Basic information on hydrogen

Why hydrogen?

The basic precondition for the application of hydrogen in all sectors concerned is the transition to a low-emission or zero-emission economy. As for the constant efforts of states across all continents, new alternatives for the development of climate-neutral technologies are sought. The European Union itself has set the goal of achieving complete climate neutrality for the year 2050, i.e., capturing and storing the same amount of greenhouse gas emissions as will be released into the atmosphere. The very fact of the development of renewable energy sources across the Member States then creates room for stabilizing their unpredictable electricity production. In this case, hydrogen will play the role of an energy carrier, which is especially suitable for seasonal accumulation and some mobility applications.

What is hydrogen?

Hydrogen is the lightest gaseous chemical element forming up two-thirds of the entire cosmic mass. It is estimated that it makes up more than 30% of the total mass of the Sun. It is the third most widespread element on Earth, yet it occurs almost never as a single molecule because it is highly reactive and forms compounds immediately. Hydrogen is ubiquitous, whether in the form of water, natural gas, or methanol. As the simplest and lightest element, it disperses into the air very quickly when escapes. When escaping, hydrogen does not pollute the environment in any way. It is an emission-free substance that is non-toxic and odourless. Hydrogen is a combustible element, but it does not support combustion, and burns with a pale blue flame**.**

What energy properties does hydrogen have?

Hydrogen is a very energy-rich fuel (33 kWh/kg) and is currently a direct competitor, especially with battery technologies.

In a direct comparison of hydrogen with batteries, the leader in the field of battery technology today is the automotive company Tesla, whose batteries reach energy densities of 250–260 Wh/kg. Hydrogen thus has almost 126 times higher energy density per 1 kg. However, each technology has its disadvantages, and that is especially the low bulk energy density of hydrogen (3 kWh/m3 at 20 °C and 1 bar). The tank, which is able to hold, for example, 6.3 kg of hydrogen, therefore, has a total capacity of 156 liters (Hyundai Nexo).

What is the history of hydrogen use?

Hydrogen is a long-known gas in the world, discovered in 1776 by the British scientist Henry Cavendish. Unfortunately, hydrogen was not widely used in industry at the time of its discovery, mainly due to the advent of cheaper fossil fuels in the 19th and 20th centuries. When pronouncing the word 'hydrogen', everyone will remember the Hindenburg airship disaster. Although "banging" hydrogen is still blamed, the catastrophe was caused by an electric shock that ignited the highly flammable material from which the hull was made. To this day, the terrifying video of the burning airship raises concerns and creates a stigma over the various applications of hydrogen. The expansion of hydrogen use was due to space research missions in the 1960s, such as the Apollo missions. Hydrogen was used at that time primarily as fuel for space rockets. In addition, during the Apollo spaceflight, hydrogen fuel cell technology was used on board to generate electricity, heat and water. In the Czech Republic, hydrogen was used as one of the main components of the well-known flue gas, which was later replaced by natural gas.

What is the use of hydrogen?

Hydrogen is a carrier (storage) of energy. It is widely used in transport, energetics and other industries. In the future, hydrogen is to serve as one of the energy carriers for the application of the so-called sector coupling, or the concept of sector integration.

The sector coupling is a process in which the full decarbonisation of most sectors (transport, energy, and other industries) should take place through the use of electricity from renewable energy sources. Hydrogen has a significant role to play in this strategy as an energy carrier in all the areas mentioned below.

In transport, hydrogen cars are a major competitor to battery electric vehicles (BEVs). Hydrogen fuel cell cars (FCEV) have a longer range (600 km and more), a short filling time (approx. 5 minutes), work better under cold conditions, and with significantly less range losses and lower consumption at higher speeds. The loss of range at higher speeds is of the same order as for internal combustion engine cars. Compared to batteries, hydrogen is expected to be preferred especially in heavy freight transport, bus transport and other types of long-distance transport. Today, hydrogen mobility works on the principle of fuel cells producing electricity by the direct electrochemical reaction of hydrogen and oxygen to water. As waste substances, only demineralized water and air are generated, which is purified by filters. It is a bit of an exaggeration to say that hydrogen cars are cleaning the planet. The mass development of FCEV is hindered only by the high acquisition price and the small infrastructure of filling stations. With the wider application of FCEV, there will be a dramatic reduction in acquisition prices due to mass production.

In energy, it is possible to use hydrogen as an energy storage. Taking into account that hydrogen stores a large amount of energy (approx. 33 kWh/kg) and can be easily stored in a large capacity, it is an ideal medium for seasonal energy accumulation (in the order of TWh). Where battery technologies fail in covering up long-term shortages of electricity in the transmission system, hydrogen works as an ideal alternative. Hydrogen stored in this way, whether in storage tanks or in the gas system, can then be in combination with oxygen converted back into electricity using fuel cell technology.

In other industries, hydrogen can replace fossil fuels. In the steel industry, it can be used, for example, to reduce iron. Today, hydrogen is primarily used for the production of ammonia, which is then used mainly in the production and processing of fertilizers. Other industrial uses of hydrogen include the production of polymers, explosives, but also in the food industry for the hardening of fats in the production of margarines. There are also pilot projects in the world testing the use of combustion of hydrogen instead coal.

How is hydrogen produced?

96% of all hydrogen produced today comes from fossil fuels. Only 4% is produced by water electrolysis. However, this ratio should change in the next decade in favour of emission-free production by means of the above-mentioned electrolysis of water.

It is currently stated that 96% of all world hydrogen production comes from fossil fuels, mainly through the so-called steam reforming of natural gas. This is the cheapest current hydrogen production technology. Steam reforming is a chemical process in which water vapor, at a temperature of 750–950 °C, is fed to methane. The mixture of methane and vapor then reacts to form hydrogen, carbon monoxide and less carbon dioxide. Subsequently, carbon monoxide reacts with additional water vapor to form hydrogen and carbon dioxide. The overall efficiency of this process is around 75%. However, it produces a large amount of CO_2, up to 9–12 kg of CO_2 is produced per 1 kg of hydrogen produced. The hydrogen thus produced is called gray.

A transitional method of hydrogen production can be a combination of technologies already known today, and these are steam reforming of natural gas with CCS (Carbon Capture Storage). In this variant, the generated CO_2 emissions are captured using CCS or CCU (Carbon Capture Utilization) technology and the hydrogen produced is virtually emission free (emissions are reduced by up to 95%). The hydrogen thus produced is called blue.

In the future, the most supported method of hydrogen production in the European Union is the production of hydrogen by electrolysis of water using electricity from renewable energy sources. Unfortunately, nowadays the production of hydrogen using electricity reaches approximately a 4% share of all production. In addition, most of this hydrogen is a by-product of chlorine production using brine electrolysis technology, i.e., white hydrogen (formed as a by-product of further chemical reactions).

If hydrogen is produced by electrolysis of water and the electricity used comes from renewable sources, then such hydrogen is called green. Green hydrogen is emission free and has the greatest potential for reducing greenhouse gas emissions. During the electrolysis of water, the chemical bond between hydrogen and oxygen in the solution is broken to form hydrogen gas and oxygen. At present, the overall efficiency is around 50–60% depending on the use of cell technology. To produce 1 kg of hydrogen, about 9 liters of water and about 50 kWh of electricity is required.

There are other methods of hydrogen production that can be found in the literature. Currently, the potential of hydrogen production in newly developed fourth-generation nuclear reactors using high-temperature electrolysis of water vapor on solid oxide cells is discussed.

In addition, hydrogen is classified into other 'colours' based on the source from which it is produced. So, we can find brown hydrogen (produced by coal gasification) or turquoise hydrogen (produced from natural gas, but the by-product is solid carbon).

How is hydrogen produced in the Czech Republic and what is the potential for the production of green hydrogen in our country?

Due to its specific position in the heart of Europe, the Czech Republic has relatively little potential for the production of so-called green hydrogen. The utilization coefficient (approximately slightly above 20%) of wind power plants is lower in our country than in neighboring coastal states, where strong and stable winds (approximately above 30%) blow over sea coasts. At present, there is no large electrolyser in the Czech Republic designed for the production of green hydrogen on a commercial basis. A small electrolyser using solar energy with an output of 6 kW is

located in ÚJV Řež and is intended only for research purposes. Nevertheless, large electrolysers exist in the Czech Republic, but they are used primarily for the production of other chemicals and the so-called white hydrogen is formed here only as a by-product. It is worth to mention the largest Czech electrolyser, which is operated by Spolchemie for the production of chlorine. As a by-product, hydrogen is also produced there, the use of which is considered for urban transport in cooperation with the town of Ústí nad Labem in the future. Most hydrogen in the Czech Republic is produced by the Unipetrol company that by means of partial oxidation of heavy oil residues, steam reforming and from the ethylene unit produces more than 85,000 tons of hydrogen per year, which is then used mainly for the production of ammonia.

What is water electrolysis?

Electrolysis is a process in which a direct electric current breaks a chemical bond between hydrogen and oxygen in an aqueous solution.

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

Very pure hydrogen is subsequently formed at the cathode in gaseous form, from where it is discharged and subsequently stored. We must not forget the evolution of oxygen at the anode, without which this technology could not work, because we cannot perform the reaction on one electrode only. The process can also be operated at room temperature and requires only electricity. The efficiency of current commercial electrolysers used for hydrogen production is around 50–75%.

What types of electrolysers do we have?

At present, there is talk of a total of three types of electrolyzers, which are advanced enough to saturate market demand. These are electrolysers using alkaline electrolysis, PEM electrolysis and high-temperature electrolysis taking place in solid oxide fuel cells.

The alkaline electrolysis is now the cheapest and currently the most commercially developed technology. In terms of attractiveness and technical properties, the PEM technology is currently the most suitable for the production of green hydrogen from surplus renewable energy sources due to its fast start-up capabilities and relatively low operating temperature. The disadvantage of PEM electrolysers is their higher price, which is mainly due to the use of more expensive materials in production, such as iridium and platinum together with the high price of the membrane.

How much water is used in electrolysis?

To produce 1 kg of hydrogen and 8 kg of oxygen, 8.92 liters of demineralized water are needed, i.e., water free from all minerals present (even purer than distilled water).

Current industrial oil processing processes use about 40% more water than is used during its electrolysis. In addition, when you reuse the hydrogen in the fuel cell, you get back a similar amount of water as you put in the process.

What water can be used for electrolysis?

The water needed to produce very pure hydrogen must be demineralized, i.e. free of all solutes and impurities. However, it can be obtained from virtually any water source.

For example, the desalination process today costs around 0.8 euros per 1 m^3 water. If we convert this process to hydrogen production, the production of hydrogen from seawater costs 0.007 euros more per 1 kg of hydrogen.

Hydrogen storage

How is it possible to store hydrogen?

At present, the compression of hydrogen in the gaseous state is mentioned as the most promising and also as the most commercially advanced technology for hydrogen storage. The hydrogen thus stored tends to escape due to the very small size of molecule. Modern storage tanks are already made of extremely strong and airtight materials, allowing safe storage with minimal losses of stored hydrogen. Compared to the competitive possibilities of hydrogen storage, the compression of hydrogen gas clearly has the least disadvantages.

Hydrogen is stored stationary in large-volume gaseous steel pressure vessels. To compress hydrogen to 350 bars, approximately 15–20% of the energy in the fuel is required. The second option is to convert hydrogen to a liquid state. However, the disadvantage of this process is that it is necessary to keep such hydrogen in this form at -253 °C in cryogenic storage tanks. During its handling and use, leaks subsequently occur as a result of the evaporation of hydrogen, which thus behaves at a temperature higher than -253 °C. Up to 30–40% of the total energy contained in the fuel is needed for liquefaction alone.

Hydrogen applications in mobility

What are fuel cells?

Fuel cells in electric cars are basically small electricity generators obtaining energy from a direct electrochemical reaction between oxygen and hydrogen. Hydrogen is stored in a tank from which it is fed to the fuel cell. There it reacts with oxygen to produce electricity. The product of this electrochemical reaction is only distilled water.

This technology is also sometimes called reverse electrolysis because the opposite happens to water electrolysis. The average efficiency of fuel cells is between 50–60%. From 1 kg of hydrogen, the fuel cell is able to produce about 16 kWh of electricity.

How do fuel cells work in electric cars?

The fuel cell is similar in construction to batteries. In the fuel cell we find the anode, cathode and membrane with a catalyst. Hydrogen enters the system on the anode side and oxygen on the cathode side. Hydrogen is decomposed into an electron at the anode and a hydrogen proton, which is transported by the membrane to the cathode, reacts there with the oxygen present. The product is only distilled water and electricity, in addition, unused oxygen leaves the fuel cell.

How is a battery electric car different from a fuel cell one?

A fuel cell vehicle (FCEV) is also an electric vehicle. The car includes a battery, electric motor and fuel cell along with a hydrogen tank.

Unlike battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs) have a small battery with a capacity of the order of kWh. Electricity generated from fuel cells is stored in a battery, from which the electric motor then takes electricity directly. The efficiency of such a system is due to the addition of a fuel cell to the whole process lower than in a purely battery system by about 40–50%, yet the whole process is more energy efficient than in the case of an internal combustion engine.

How is a hydrogen electric car refueled?

Refueling takes place at filling stations. The whole process is very similar to refueling traditional fossil fuels. After connecting the filling gun to the tank valve, you press the lever and the whole system will take care of the rest of the work. Filling the tanks takes 5 minutes and gives the car full capacity.

The whole system works highly automatically and when the filling pistol clicks, the system closes and locks. It is therefore not possible for hydrogen to escape from the filling station to the surroundings. After refueling, you simply "click out" the filling pistol, pay and move on.

How many filling stations do we have in the Czech Republic?

At present, no public access to the filling station in the Czech Republic is open. One filling station, which is used mainly for research purposes, is located in Neratovice.

However, a total of three are being prepared for 2021, which will be managed by the Unipetrol company – in Litvínov, Prague and Brno.

The National Action Plan for Clean Mobility assumes that a total of 80 publicly accessible hydrogen filling stations should be operational in the Czech Republic by 2030.

How does a hydrogen electric car work in cold weather?

The advantage is the reliability of the whole system in cold weather. Compared to battery packs, fuel cells are not subject to degradation during cold weather.

The efficiency of the whole car is better in winter conditions than in the case of battery electric cars, because the hydrogen electric car does not need to heat by the electricity produced, but can work with the waste heat generated during the operation of fuel cells. In winter, on the other hand, the efficiency of a battery-powered electric car drops roughly to the level of FCEV, which retains its efficiency even at low temperatures.

Can't the wastewater in the hydrogen electric car system freeze?

Fuel cell systems and water drainage are currently designed so that water cannot freeze throughout the car system.

For example, the developers of the Hyundai Nexo hydrogen electric car guarantee that their system works without any problems in the range of -30 °C to +50 °C.

Is battery electromobility a better transport solution than fuel cells?

It depends on who you ask and what type of transport we are talking about. However, hydrogen and batteries should be two complementary technologies that will complement each other. Why?

Long-distance freight transport: Hydrogen currently offers greater potential for the transport of goods over longer distances. Despite the hypothetical technological evolution of batteries (solid electrolyte batteries), it is unlikely that within ten years it will be possible to recharge the batteries so that to use the increased capacity for journeys over 1000 km without major problems. In addition, current batteries are very heavy, and even if you double the energy density from the current 260 Wh per 1 kg battery to 500 Wh per 1 kg, you would still need a battery with a minimum capacity of 1.5 MW and a battery weighing 3 tons for long-distance transport over 1000 km. Charging such a striking amount of electricity is also a problem. What power consumption would the chargers need to charge 1.5 MW overnight between shifts? With the hypothetical idea of 20 such trucks standing in the parking lot in a row, we get to the numbers, due to which it is no longer possible to build only a stronger transformer station, but a small power plant near such chargers. For that reason alone, it is obvious to think of turning electricity into another, easily storable energy carrier that we can produce continuously from renewable energy sources. We can transport hydrogen to the truck significantly faster and we would not endanger the stability of the transmission system during charging/refueling. Hydrogen currently offers greater potential for the transport of goods over longer distances.

Haulage in cities: In cities, on the other hand, battery electromobility can play a more significant role due to its high efficiency and low cost. The battery is great for city traffic where operators do not need a long range. In addition, the advantage of the entire solution is supported by low operating costs and high efficiency due to energy recovery and low transport speeds.

Passenger car transport: The BEV (battery electric vehicle) market is currently a relatively developed market. In addition, every year there is a significant progress towards achieving the driving characteristics of internal combustion cars (range, charging speed). BEVs are the ideal solution for standard daily driving and charging at home from the socket. Today, BEVs already offer a decent range of 400 km, are highly efficient and locally emission free. Especially for urban transport, there will be no equivalent competitor for BEV at present or in the near future. Fuel cell passenger cars (FCEVs), on the other hand, cannot compete in some areas of the BEVs, although their application is possible, in particular taking into account their specific characteristics. They offer a higher and more stable range, even at higher speeds, especially on motorways, and their properties are similar to internal combustion engines in terms of range. FCEVs can also be a suitable alternative for drivers who live in densely populated areas without adequate home charging options. However, the development of FCEVs is currently hindered by high acquisition costs and insufficient infrastructure of filling stations, which are also significantly more expensive compared to the construction of charging stations.

Bus transportation: For urban transport with driving distances in the order of tens of kilometers, the most efficient solution is a battery bus, similarly to the urban freight transport. Hydrogen buses have greater potential, especially in intercity and long-distance transport, as they offer a more stable and higher range.

Train transport: Hydrogen has the potential to replace diesel train transport in such parts of countries where there is no electrified railway. Today, pilot projects are already operating around the world, for example in France, which plans to test hydrogen trains from 2023. Similar to the Czech Republic, where hydrogen trains could hit the tracks, especially in the northern part of Bohemia.

How heavy are hydrogen storage tanks in cars?

With the hypothetical storage of 4.2 kg of compressed hydrogen at a pressure of 700 bar, we need a tank in cars weighing about 135 kg. The tanks are currently made of reinforced carbon fiber.

Compared to a vehicle burning petrol, the hydrogen tank has 4–5 times higher volume and 10 times more weight.

Couldn't hydrogen be liquefied and then refueled like standard petrol?

This solution is extremely energy inefficient. Liquid hydrogen needs to be maintained at -253 °C and if such conditions are not met, hydrogen will evaporate.

The effect of heat on the fuel tank can be caused by the environment, heat from the engine and other aspects. This results in large losses (usually about 3% of the stored energy per day) and at the same time excess pressure is built up in the fuel tanks, which must then be compensated by releasing it from the fuel tank.

Is hydrogen safe?

All fuels contain a high concentration of energy and can therefore be dangerous under certain conditions. However, hydrogen can be considered as similarly safe or even safer than any other fuel. In addition to standard crash tests, hydrogen tanks are also tested to withstand firing from a sniper rifle. The tanks can withstand twice the pressure that will be achieved under standard conditions. Filling stations, which have a number of systems focusing on safety when working with high pressure, are similarly safe.

The advantage in the safety of the use of hydrogen is also its very low density, when hydrogen rises rapidly when the tank is punctured, therefore it does not accumulate near the accident. In the event of fire, a flame will be created, which will rise vertically upwards and the vehicle will not fire as it is in case of liquid fossil fuels.

Hydrogen production has been going on for decades and there are practically no extraordinary tragedies. Hydrogen is also, among other things, a gas that is not harmful to health, so you do not have to worry about its leakage. In addition, the systems in modern hydrogen electric cars are developed so that they close in the event of an accident and sudden ignition cannot happen.

Hydrogen economy

How much does it cost to produce 1 kg of hydrogen?

The price depends mainly on the method of production. In addition, for the production of green hydrogen, it is necessary to take into account the different price in different parts of the world, depending on how much it costs to produce electricity from renewable energy sources. According to the International Energy Agency, the price of hydrogen production is as follows:

Steam reforming of natural gas $ 1–3.5/kg

Coal gasification $ 1.2–2.2/kg

Water electrolysis $ 3–7.5/kg

How much does 1 kg of hydrogen cost at filling stations?

For the end user, the price of hydrogen per kg is currently set at 9.5 euros in Germany (where most filling stations are located). Converted to kilometers and with an average consumption of 1 kg per 100 km, 1 km in a hydrogen electric car will cost you ~ 0,094 EUR.

Compared to conventional fuels, a hydrogen electric car is currently more expensive to operate. However, the price should decrease in the future with increasing production. Filling the full tank of a Hyundai Nexo (6.3 kg) with a reported range of 666 km would cost you around 60 EUR today.

How will the price reduction be achieved in the next 10 years?

The hydrogen economy will not be sufficiently developed without the help of state subsidies. In order to reduce the price, it is necessary to invest in production. In the coming years, support for low-emission and zero-emission (green hydrogen) will prevail in Europe, with the aim of building 40 GW electrolysers within the EU by 2030 and supporting the construction of another 40 GW electrolysers across borders to increase imports. In addition to increasing production capacity, the price of green hydrogen will also be reduced by technological progress and increasing the efficiency of the electrolysers themselves.