groningen (NL)) in the public transport system and operate them in fleets and in the same time demonstrated the technical and operational quality. It contributed in showing their value in creating a clean and highly attractive public transport service (/system) and facilitated the modular shift that local transport policies were and still are envisioning. During the projects’ lifetime, all 14 buses and 3 planned HRSs (and 1 additional HRS) were delivered and operated in the 4 European regions, operating and fuelling these hydrogen electric hybrid buses in different parts of Europe under deviant geographical-, climate- and operational conditions.	January 2012 – December 2019	● Groningen: by using H_2 taken by a pipeline as a by-product from chlorine production ● 2 FCEV buse provided by QBUZZ	the total project budget was €30.5 million, of which €13.5 million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
JIVE2	The JIVE 2 (Joint Initiative for hydrogen Vehicles across Europe) project seeks to deploy 152 new zero emission fuel cell buses and associated refueling infrastructure across 14 European cities throughout France, Germany, Iceland, Norway,	January 2018 – December 2023	20 hydrogen busses and a HRS station	the total project budget was €102.5 million, of which €32 million was

	Sweden, the Netherlands and the UK. The project consortium comprises 23 partners from nine countries.			co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
HECTOR	The 'Hydrogen Waste Collection Vehicles in North West Europe' demonstration project tests fuel cell garbage trucks in various operational settings. Seven FCH waste collection trucks will be operated in urban and rural areas on fixed and flexible schedules while using existing HRS infrastructure.	January 2019 – December 2023	Groningen will deploy one hydrogen DAF garbage truck. and will refuel at a HRS outside of Groningen.	the total project budget was €9.28 million, of which €5.5 million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
REVIVE	REVIVE will significantly advance the state of development of fuel cell refuse trucks, by integrating fuel cell powertrains into 15 vehicles and deploying them across 8 sites in Europe. REVIVE's overall objective is to be the largest demonstration of fuel cell-range extender trucks to date, one of very few options for the decarbonization of heavy duty vehicles. For urban trucks, there is an increasing need for zero emission solutions to comply with upcoming access restrictions imposed by cities as part of pollution reduction strategies.	January 2018 – June 2024	Groningen will deploy two hydrogen DAF garbage truck. and will refuel at a HRS outside of Groningen.	the total project budget was €9 million, of which €5 million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
HyTrEc2	Partners from the UK, Germany, The Netherlands, Sweden and Norway are working together to support the use of Hydrogen in the transport and	January 2018 – December 2020	6 municipal hydrogen vehicles and a refueling station: ● 2 Hyundai ix35	no data available

	energy sectors in the North Sea Region (NSR). The HyTrEc 2 project brings together eight organisations with an interest or experience in H_2 to collaborate on the development of a strategy and initiatives across the NSR. This will support the further use of Hydrogen Fuel Cell Electric Vehicles (FCEVs) in the NSR.		● Streetscooter ● Kangoo ● Small bus for the city centre. ● Street sweeper	

Table 29. Stakeholders' list involved in Groningen's hydrogen mobility initiatives

LEAD DEVELOPER Municipality of Groningen, New Energy Coalition
PROJECT PARTNERS CEA, Element Energy, Tractebel, WaterstofNet, Suez, ARPGAN, AGR, OV-bureau Groningen-Drenthe, Gasunie, Nouryon, Engie, Emmtec, Groningen Seaports, Nederlandse Aardolie Maatschappij, QBuzz, PitPoint, Energie Beheer Nederland, Lenten Scheepvaart BV, Green Planet, HyEnergy TransStore.
MAIN POLITICAL SPONSORS Municipality Groningen, Municipality Hoogeveen, Municipality Emmen, Province of Groningen, Province of Drenthe, The Netherlands Ministry of Economic Affairs and Climate, The Netherlands Ministry of Infrastructure and Water Management.
SYSTEM INTEGRATORS (VEHICLES, FUEL CELLS) E-trucks Europe / Renova, Proton Motor Fuel Cell, PowerCell, Suez, PowerCell, Proton Motor.

QBuzz is a private bus company, executing public transport operations in the north of the Netherlands. **Qbuzz bus network as Groningen's public bus operator (90% bus lines coverage)**, currently has 350 regular bus fleet, more specifically [58]:

- 97 standard (12m &18m length) with 8 buses (18m length) being FCEV manufactured by VanHool,

- 5 electric minibus,
- 4 minibus for disabled.
- 8,5 M travelers/year
- 323 employees including 246 drivers

QBuzz is operating the buses in suburban routes with a high daily mileage, a high average speed and lower stop frequency. The buses are performing very well and the highly demanding routes are nearing the operation of the Aberdeen buses in HyTransit [56]. Nowadays, Groningen city has acquired 22 FCEV from Van Hool and they expect 10 more buses during the Q4 2021-Q1 2022.

Table 30. Van Hool A330 hybrid FCEV Technical characteristics

Bus type	Class I bus - right-& left hand drive
Passengers capacity	44 (seated)
Top speed:	>80km/h
Hydrogen storage	35-40kgs
Fuel economy	>11km/kg
Range	>350km
Fuel cell life	>12,000 hours under warranty

Figure 36. FCEV bus in Groningen city

In the same context, Groningen city acquired three (3) hydrogen DAF garbage trucks to collect all organic and recyclable waste in the municipality of Groningen and nearby areas. Additionally, 6 municipal hydrogen vehicles were deployed during the execution of the aforementioned EU-funded projects in the city. These vehicles are and will be refueled at a HRS outside of Groningen.

Figure 37. FCEV waste collector truck in Groningen city

Table 31. E-Truck FCEV waste collector truck Technical characteristics

Weight carriage capability	27000kg
Fuel Cell power:	30 kW
Engine power/capacity:	188kw (256pk) Nominal/ 136kWh
Engine type:	3-phase electric motor (PEM)
Hydrogen storage	20kg

In Delfzijl, to the east of Groningen, Akzo-Nobel owns an industrial plant operating a large electrolyser. At this plant, similar to Antwerp the electrolyser also produces high quality fuel cell grade hydrogen. Together with the partner PitPoint it was decided to build an HRS beside the industrial area adjacent to the public road.

Here it was also decided to use a containerised concept of a HRS, where the station was connected to the local hydrogen pipeline, feeding the compressor, storing the hydrogen and fueling the buses. PitPoint, who already had experience with 2 HRSs was able to build the station in a short time and operation followed soon after the permit was granted and commissioning completed. This station was constructed in 2018 and is the smallest of the project, because it only needed to refuel 2 buses. Nevertheless, it also showed a high reliability and an availability of 99% *[56].*

On Friday 11th June 2021, the new hydrogen filling station at the Qbuzz bus depot on Peizerweg in Groningen was taken into use. Twenty new hydrogen buses were also presented. The gas station has two filling points. A bus is refueled in less than ten minutes and can cover about 400 kilometers.The refueling stations are producing hydrogen from solar energy and off-shore wind parks from North Sea with on-site PEM and ALK water electrolysis [60].

In addition, other transport applications are being replaced by zero emission hydrogen technology in the region: fuel cell taxis are being deployed as well as municipal road sweeping vehicles and 10 fuel cell garbage trucks while there are discussions to consider the option of hydrogen trains. They are part of a wider plan from Northern Netherland to turn the region into a hydrogen-based region. Excess renewable electricity will be transformed to hydrogen and stored in hydrogen form and then used by consumer's indifferent applications: by industry, mobility and houses, thus acting as an enabler for a zero emission society [59].

Figure 38. Groningen's Hydrogen Refueling Station (HRS) [56]

Table 32. Groningen HRS key characteristics

Key information	**Details**
HRS Supply type	• on-site Water electrolysis with PEM electrolyser with daily production capacity of 3x370 kg/day • on-site Water electrolysis with ALK electrolyser with daily production capacity of 2x500 kg/day
Power supply	Offsite Renewables (hydropower, wind & solar)
HRS Availability during operation time	99%
H_2 Refueling capacity (kg H_2/day)	3x350 & 2x420 kg H_2/day respectively
High SOC Refueling time	<10 min
HRS Available dispensers	• 350bar for bus/coaches • 700bar for cars

Key outcomes of best practice

Currently, Groningen is still actively participating in several EU-funded projects (JIVE2, REVIVE and HECTOR) for which key results have not been published yet. In parallel, **"HEAVENN - Hydrogen Energy**

Applications in Valley Environments for Northern Netherlands" initiative is considering a highly important and huge investment in the area and as it will be completed during 2026, the results presented below highlight published data and information gathered during the implementation of High V.LO-City & HyTrEc2 EU-funded projects. Although, going step-by-step from a local demonstration project to a regional Hydrogen Valley with European funding is a promising path for future projects as well. It pays off to break down your project/Valley into stages or phases – and proceed from one to another learning-by-doing-mode.

Furthermore, the results presented in each scenario- best practice highlight important key performance indicators (KPIs) which are set by the EU-funded projects' stakeholders enhanced with the regional objectives of each area (presented in subchapter above). These KPIs highlight significant, environmental, financial and technological measures resulted by these initiatives.

For **Groningen city & Northern Netherlands**, High V.LO-City & HyTrEc2 projects provided important information on the installation costs (CAPEX) and operational/maintenance costs (OPEX) of both HRS facilities established and FCEV buses deployed. More specifically, these projects shown that the maximum FCEV bus purchase price is approximately €650 thousand euros [45] and the maximum waste truck purchase price is approximately €1-1,1 million euros respectively [46]. This shows the high CAPEX costs of these vehicles, which are still significantly higher than the relevant ICE (diesel) ones. At the same time, Remotely-supplied HRS construction cost is currently in the 5,300-7,100€/(kg/day) range. CAPEX for HRS with small-scale on-site electrolysis goes up to 13,000- 19,000€/(kg/day capacity; thus, the estimated CAPEX of HRS infrastructure could be between 5-9.5 million €.[17].

Additionally, important KPIs and figures related to technological specifications of the FCEV buses and HRS infrastructure along with environmental footprint findings from High V.LO-City project are shown in the following table (Table *33*) and figures (Figure 39 & Figure 40Figure 39. LCA: Greenhouse gas emissions from well to wheel from High V.LO-City project [56]):

Table 33. KPI outcomes table from HEAVENN initiative

Key information	Details
HRS Availability during operation time	99%
H_2 Refueling capacity (kg H_2/day)	350 & 420 kg H_2/day respectively
High SOC Refueling time	<10 min
HRS Available dispensers	• 350bar for bus/coaches • 700bar for cars

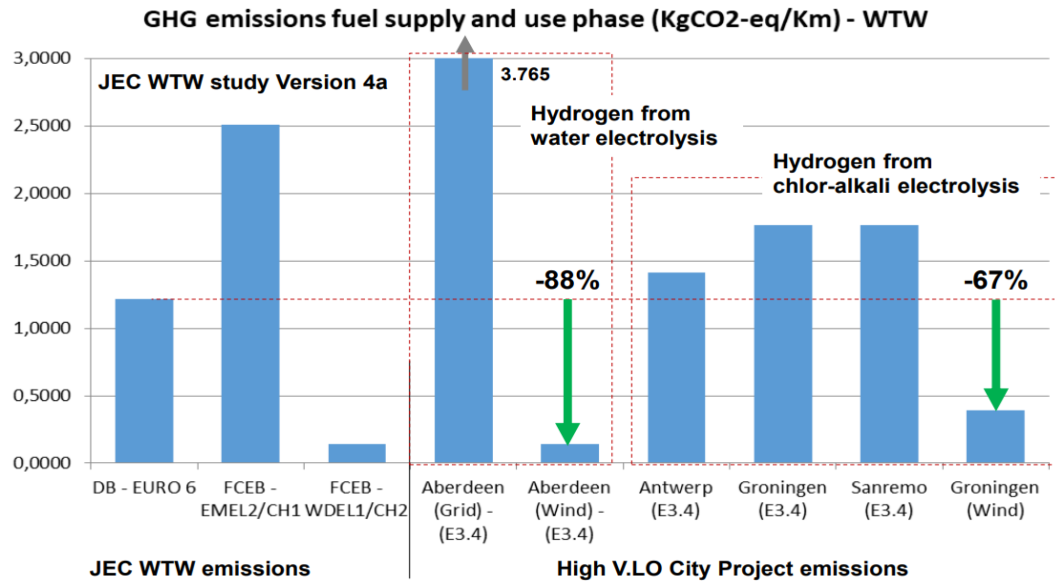


Figure 39. LCA: Greenhouse gas emissions from well to wheel from High V.LO-City project [56]

Table 2: Scenario results LCOH and amount of direct green electricity

Scenarios	LCOH	Green electricity
1: Local solar	16 €/kg H_2	62%
2: Local solar and wind	16 €/kg H_2	72%
3: Only green electricity	19 €/kg H_2	100%
4: High full load hours	14 €/kg H_2	54%

Figure 40. Scenario results LCOH and amount of direct green electricity from HyTrEc2 project [65]

Case D – Gelderland region/Arnhem city, Netherlands

Gelderland area presentation

Gelderland is a province of the Netherlands, occupying the center-east of the country. With a total area of 5,136 km^2 of which 173 km^2 is water, it is the largest province of the Netherlands with a population of 2,084,478 as of November 2019. The capital is Arnhem (population: 159,265); however, Nijmegen (population: 176,731) and Apeldoorn (population: 162,445) are both larger municipalities. Arnhem features the same climate as all of the Netherlands; however, its location on the foothills of the Veluwe, the largest forest in the Netherlands, contributes to some higher precipitation values. Temperatures of 30 °C or higher occur sporadically; the average daytime high is around 22 °C. Very rainy periods are common, especially in spring and summer. Average annual precipitation is about 800 mm. Winters are cool; on average above freezing, although frosts are common during spells of easterly winds. Night-time temperatures of −10 °C or lower are not uncommon during cold winter periods [67].

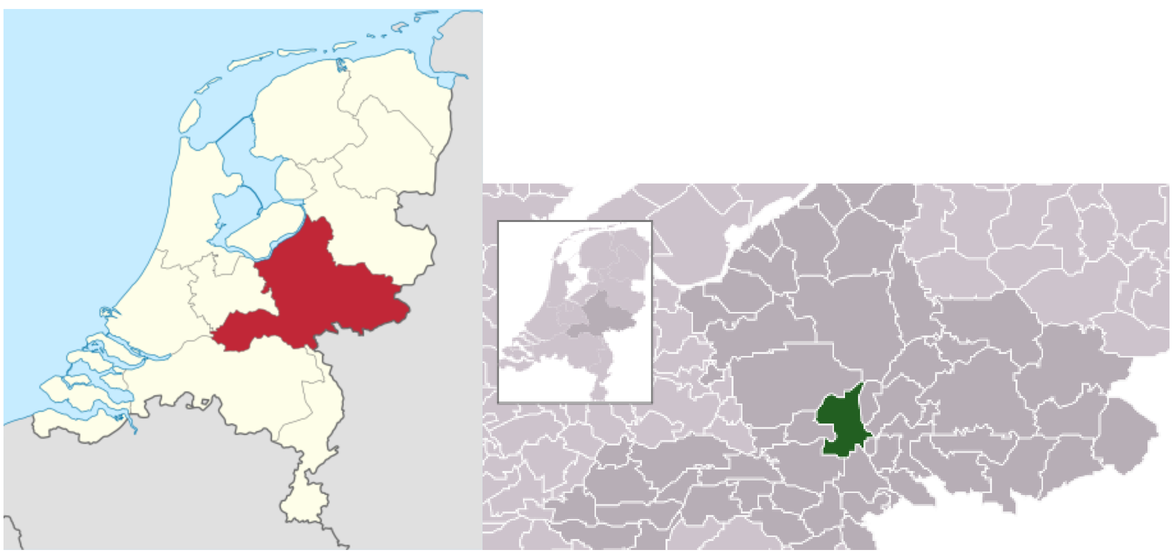


Figure 41. Gelderland area & Arnhem city location

Objectives on hydrogen exploitation & mobility

Gelderland region is considered one of the hydrogen "early-adopters" in the EU (green hydrogen applications in energy production, mobility, etc.). Although other similar regions focused on the creation of hydrogen mobility infrastructure in the long-term scope, **Arnhem city's stakeholders** together with hydrogen specialized corporations ***targeted the promotion and exploitation of hydrogen mobility with***

different business approach (***leasing FCEV buses rather than purchasing them, incentives to citizens for hydrogen vehicle purchase***). This was done in order to reach the following regional/national objectives quicker than others (less than 3-year period; starting from 2018) [62] [63] [68]:

- The creation of awareness about the fact that road transport is an essential part of the overall energy transition and requires the transition to zero emission vehicles.
- The creation of awareness about the characteristics of FCEVs as one of the two zero-emission alternatives to ICE vehicles (BEVs are the other zero-emission alternative).
- The establishment of a basic HRS network coverage to facilitate growing demand as a result of upscaling that originates at the national level.
- The branding of the region as an economic hydrogen region. The region already includes a wide range of highly innovative companies that are active in various segments of the hydrogen market.

Detailed description of the best practice

The regional (province of Gelderland) and local (municipality of Arnhem) public bodies understood that public policy-making and public-private network building are essential parts for the development of an innovative technical and economic cluster. Hydrogen-related businesses already employed a regional workforce, with a high growth potential if the region would succeed to maintain and expand its base for hydrogen and fuel cell development. Furthermore, it is expected that hydrogen will play a significant role in the overall energy transition, for example with respect to energy storage and transport, and to provide industrial high temperature heat. The initiation of hydrogen for mobility projects may enhance projects including alternative application of hydrogen.

The regional public partners of the **Arnhem H2Nodes project** already supported such a demonstration project in 2010, which led to the first publicly accessible hydrogen refueling station in the Netherlands, a 350 bar station in Arnhem, fully integrated into a 'normal' public refueling station. The Arnhem based company HyGear co-funded the HRS and supplied the hydrogen, produced with its steam methane reforming (SMR) technology. The HAN University of Applied Sciences retrofitted a privately owned rally car to use hydrogen as fuel, as part of its automotive innovation programme.

The **H2Nodes project** offered the opportunity to execute the initial intention to equip the multifuel station Westervoortsedijk with a hydrogen refueling facility. Additionally, it created the opportunity to also establish a larger and more solid revenue base for it by the deployment of three FCE buses and the availability of a 700 bar facility, allowing lighter vehicles with a 700 bar installation to fill up completely [66].

As both the development of refueling stations and the production of FCE buses were not off the shelf products yet, unexpected delays could happen in either of the two products. Such delays can however cancel all preliminary efforts made to expand the FCEV user base as the FCEVs that are supposed to serve as real life proof of the advantages of FCEVs are not operational, either because they are not delivered, or they lack facilities to refuel. This structured process resulted in the following additional partnership aspects:

(a) Total Gas Mobility agreed to the development of an HRS supplied by hydrogen produced by HyGear using SMR (as desired by Arnhem) and accepted a predetermined return on investment;
(b) The Ministry of Infrastructure and Water Management nominated the HRS Arnhem project for a grant from a new facility to stimulate innovation with respect to investments in sustainability;
(c) The municipality of Arnhem and the province of Gelderland agreed to avail a budget to accelerate hydrogen sales by mobilizing and contracting new local FCEV users.

Taking these implications into account, the **"H2-Drive initiative"** is launched in 2019 and supported during its implementation phase by four major EU-funded projects (JIVE 2, REVIVE, HECTOR and H2Nodes [61],[62],[63],[68]), which were funded from three different EU sources: FCH JU (Horizon 2020), Connecting Europe Facility (CEF) and LIFE-ProgramA short description of each project is presented in the table (Table 34) and involved stakeholders (Table 35) are shown below:

Table 34. EU Hydrogen projects that Gelderland region participates

Project Title	Small description	Project duration	Outcome of the project in the Bolzano regional area	Total funding amount of the project
JIVE2	The JIVE 2 (Joint Initiative for hydrogen Vehicles across Europe) project seeks to deploy 152 new zero emission fuel cell buses and associated refueling infrastructure across 14 European cities throughout France, Germany, Iceland, Norway, Sweden, the Netherlands and the UK. The project consortium comprises 23 partners from nine countries.	January 2018 – December 2023	10 Solaris hydrogen busses and a HRS station with production capacity of 350 kg/day	the total project budget was €102.5 million, of which €32 million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
H2 Nodes	H2Nodes aims to support the growth of new hydrogen infrastructure in Arnhem, Riga and Pärnu, centred on the development of strong local	January 2018 – December	2 Keolis hydrogen busses and a HRS station with production capacity of 260 kg/day	no data available

	activity by engaging key stakeholders, fostering a positive market-led route to clean urban transport and rising numbers of FCEVs along the TEN-T corridors. H2Nodes is developing hydrogen as an innovative technical solution with a focus on public transport, optimising existing bus and trolleybus route networks, promoting public transport and reducing pollution and greenhouse gas emissions.	2020		

Table 35. Stakeholders' list involved in Groningen's hydrogen mobility initiatives

LEAD DEVELOPER Municipality of Arnhem, the Province of Gelderland
PROJECT PARTNERS TOTAL Group, Parox Energy, HyMove, HyGear.
MAIN POLITICAL SPONSORS Municipality of Arnhem, the Province of Gelderland, the Ministry of Infrastructure and Water Management, The Netherlands Ministry of Economic Affairs and Climate, The Netherlands Ministry of Infrastructure and Water Management.
SYSTEM INTEGRATORS (VEHICLES, FUEL CELLS) Syntus Gelderland, ZETT, Keolis, Solaris, Ballard Fuel cells.

Furthermore, a dedicated H2 Drive website was launched, including information about fuel cell vehicles in general and the **H2 Drive initiative and incentive package in particular.** The incentive package for each vehicle included:

- 50% discount on the hydrogen refueling costs at HRS Arnhem during a five-year period and up to a maximum of EUR 3.000;

- a mobility service package including free towing / replacement vehicle / alternative transport in case of HRS default or in case of an empty tank in The Netherlands during a five-year period and up to a maximum of EUR 6.000;

- access to H2-Driver Community providing services including vehicle driving instructions and provisions for vehicle maintenance.

The package was available until 24 July 2020 for anyone who bought or leased an FCEV as from 11 December 2018 and works or lives within a 30 km radius around Arnhem, and therefore is likely to predominantly use the Total Gas Mobility HRS Arnhem to refuel. This process was published as a tender form the province of Gelderland authorities in pre-defined contracts valued until 2030. The tender will be published within 2022 and will be finalized and operated by Q1 2023. [66]

Additionally, in the "KEOLIS Hydrogen buses on the Veluwe" project [69], the province of Gelderland in the Netherlands accommodates a fuel cell hydrogen project with 2 buses in public transportation. The buses are leased by ZETT, a private company, to Keolis, a public transport company in the Netherlands, and funded by the province of Gelderland. The project is of particular interest because it refers to **leasing rather than building or buying the Hydrogen buses**. **The two buses are leased for a fixed price per kilometer, including service, maintenance and hydrogen consumption**. The buses are operated on inner-city and regional bus lines, connecting surrounding cities within a 40 km radius.

ZETT is a private bus leasing company [70], executing public transport operations in the north of the Netherlands in close cooperation with KEOLIS FCEV buses manufacturing company.

Table 36. Keolis FCEV Technical characteristics

Bus type	Class I bus - right-& left hand drive
Passengers capacity	95 (total)
Top speed:	>80km/h
Hydrogen storage	30kg
Fuel economy	>11km/kg
Range	>350km

Table 37. Solaris Urbino 12 buses/coaches Technical characteristics

quantity of hydrogen	37 kg with 350 bar
Travel range with one charge	up to 350 km
consumption	7-11 kg / 100 km
maximum power to the drive wheels	2 x 110 kW
maximum torque to the drive wheels	2 x 10,500 Nm
Km traveled	More than 300,000 / bus (data updated to December 2020)

Figure 42. FCEV bus in Arnhem city

Buses and cars can fuel up with hydrogen in the city of Arnhem at the new hydrogen refueling station on Westervoortsedijk. The refueling station has been developed in a close collaboration between the Municipality of Arnhem, the Province of Gelderland, the Ministry of Infrastructure and Water Management and clean fuel supplier formerly known as PitPoint, who is now fully integrated into the TOTAL Group [71].

Figure 43. Arnhem's Hydrogen Refueling Station (HRS) [71]

Table 38. Arnhem HRS key characteristics [71]

Key information	**Details**
HRS Supply type	on-site Steam Methane Reformation (SMR) with green certificates with daily production capacity of 260 kg/day
Power supply	Offsite Renewables (off-shore wind & solar)
HRS Availability during operation time	98%
H_2 Refueling capacity (kg H_2/day)	240 kg H_2/day
High SOC Refueling time	<10 min
HRS Available dispensers	● 350bar for bus/coaches ● 700bar for cars

Key outcomes of best practice

The H2-Drive initiative became a success right after its launch. However, the outbreak of the COVID-19 pandemic, had a significant impact on the sale of vehicles in general and also caused a decline in FCEV sales. Still, a total of 70 H2-Drive packages were awarded. About 30 packages were awarded within a period of a few months after the H2-Drive launch. About 40 packages were awarded shortly after it was announced that due to the impact of Covid-19 the H2-Drive initiative would not be extended beyond the July 2020 expiration date. This total of 70 FCEVs is less than the targeted 80, but still an impressive result, given the impact of Covid-19 on overall car sales. According to H2-Drive report shows that the hydrogen buses chosen by Keolis can be used in public transport without any problems. With their long range and short refueling times, the hydrogen buses form a one-to-one substitution for diesel or CNG buses. The flexible employability in public service means that these buses can operate without any adjustment to the timetable [66].

The very efficient HyMove Fuel Cell systems gives the fuel cell Solbus at Keolis a hydrogen consumption of 5.9 kg/100km irrespective the season. For the Ursus bus, consumption in the winter months is 2.2 kg/100 km higher due to the use of the electric heater. Consumption is approx. 40% lower (4 kg/100 km) than for the hydrogen buses referred to in the final report of the European project HIGH V.LO-CITY, with information about projects in various European cities. The low hydrogen consumption ensures that the TCO is low enough to make switching from conventional buses to hydrogen affordable [69].

Main conclusions of the operation of the 2 hydrogen buses between September 2018 and October 2020 [69]:

- Keolis Syntus appreciates the deployment of the two hydrogen buses. The buses are fit for use in both regional and city traffic.
- Maintenance and repair is around 4%, so that the total availability of the buses amounts up to 96%.
- Maintenance cost are around 0,25 euro/km, which is well below the target levels set in European subsidy programs such as JIVE2.
- Hydrogen consumption is low; for the Solbus consumption is 5.9 kg/100km throughout the year, the consumption of the Ursus bus is average 6.3 kg/100km. In wintertime one of the buses shows a higher consumption due to the electric heating of the passenger compartment. The other bus uses the waste heat of the Fuel Cell systems to heat the passenger compartment. This bus shows the low hydrogen consumption year-round, independent of the ambient temperature (see below diagram).

Drivers are enthusiastic about the driving characteristics of the hydrogen buses. The buses are easy to use and drivers enjoy saving energy by recuperative braking instead of mechanical braking.

Potential implementation of existing best practices in the Municipality of Delphi

In December 2020, 22 EU countries and Norway signed a manifesto paving the way for a cleaner hydrogen value chain and committing to launch IPCEIs in the hydrogen sector. IPCEI investment is meant to enable the scale up of hydrogen production projects.

Greece hasn't yet launched any project related hydrogen, though some major steps have begun in order to launch relevant activities. The Hellenic Ministry of Energy has submitted five potential hydrogen projects to the EU Commission and wait to be approved their participation in the first wave of important projects of common European interest (IPCEI) [32]. The five projects include:

1. White Dragon – a green hydrogen project set to support the phase out 2.1GW of lignite-fired capacity by 2029. The 250,000 tons of hydrogen/year project aims to use large-scale solar capacity to produce green hydrogen by electrolysis in the region of Western Macedonia for use in Greek heating and power, with an overall goal of replacing lignite plants.
2. Blue Med – a project dedicated to production of blue and green hydrogen set to start in 2025.
3. Green HIPo – US-based Advent Technologies Holdings project for the construction of a plant to produce innovative electrolytes and fuel cells in Western Macedonia.
4. H2CAT TANKS – project for the construction of hydrogen storage, especially for the transport sector.
5. H2CEM – TITAN – a project for the production, storage and use of green hydrogen for combustion to produce energy in furnaces with the aim of carbonizing the cement plants of the Greek firm TITAN.

The five projects are set to boost Greece's energy strategy. The country aims to exit its coal capacity by 2028 and hydrogen is expected to play an important role in the further decarbonisation of the Greek energy mix and boost the country's energy transition. Greece could produce up to 500MW of blue hydrogen by 2030, while the creation of a hydrogen index is set to attract trading interest, market participants said during an energy conference on 4th June 2020 [32]. Similarly, several energy corporations established in Greece announced important funding mechanisms and investments in the hydrogen energy and mobility sector.

On 24th June 2020, the shareholders at Hellenic Gas Transmission System Operator (DESFA) approved €500m loan package for infrastructure investments between 2021-2030 including a €110m support for the White Dragon project. Greek industrial group MYTILINEOS, renewable developer PPC Renewables and infrastructure investor Copelouzos Group announced plans to planning to invest in potential hydrogen projects by 2030 [32]. These announcements could influence future energy transition initiatives in Greece in national and regional level to focus on hydrogen mobility exploitation and potential pilot testing activities.

Plus, Greece could benefit from the high production quantities of olive products as the olive by-products can be re-used as secondary energy source (Figure 44) [33].

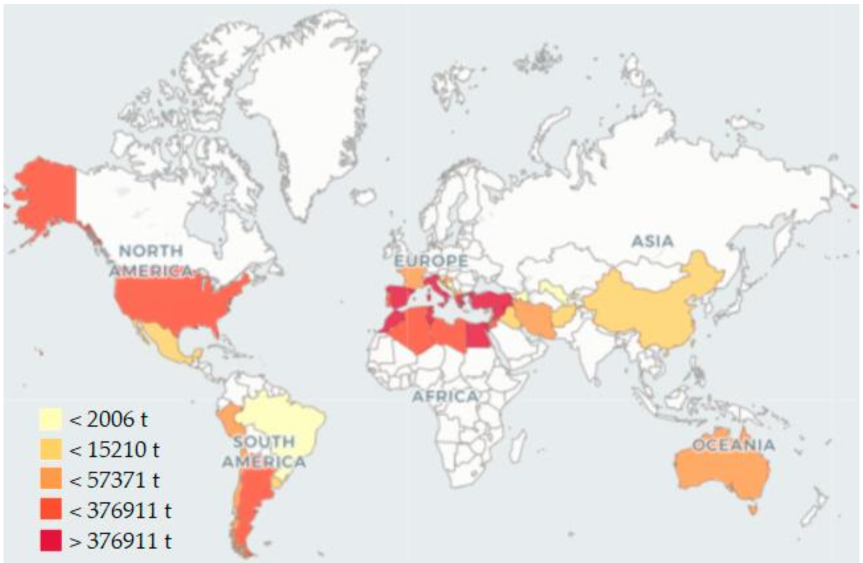


Figure 44. Average production of olives by country between 1994 and 2017. Reproduced with permission from FAOSTAT and OpenStreetMap [33]

More importantly, Phocis region and Municipality of Delphi due to their touristic and historical value, could take part in these initiatives. As it was mentioned in the SMART HY AWARE project's first deliverable submitted by the Municipality of Delphi in collaboration with CERTH-HIT with title "Energy potential from biomass and other RES", olive tree prunings could be the most important source of biomass in the wide area of Amfissa's olive grove that could be processed through biomass gasification, SMR or other relevant hydrogen production technology. These olive by-products are considered an excellent solid biofuel choice to be used in industrial boilers and in electric power generation industries or hydrogen generation facilities [16].

This could create a significant amount of pure hydrogen produced in a regional/local level and be distributed to the potential HRS that could be established in the Phocis region. Additionally, results showed that the Phocis area has a remarkable potential for the energy production from RES and more specifically from the on-shore wind farms considering the significant wind potential that exists in Phocis and the nearby area.

Furthermore, due to Greece's huge coastline length and the location of Phocis region (seaside and mountainy region), the use of sea water as a primary water source used for regional agricultural, operational and energy production activities can be done by adding a desalination infrastructure in the Phocis or nearby area accompanied with wind sourced primary electricity generation. Tenerife island has used this technology in order to create pure water from sea water and use it as a water primary source for their hydrogen production local plan, which uses water PEM electrolysis technology [34]. This was accomplished through the EU-funded project SEAFUEL.

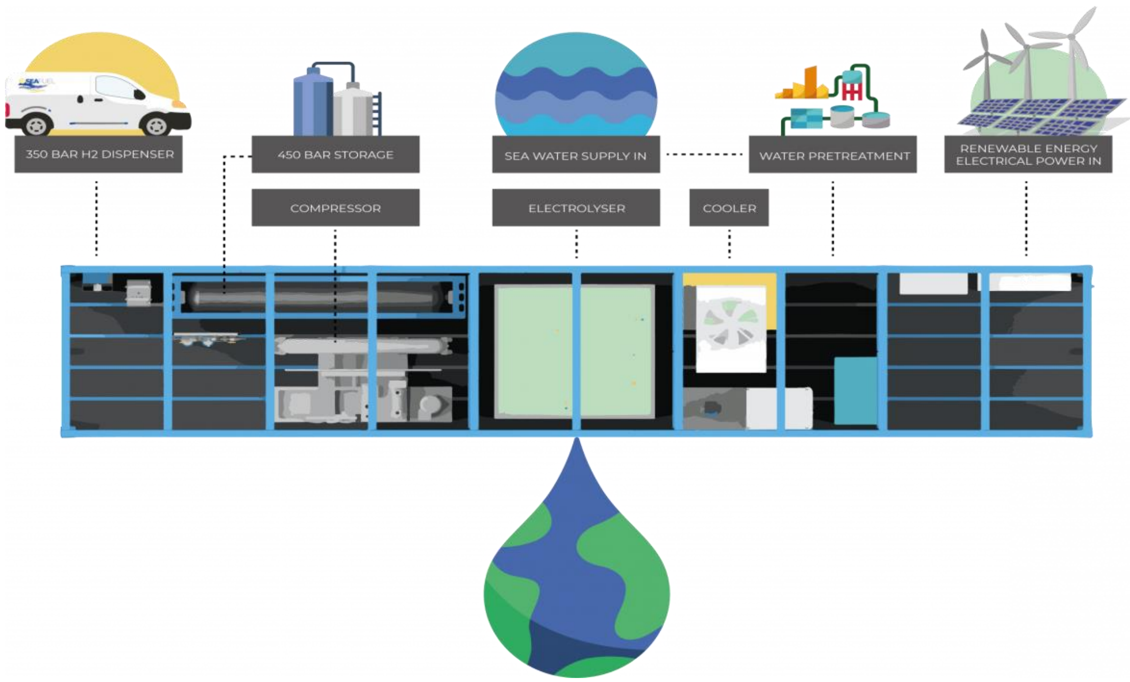


Figure 45. Sustainable integration of renewable fuels in local transportation in Tenerife, Spain [34]

These hydrogen production technologies are feasible only if they are in accordance with the national hydrogen plan that should be established by the Hellenic Ministry of Energy in close consultation with the Municipality of Delphi and other important regional stakeholders. All these approaches could formulate a sustainable, zero-emission green mobility framework in the Phocis area that could be used for public transport and duty service vehicles in order to boost touristic activities in the Delphi city and preserve the ancient monuments and Natura 2000 territories in the Phocis region (forestry, monuments, ancient city, etc.).

Detailed analysis and proposals regarding the exploitation of hydrogen mobility in the Municipality of Delphi and Phocis region will be presented in the next deliverable (Deliverable 3) that will contain the Regional Action Plan (RAP).

References

[1] Guy Meunier, Lucie Moulin and Jean-Pierre Ponssard, 2019. *“Why local initiatives for the energy transition should coordinate: The case of cities for fuel cell buses in Europe”*. International Conference on Mobility Challenges CentraleSupélecAt: Université Paris Saclay France. Available from: https://www.researchgate.net/publication/338096396_Why_local_initiatives_for_the_energy_transition_should_coordinate_The_case_of_cities_for_fuel_cell_buses_in_Europe

[2] https://nacfe.org/wp-content/uploads/2020/12/Hydrogen-Color-Spectrum-HiRes-2.png

[3] USA TODAY website. Available from:]https://eu.usatoday.com/story/money/2020/10/26/hydrogen-trucks-nikola-gm-toyota-hyundai-zero-emissions/5981340002/ (Data assessed on 23 January 2022)

[4] TRACETBEL-ENGIE website. Available from: https://tractebel-engie.com/en/news/2021/waste-to-wheels-driving-sustainable-urban-waste-transport (Data assessed on 23 January 2022)

[5] Hydrogen Europe website. Tech descriptions. Available from: https://hydrogeneurope.eu/industry/tech-descriptions/ (Data assessed on 25 January 2022)

[6] Hydrogen Europe website. Industry. Available from: https://hydrogeneurope.eu/industry/in-a-nutshell/ (Data assessed on 25 January 2022)

[7] IRENA, 2019. *HYDROGEN: A RENEWABLE ENERGY PERSPECTIVE*. Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

[8] Agarwal, A.K., Gautam, A., Sharma, N., Singh, A.P., 2019. Methanol and the alternate fuel economy.

[9] Wijayanta, A.T., Oda, T., Purnomo, C.W., Kashiwagi, T., Aziz, M., 2019. *Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review*. Int. J. Hydrog. Energy 44, 15026–15044. https://doi.org/10.1016/j.ijhydene.2019.04.112

[10] REVIVE project website. Available from: https://h2revive.eu/about-hydrogen-and-fuel-cells/ (Data assessed on 23 January 2022)

[11] Lepage, T., Kammoun, M., Schmetz, Q., and Richel, A., 2021. *Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment*. Int. J. Biomass and Bioenergy 144, 15026–15044. https://doi.org/10.1016/j.biombioe.2020.105920

[12] New Bus ReFuelling for European Hydrogen Bus Depots High-Level Techno- Economic Project Summary Report.

[13] FCH Observatory website. Cumulative data on installed HRS. Available from: https://www.fchobservatory.eu/index.php/observatory/technology-and-market/hydrogen-refueling-stations/cumulative-data (Data assessed on 25 January 2022)

[14] FCH Observatory website. Levelised Cost of Hydrogen. Available from: https://www.fchobservatory.eu/index.php/observatory/technology-and-market/levelised-cost-of-hydrogen-green-hydrogen-costs (Data assessed on 25 January 2022)

[15] IEA Bioenergy. Hydrogen from biomass gasification

[16] Juan Francisco García Martín et al, 2020. Energetic Valorisation of Olive Biomass: Olive-Tree Pruning, Olive Stones and Pomaces. MDPI Processes 2020, 8, 511; Available from: https://www.mdpi.com/2227-9717/8/5/511/htm

[17] Monitor Deloitte. Fueling the future of mobility: Fuel cell buses. Available at: https://h2chile.cl/wp-content/uploads/2021/11/fueling-the-future-of-mobility-fuel-cell.pdf

[18]https://i0.wp.com/hydrogentoday.info/wp-content/uploads/2019/10/21234886_2019_-_V_hicules_Utilitaires_Z_E_33_H2_HYDROGEN.jpg?ssl=1

[19] HECTOR project website. Available from: https://www.nweurope.eu/projects/project-search/hector-hydrogen-waste-collection-vehicles-in-north-west-europe/ (Data assessed on 23 January 2022)

[20] Life 'N Grab Hy. Layman Report 2021. Clean cities, clean air with garbage trucks on hydrogen!

[21] FCH Report. Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities.Brussels, Fall 2017.

[22] Hyundai Motor website, 2020. *World's first fuel cell heavy-duty truck, XCIENT Fuel Cell, heads to Europe for commercial use*. Available from: https://www.hyundai.com/au/en/hyundai-info/news/2020/07/worlds-first-fuel-cell-heavy-duty-truck-xcient-fuel-cell

[23] DAF Motors website. Available from: https://www.daf.com/en/about-daf/sustainability/alternative-fuels-and-drivelines/hydrogen (Data assessed on 28 January 2022)

[24] Stellantis Press Kit 2021. Hydrogen Fuel Cell Zero Emission.

[25] Citroen International website. *CITROËN Ë-JUMPY HYDROGEN - AN EVEN WIDER ELECTRIFIED RANGE*. Available from: https://www.citroen.com/en/Highlight/167/citroen-e-jumpy-hydrogen-an-even-wider-electrified-range (Data assessed on 28 January 2022)

[26] Blue Fuel Solutions website. Available from: https://h2dualpower.com/en (Data assessed on 28 January 2022)

[27] NPROXX website, 2021. *NPROXX powers London's first hydrogen ambulance*. Available from: https://www.nproxx.com/nproxx-powers-londons-first-hydrogen-ambulance/

[28] Red Social Innovation website. *Kumamoto Hospital launched a zero-emission hydrogen ambulance*. Available from: https://red-social-innovation.com/en/solution/kumamoto-hospital-launched-a-zero-emission-hydrogen-ambulance/

[29] Wikipedia. *Hydrogen vehicle*. Available from: https://en.wikipedia.org/wiki/Hydrogen_vehicle (Data assessed on 26 January 2022)

[30] Hydrogen Mobility Europe website, 2021. *Interim and final summary reports on technical performance of vehicles and stations in the project*. Available from: https://h2me.eu/publications/interim-and-final-summary-reports-on-technical-performance-of-vehicles-and-stations-in-the-project/

[31] LIFEalps project website. Available from: https://www.life-alps.eu/project/progress-fleet/ (Data assessed on 23 January 2022)

[32] ICIS website, 2021. *Greek hydrogen projects move closer to EU funding*. Available from: https://www.icis.com/explore/resources/news/2021/09/07/10682510/greek-hydrogen-projects-move-closer-to-eu-funding/

[33] The Food and Agriculture Organization. Crops. Available online: http://www.fao.org/faostat/en/#data/QC/visualize (accessed on 3 February 2020).

[34] SEAFUEL project website. Available from: http://www.seafuel.eu/h2-station/ (Data assessed on 27 January 2022)

[35] SEAB website, 2019. SEAB e ASM Merano collaborano al progetto REVIVE. [Italian] Available from: https://www.seab.bz.it/it/news/seab-e-asm-merano-collaborano-al-progetto-revive

[36] SEAB website, 2020. SEAB investe in mezzi di nuova generazione. [Italian] Available from: https://www.seab.bz.it/it/news/seab-investe-in-mezzi-di-nuova-generazione

[37] SASA website. Mobilità sostenibile. [Italian] Available from: https://www.sasabz.it/index.php/mobilita-sostenibile/ (Data assessed on 7 January 2022)

[38] Sustainable bus website, 2021. *SASA Bolzano launches 12 Solaris hydrogen buses, to be powered with filling station within the depot*. Available from: https://www.sustainable-bus.com/news/sasa-bolzano-hydrogen-buses-solaris/

[39] Wikipedia. Bolzano – Transport. Available from: https://en.wikipedia.org/wiki/Bolzano#Transport (Data assessed on 7 January 2022)

[40] Wikipedia. South Tyrol. Available from: https://en.wikipedia.org/wiki/South_Tyrol (Data assessed on 7 January 2022)

[41] REVIVE project website. Demonstration – Bolzano. Available from: https://h2revive.eu/demonstrations/bolzano/ (Data assessed on 7 January 2022)

[42] FCH JU website. Best practices: Hydrogen Valley South Tyrol. Available from: https://www.h2v.eu/analysis/best-practices/hydrogen-valley-south-tyrol (Data assessed on 7 January 2022)

[43] Fuel Cell Electric Buses website. CHIC project. Available from: https://www.fuelcellbuses.eu/projects/chic (Data assessed on 7 January 2022)

[44] Fuel Cell Electric Buses website. JIVE project. Available from: https://www.fuelcellbuses.eu/projects/jive (Data assessed on 7 January 2022)

[45] Element Energy Ltd report, 2017. *Fuel cell bus joint procurement clusters*. FCH JU Stakeholder Forum. Available from: https://www.fch.europa.eu/sites/default/files/S4_P1_Pres3_MADDEN_FC%20bus%20cluster%20process%20new.pdf

[46] FCH JU website. Study on Fuel Cells Hydrogen Trucks. Available from: https://www.fch.europa.eu/news/new-study-hydrogen-trucks-released (Data assessed on 8 January 2022)

[47] Wikipedia. Pau. Available from: https://en.wikipedia.org/wiki/Pau,_Pyr%C3%A9n%C3%A9es-Atlantiques#Demographics (Data assessed on 8 January 2022)

[48] JIVE/MEHRLIN project presentation. FEBUS: Pau's Zero Emission Public Transport Project. Available from: https://ec.europa.eu/regional_policy/rest/cms/upload/25092019_104140_Pau_Region_week_presentation_oct19.pdf

[49] Pau Capitale humaine website, 2019. Pau 2030 : un projet urbain. [French] Available from: https://www.pau.fr/article/pau-2030-un-projet-urbain

[50] Sustainable bus website, 2019. *Pau (France) welcomes the launch of the world's first hydrogen BRT*. Available from: https://www.sustainable-bus.com/news/pau-welcomes-the-launch-of-the-worlds-first-hydrogen-brt/

[51] Pau Capitale humaine website, 2019. *"Fébus alimenté par de l'hydrogène 100% palois [+ le parcours de Fébus]".* [French] Available from: https://www.pau.fr/article/pau-sengage-pour-le-climat-avec-son-febus-hydrogene

[52] Pau Capitale humaine website, 2019. *Fébus révolutionne nos déplacements.* [French] Available from: https://www.pau.fr/article/febus-revolutionne-nos-deplacements

[53] SNCF website. FÉBUS: PAU LAUNCHES THE WORLD'S 1st HYDROGEN-POWERED BRT. Available from: https://www.sncf.com/en/network-expertise/public-transport-/febus-pau-all-aboard-worlds-first-hydrogen-brt (Data assessed on 8 January 2022)

[54] FEBUS project website. Available from: https://www.pau3d.fr/febus/ (Data assessed on 9 January 2022)

[55] Caponi, R., A.M.F., L.D.Z., and Bocci, E., 2021. *Hydrogen refueling station cost model applied to five real case studies for fuel cell buses*. 76° Italian National Congress ATI. E3S Web of Conferences 312. https://doi.org/10.1051/e3sconf/202131207010

[56] Fuel Cell Electric Buses website. HIGHVLOCITY project. Available from: https://fuelcellbuses.eu/sites/default/files/documents/final1-hvlo-final-report.pdf (Data assessed on 9 January 2022)

[57] Wikipedia. Groningen. Available from: https://en.wikipedia.org/wiki/Groningen (Data assessed on 9 January 2022)

[58] Urban Transport Group. *Public Transportation "Made by OVbureau" How do we do it ?*. Available from: https://www.urbantransportgroup.org/system/files/general-docs/Presentation%20Groningen%20Drenthe.pdf

[59] Fuel Cell Electric Buses website, 2019. *SPOTLIGHT ON GRONINGEN: A HYDROGEN SOCIETY IN THE MAKING – FOCUS ON MOBILITY*. Available from: https://fuelcellbuses.eu/public-transport-hydrogen/spotlight-groningen-hydrogen-society-making-%E2%80%93-focus-mobility

[60] Hydrogen Central website, 2021. *Official opening of new hydrogen filling station in Groningen, with 20 new hydrogen buses*. Available from: https://hydrogen-central.com/hydrogen-filling-station-groningen-20-hydrogen-buses/

[61] Fuel Cell Electric Buses website. JIVE-2 project. Available from: https://fuelcellbuses.eu/projects/jive-2 (Data assessed on 9 January 2022)

[62] REVIVE project website. Municipality of Groningen. Available from: https://h2revive.eu/partner/gemeente-groningen/ (Data assessed on 9 January 2022)

[63] Interreg North Sea Region website. HyTrEc2 project. Available from: https://northsearegion.eu/hytrec2/ (Data assessed on 9 January 2022)

[64] FCH JU website. Best practices: HEAVENN - Hydrogen Energy Applications in Valley Environments for Northern Netherlands. Available from: https://www.h2v.eu/analysis/best-practices/heavenn-hydrogen-energy-applications-valley-environments-northern (Data assessed on 11 January 2022)

[65] Interreg North Sea Region website. Hydrogen Fuel Station rapport. Available from: https://northsearegion.eu/media/18045/hytrec2_wp4_case_study_hydrogen-province-of-drenthe.pdf

[66] H2Nodes project report. *Milestones H2Nodes Milestone 17 Mobilisation of Local Actors and Users*. Available from: https://rwsduurzamemobiliteit.nl/publish/pages/186007/201231-h2nodes-m17-arnhem-final.pdf

[67] Wikipedia. Gelderland. Available from: https://en.wikipedia.org/wiki/Gelderland (Data assessed on 11 January 2022)

[68] H2Nodes project website. Available from: https://www.h2nodes.eu/en/ (Data assessed on 12 January 2022)

[69] HyMove project website. *Report on 2 hydrogen buses in public service at Keolis*. Available from: https://www.hymove.nl/two-hydrogen-buses-in-public-service-at-keolis-2018-2020/

[70] ZETT website. Available from: https://zettzero.com/en/about-us/ (Data assessed on 12 January 2022)

[71] H2Nodes project website. Arnhem city. Available from: https://www.h2nodes.eu/en/regions/arnhem.html (Data assessed on 12 January 2022)