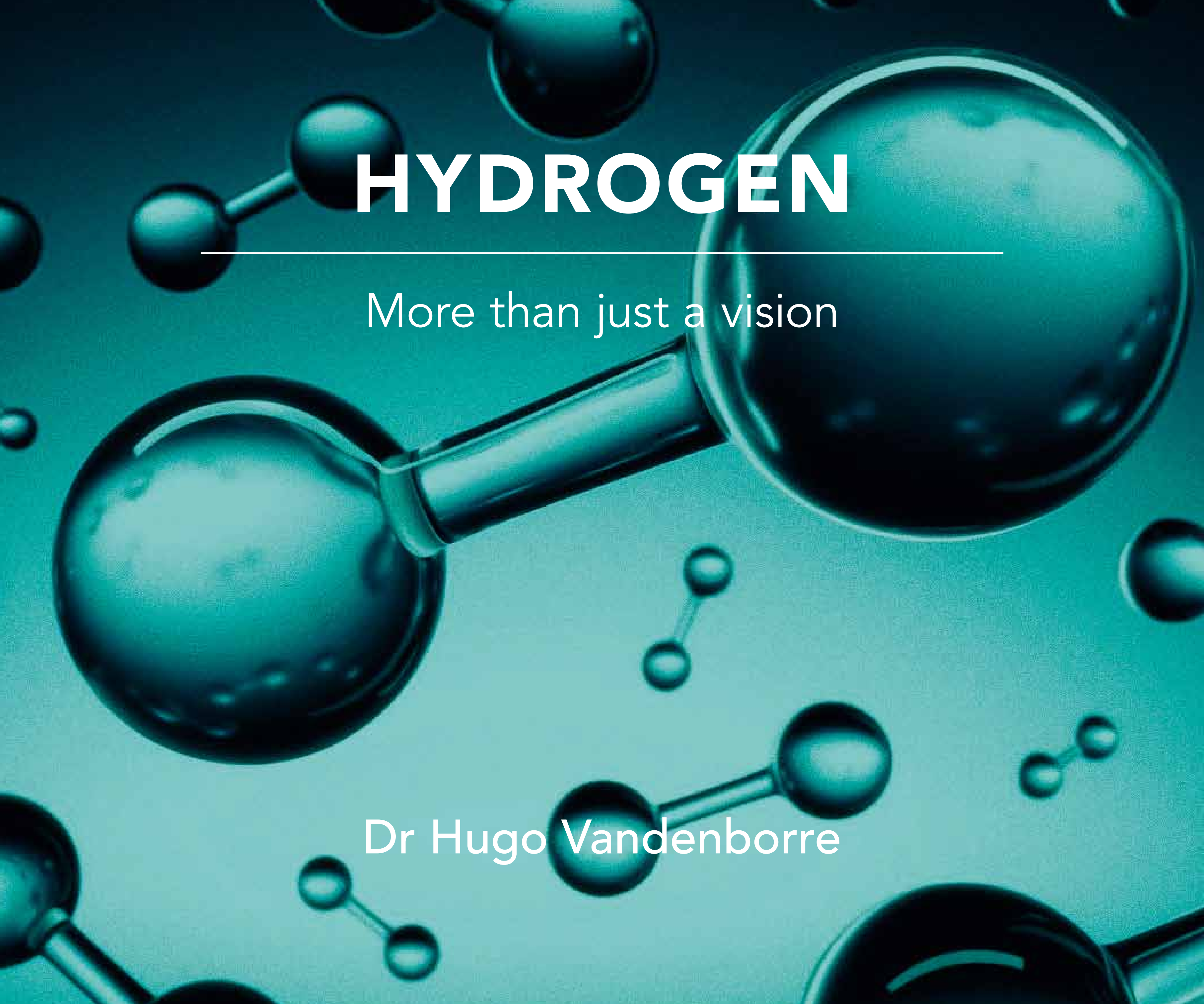

HYDROGEN

More than just a vision

Dr Hugo Vandenborre

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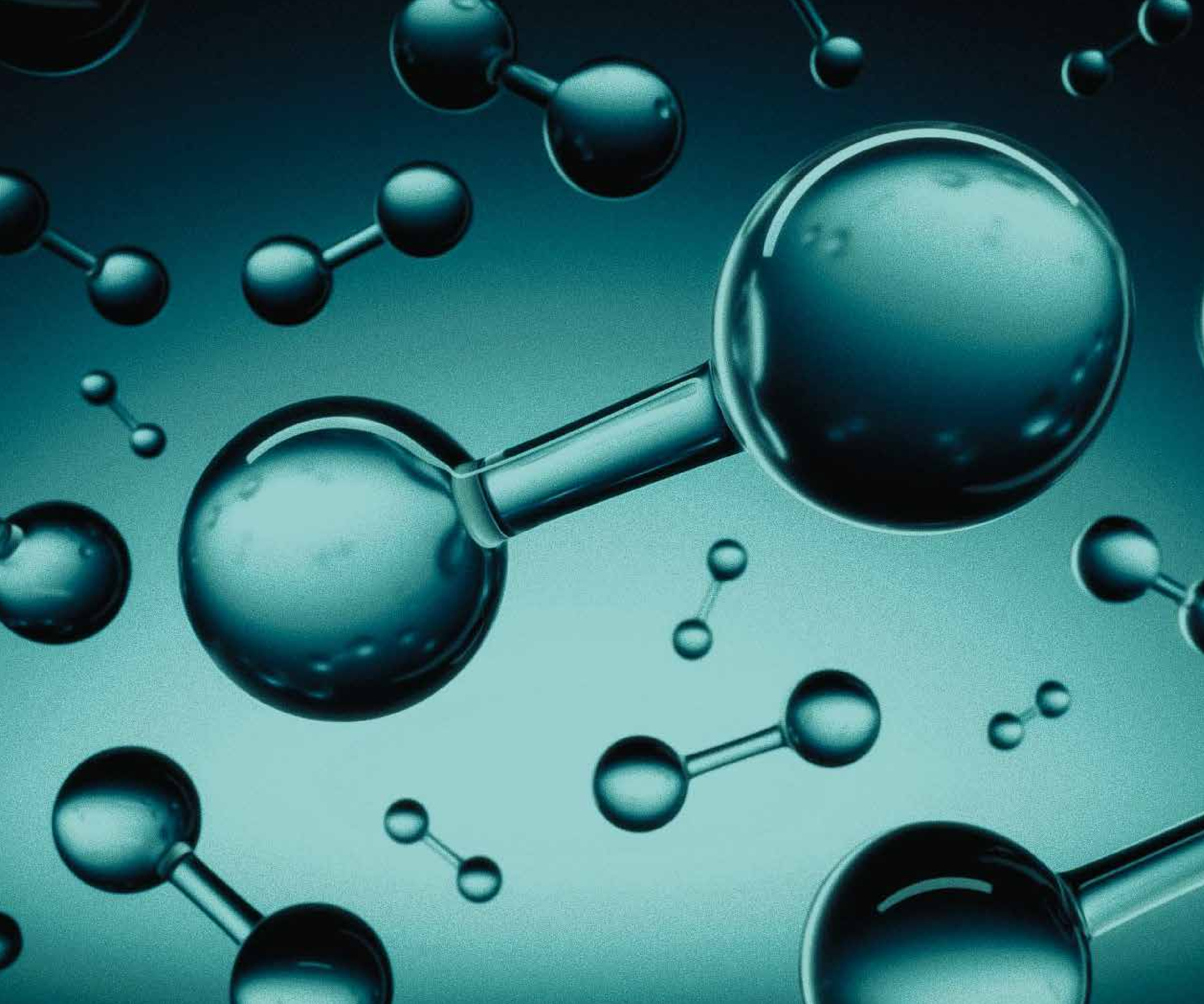


HYDROGEN

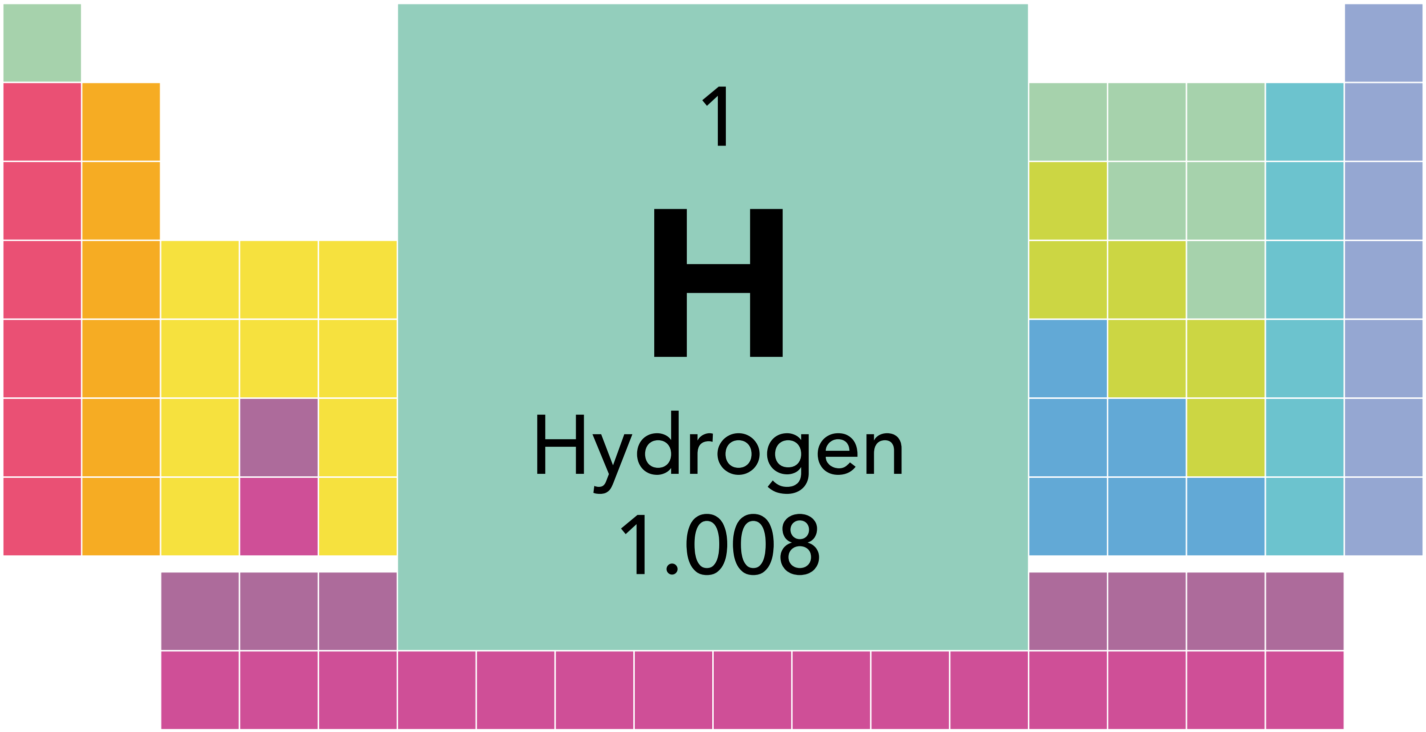
More than just a vision

Dr Hugo Vandenborre

'A world based on a green and blue energy system, sustainable energy and water might not just be a dream for my grandchildren Kaat, Janne, Joke, Laura, Toon, Jonas, Roos and Floor. It will be my gift for their future and the future of everyone.'

Dr. Hugo Vandenborre

BMW pioneering on liquid hydrogen (LH) with their 520h model in 1979 - Image courtesy of BMW



Composed of a single proton and a single electron, hydrogen is the simplest and most abundant element in the universe. It is estimated that 90% of the visible universe is composed of hydrogen. Hydrogen is the raw fuel that most stars 'burn' to produce energy. It is colourless, odorless, tasteless and non-toxic. Hydrogen, just like gasoline and natural gas is readily flammable and can therefore be used as a fuel.

Hydrogen is by definition a zero emission fuel.

Content

Preface

We cannot change our transportation and energy systems overnight, but with the right strategy we can gradually bring about an evolution in the way we use our transportation system, store our energy, and heat our homes and buildings.

Many of the technological breakthroughs to enable this future already exist and a gradual transition to hydrogen as a fuel could begin today. Improvements to current technologies and new technological discoveries will undoubtedly continue to evolve, but the political will is needed to start a real transition as of now.

By making the right decisions today, hydrogen can stimulate economical growth and make our world cleaner, more livable and sustainable.

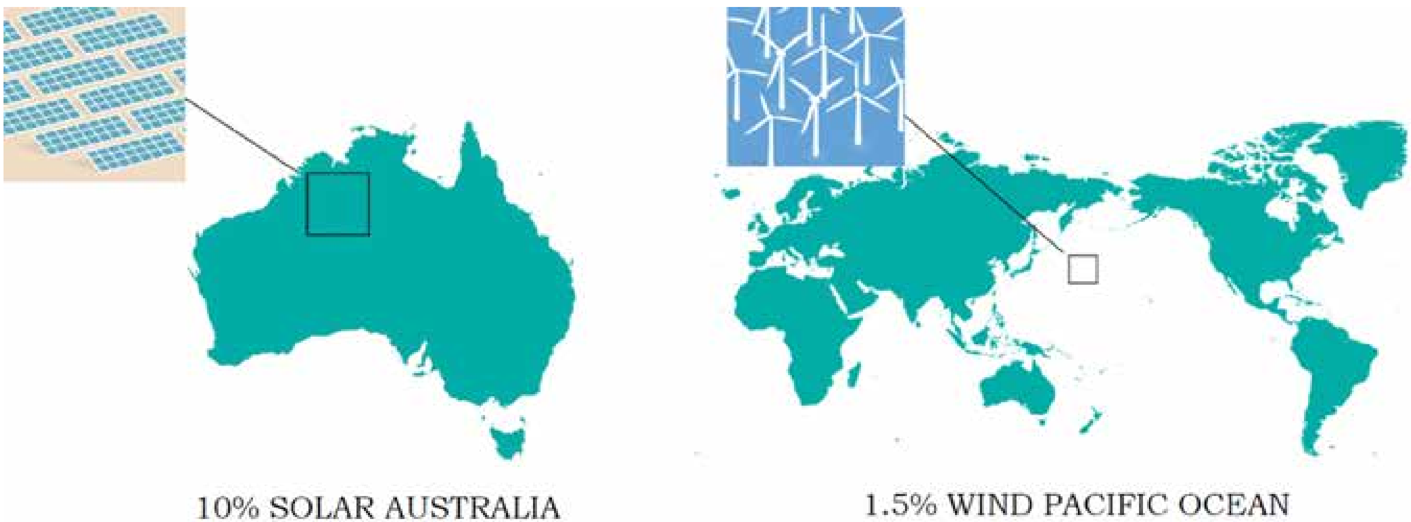
However, there is still a fear of hydrogen. Fear about its safety and physical properties, but more than anything, this is fear of the unknown. A fear we need to overcome.

This is the third in what is set to become a series of books on the reality of a hydrogen society and a plea for its speedy adoption.

"Do not go where the path of fossil fuels may lead;
go instead where there is no path and leave a TRAIL."

Dr. Hugo Vandenborre

Mercedes GLC F-CELL Fuel cell car



Portion of renewable generation per type to equalize actual worldwide primary energy consumption
Photo courtesy of Prof.dr. A.J.M. van Wijk

Hydrogen

Composed of a single proton and a single electron, hydrogen is the simplest and most abundant element in the universe. It is estimated that 90% of the visible universe is composed of hydrogen. Hydrogen is the raw fuel that most stars "burn" to produce energy. It is colourless, odourless, tasteless and non-toxic. Hydrogen, just like gasoline and natural gas, is readily flammable and can therefore be used as a fuel.

There are different types of hydrogen. Grey hydrogen is the most common form and is generated from natural gas and methane, through a process called steam reforming. With the production of grey hydrogen there is still an amount of polluting CO_2 emission. Green hydrogen however is the purest form of hydrogen. It is produced by splitting water into hydrogen and oxygen through electrolysis, whereby the necessary electricity comes from renewable energy. Green hydrogen is a zero emission fuel. Its only exhaust is water in the form of droplets.

Dutch professor Ad Van Wijk states in in the book "Hydrogen Rocks" that to produce 170.000 TWh (actual yearly worldwide primary energy consumption) we would only need either solar cells on a surface equal to 10% of Australia, or wind turbines on a surface of 1,5% of the Pacific Ocean.

European Commission president Ursula Von der Leyen

Vision of the EC: Ursula Von der Leyen

According to Ursula Von der Leyen, President of the European Commission, Europe should become the first carbon-neutral continent by 2050. To reach that goal, the use of green hydrogen is a key factor.

In November 2021, the European Hydrogen week was held in Brussels where Von der Leyen gave a speech on her vision for the future of hydrogen. In her speech, she states that clean hydrogen should have a central place in the climate-neutral economy of the future. In the past the issue was often that the price for green hydrogen was too high. But, because of the current rise in gas prices we all see, green hydrogen today can even be cheaper than grey hydrogen.

"Our target should be to bring the cost below EUR 1.8 per kilo by 2030. And this goal is within reach. We have to scale up clean hydrogen production, expand its applications, and create a virtuous circle where demand and supply feed each other and bring the prices down. That is the principle."

In order to reach this principle, the European Commission wants to focus on three key factors. First, strong public investment to innovate and scale up. Second, international cooperation to build a global market for hydrogen. And third, a partnership between the EU with the private sector and researchers.

Henry Cavendish (1776)

Antoine Lavoisier (1780)

William Grove (1838)

Jules Verne (1874)

Pioneers in hydrogen

Hydrogen in history

In his 1874 work, L'île mystérieuse, Jules Verne wrote "I believe that one day water will be used as a fuel, that the hydrogen and oxygen of which it is composed, will supply an inexhaustible source of heat and light."

Hydrogen is the most common element in the universe. For over 500 million years, plants have been using solar energy to convert carbon dioxide and water into oxygen and carbohydrates through photosynthesis. This organic material was then covered with a layer of sediments and converted into hydrocarbon and fossil fuels through heat and pressure. It would take millions of years before people would learn how to use them.

The Chinese are technically the first users of oil. In 2000 BC, they already used a type of refined crude oil to light and heat their houses. The Greeks on the other hand established the foundations for our current knowledge about hydrogen, electricity and solar energy.

In 500 BC, the philosopher Heraclitus described a world in which there is a constant interaction of 'fluxes' between earth, fire and water – the basic elements known at the time. And even though renewable energy generation through hydro power, wind and solar, was known for centuries before our modern calendar began – people still used fossil fuels first.

In 1776, the British scientist Henry Cavendish discovered that hydrogen is a specific element. He described it as “highly flammable air”. In 1780, the French chemist Antoine Lavoisier gave Cavendish’s “inflammable air” its final name, hydrogen. The name was chosen because the gas can be extracted from water, and it turns into water again upon combustion.

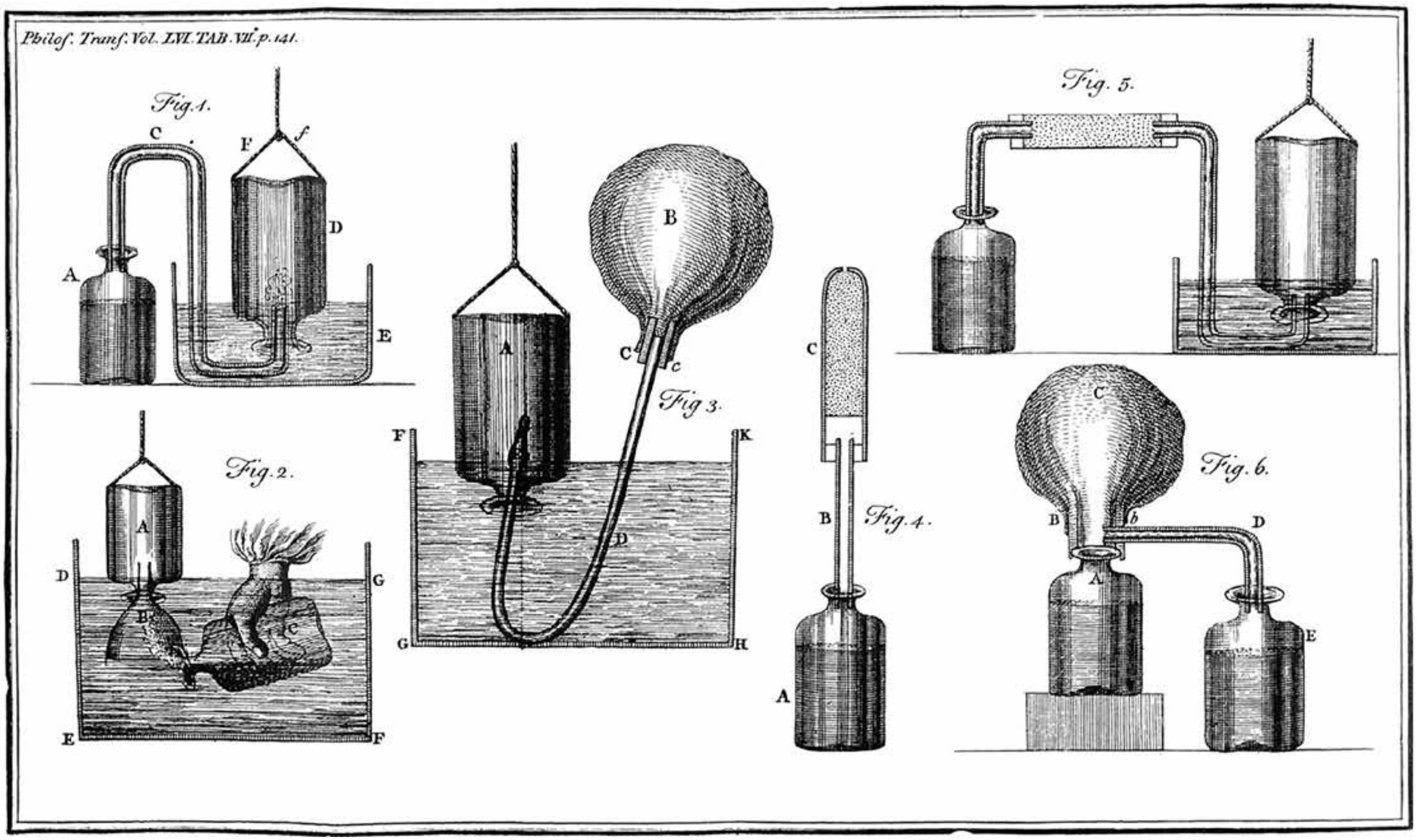
But it was the Dutchman Adriaan Paets van Troostwijk, who in 1789 succeeded in extracting hydrogen through the electrolysis of diluted acids.

English scientist and lawyer William Grove discovered in 1850 that it was possible to generate power by combining gases over a catalyst. This made him the inventor of the present-day fuel cell.


Francis Bacon (1959)

From 1941 to 1961, Francis Bacon organized several inter-disciplinary research teams in Great Britain, supported by engineer Charles Metz, the Electrical Research Association, and the National Research and Development Corporation. During this period, the “Bacon cell” emerged as a benchmark of fuel cell technology, with a 6 kW version demonstrated in 1959.

The oil crisis of the 1970’s prompted the development of alternative energy technologies, including hydrogen fuel cells for conventional commercial application. Pratt and Whitney from NASA subsequently licensed the design from Bacon, to power the Apollo space vehicle. Though the “Bacon Cell” found no niche outside space application, owing to its requirement for pure hydrogen and oxygen, its success in that role served as a technological exemplar in the post-war period.



Apparatus used by Henry Cavendish in 1776 in his studies of hydrogen, carbondioxide, atmospheric air and water

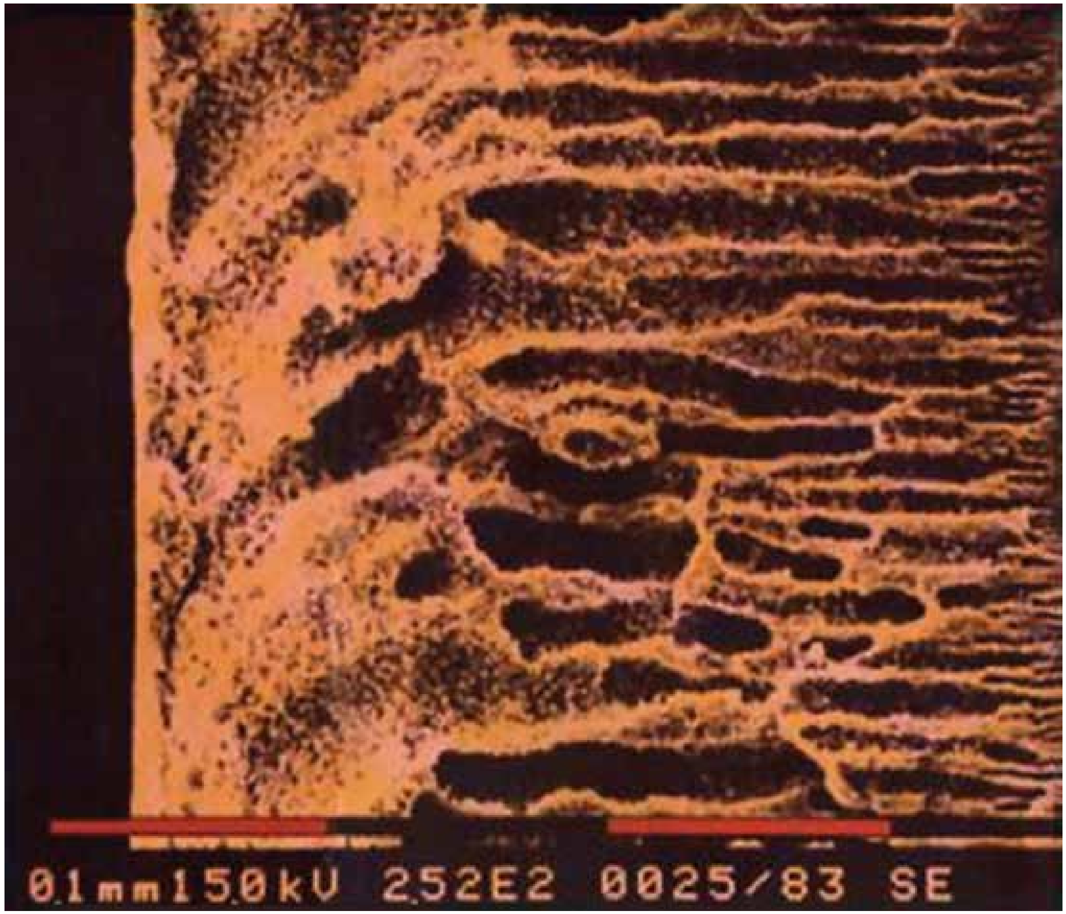
Under the guidance of former US secretary of state Henry Kissinger, I started my own research into a new hydrogen membrane in 1977, after I became fascinated by the concept of the fuel cell during my PhD studies in the US.

In 1985, I discovered how a membrane could be made from inorganic ion exchangers to split water into hydrogen and oxygen with an efficiency of over 90%.

The idea was to take advantage of amphoteric ion exchangers and to embed them into a chemical stable organic binder.

The cross section of such a membrane (0.3 mm thick) is shown on the right whereby one can easily distinguish three layers with different structure. These layers are the result of the manufacturing parameters. The structure at the right end is called the skin of the membrane. It is here that the hydrogen production takes please. Due to the narrow diameters of the pores, capillary forces prevent that hydrogen molecules could migrate to the left where the oxygen bubbles are generated.

Today we are still burning fossil fuels – which took millions of years to be synthesized – and pollute our planet. Why this is the course that history took, continues to surprise me.



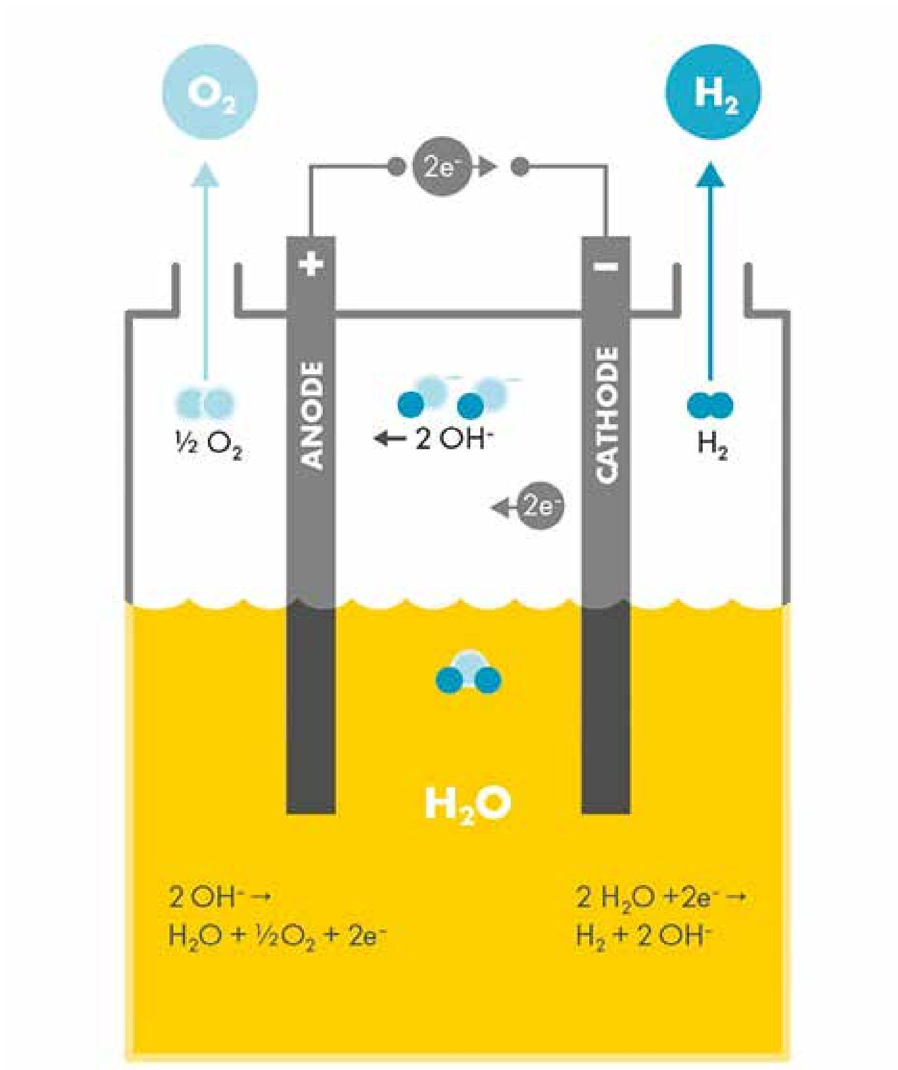
Basic invention: Three layer membrane based on amphoteric ion exchangers

Production: Electrolysis

Hydrogen is strictly speaking not an energy source like natural gas, oil, coal or wood. In fact, it is an energy carrier. In this respect, hydrogen can be used the same way as electricity, to transport energy or to store energy.

It is also a very flexible fuel. It can be used both in an internal combustion engine (mechanical energy), in a fuel cell (electric energy) and in catalytic combustion (thermal energy). In the case of hydrogen as a by-product of natural gas, oil or coal, CO_2, the creation of the much-feared greenhouse gases is inevitable. This is referred to as 'brown hydrogen'. But even when produced through this method, it is more environmentally friendly than oil.

When hydrogen is produced through water electrolysis, the only other by-product is oxygen and therefore is fully 'green'. All excess of electricity due to surplus of renewable production or affordable grid electricity prices can be stored as hydrogen in a pressurized form by splitting water into oxygen and hydrogen through this electrochemical process.



Water electrolysis illustration - Photo courtesy of Shell

Hydrogen production of 90,000 liter/hour through electrolysis and integrated in a 20 ft sea container
Photo courtesy of Hydrogenics Europe N.V.

Either tap or rainwater can be used as input, prior deionization. This water flows through the anode side of the electrolyser. Power is applied to the cathode and anode current collectors. From the former water molecules composed of two hydrogen atoms and one oxygen atom on the anode side, the electrically insulated proton exchange membrane (PEM) will only let the hydrogen ions pass on to the cathode side of the membrane. Those hydrogen ions will become hydrogen molecules due to the hydrogen reduction. This process will build pressure on the cathode side of the membrane.

After dryness, this hydrogen will be safely stored in gas cylinders until duty time. While the water is circulating on the anode side, heat is dissipated, and efficiently recovered through heat exchangers.

Integrating the electrolyser into standard shipping containers of 20ft or 40ft does not only facilitate the transport to the client but reduces also substantially the installation and commissioning time. I have been a pioneer in doing so but unfortunately could not anchor this idea into a patent.

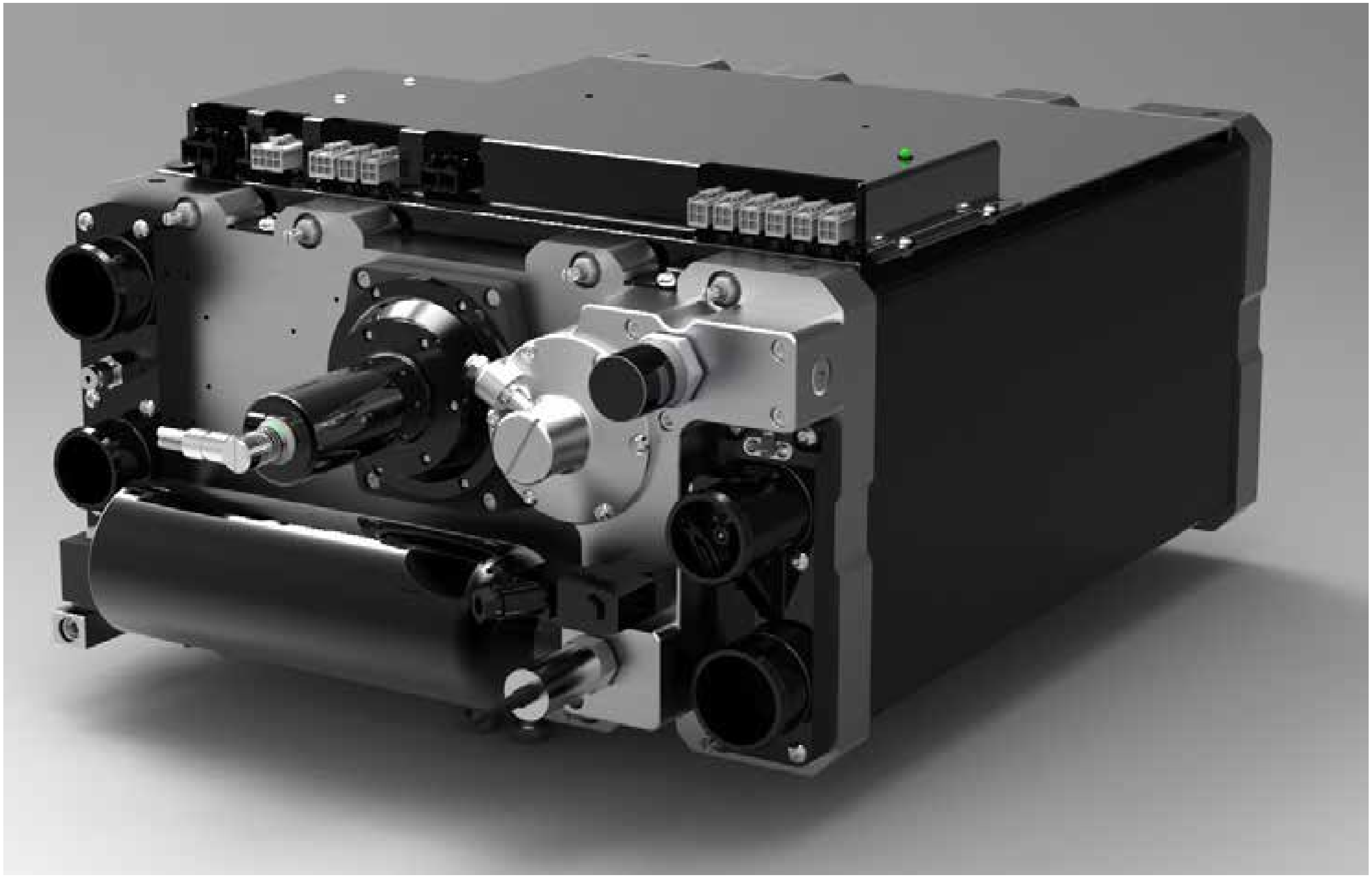
Once hydrogen is produced, how can it be stored? The biggest challenge is volume. Hydrogen is the lightest gas in the universe and is fourteen times lighter than the air we breathe. Whereas it has high energy density when it comes to weight, hydrogen takes up sizeable dimensions under normal atmospheric pressure.

Usage: Fuel Cell principle

The fuel cell is a device that converts chemical energy into electrical and thermal energy. Hydrogen is combined with oxygen (mostly obtained from the air) within a fuel cell to electrochemically produce electricity, heat and water.
The heart of the fuel cell generally consists of three primary parts: an anode, a cathode and an electrolyte. The electrical current flows from the cathode to the anode. There are different types of fuel cells depending on whether they are used in stationary, portable or mobile applications. In mobile (car or forklift) and most stationary applications the fuel cell is composed of a proton exchange membrane which acts as the electrolyte and is referred to as PEM-Fuel Cell.

The anode is coated with a catalyst (mostly noble metal based) which helps to split the hydrogen molecules into positively charged protons and negatively charged electrons. The electrolyte membrane allows only the protons to pass through this membrane to the cathode. The electrons cannot pass through this membrane and as a result, they flow in the form of an electrical current through an external circuit to get to the cathode. Oxygen supplied at the cathode then combines with the protons to form water.

Individual fuel cells are combined into a so-called fuel cell 'stack'. The number of fuel cells in the stack determines the total voltage (1 fuel cell is typically 0.7 Volt). The surface area of each fuel cell determines its total current - typically 0.5 to 1.0 Ampere/cm^2. Multiplying the voltage by the current yields the total electrical power generated, measured in kilowatts.



Fuel Cell stack - Photo courtesy of Cummins

Hydrogen - Aviation

A hydrogen-powered aircraft is an airplane that uses hydrogen fuel as a power source. Hydrogen can either be burnt in a jet engine or another kind of internal combustion engine. Or it can be used to power a fuel cell to generate electricity to power a propeller.

Since 2010, Airbus has been focusing on zero-emission technologies, as the aim for the aviation industry is to achieve climate neutrality starting from 2050. Hydrogen can mean zero CO_2 emissions if it is generated from renewable energy through water electrolysis. Hydrogen may also enable a significant reduction, or even the elimination of Nitrogen Oxide (NOx).

In 2020, Airbus presented three concept planes: a 100-passenger turboprop, a 200-passenger turbofan, and a futuristic design based around a blended wing body. According to Airbus CEO Guillaume Faury, these planes could be ready for deployment by 2035. All three designs are envisaged as hydrogen hybrids, which means they would be powered by gas-turbine engines that burn liquid hydrogen as fuel and generate electricity via hydrogen fuel cells.

Airbus is also planning to test a hydrogen-powered engine with its A380, the world's largest passenger plane. They specifically chose this type because it has the room to store the liquid hydrogen tanks and other equipment. Test flights could begin in 2026.

In 2023, Lyon-Saint Exupéry Airport - under the umbrella of the VINCI group - will take the first step for the decarbonization of the aviation sector. A partnership between VINCI airports, Airbus and Air Liquide will make the airport of Lyon a pilot location for the deployment of a hydrogen infrastructure. With a roadmap until 2030 and beyond, their plans include a hydrogen gas distribution station for ground vehicles, and a liquid hydrogen infrastructure for future aircrafts.

The Blended-Wing Body (left), Turboprop (right), Turbofan (bottom) - Photo courtesy of Airbus

Hydrogen - Maritime

The use of hydrogen in the navigation sector also plays an important part in decarbonizing transportation. Navigation is responsible for 2,6% of the total CO_2-emission. Hydrogen is a promising option to use on boats as the ratio between transported weight and average kilometers per day/per trip is very high.

The first ship in the world that uses solely green hydrogen is the French Energy Observer. The hydrogen is made on board from seawater with the help of solar panels on deck. It was built by two Frenchmen: former sailor Victorien Erussard, and driver & documentary maker Jérome Delafosse, who wanted to contribute to solutions against global warming and show that boats can sail on green energy instead of heavily polluting fuel from oil refineries.

The Energy Observer uses the Toyota REXH3 fuel cell and already made more than 7,000 nautical miles including trans-Atlantic crossings.

Dr. Hugo Vandenborre (left) and Victorien Erussard (right)

The New Energy Observer - Photo courtesy of Energy Observer

The HydroBingo in Japanese waters - Photo courtesy of CMB

In August of 2021, Compagnie Maritime Belge (CMB) and Japanese shipbuilder Tsuneishi, presented the HydroBingo, the world's first hydrogen powered passenger ship. This hydrogen-powered ferry is an eco-ship that significantly reduces the amount of CO_2 and other harmful gases. CO_2 emissions are up to 50% lower compared to a conventional diesel engine.

It can carry 80 passengers, has a tonnage of 90 tonnes and can reach a maximum speed of 26 knots (around 46 km/hours). The HydroBingo will provide a service between the islands of Seto Inland Sea in Japan.

Also when it comes to cargo ships, things are moving in a good and "green" direction. In the Netherlands, a big hydrogen vessel is being built to transport salt within Dutch waters. The cargo ship will be named Antonie and should start sailing with cargo as of 2023. Dutch minister of Infrastructure and Water Cora Van Nieuwenhuizen is investing 4 million euros to build the 135m tall hydrogen ship. She claims the boat is a nice step forward on the route to an inland navigation without CO_2 emission.

Cargo ship Antonie

Hydrogen - Railroad

For several years already, Alstom is experimenting in Germany with trains, driven by fuel cells of Hydrogenics, the previous company I co-founded. In 2018, this model was introduced in France. If you know that in France still 45% of the trains are driving with Diesel fuel because no electrical infrastructure exists, it is clear that for environmental reasons the hydrogen trains are very welcome there.

The Coradia iLint trains can drive up to 1,000 km on a full tank of hydrogen. Steam and water are the only exhausts.

In Italy, Ferrovie Nord Milano, the national railway operator, made an agreement with Alstom for the delivery of six hydrogen trains. They will be used in the North of Italy and will produce zero emission electrical power.

They will have a low sound level and can reach a speed of up to 140 km/hour and drive as far as 600 to 800 km. Also Switzerland, the Netherlands, Austria and Denmark have showed an interest in buying this type of trains.

The Coradia iLint train on the rails in Germany - Photo courtesy of Alstom

Hydrogen - Road

Busses

In Belgium there is a dominant player on the market that invests in hydrogen busses, i.e. Van Hool. Already back in 2005, Van Hool started building hydrogen busses for the American Market. Europe followed two years later. All the Van Hool busses are equipped with the fuel cell model built by Canadian Geoffrey Ballard and commercialized by Ballard Power Systems.

Hugo Vandenborre behind the wheel of a zero-emission hydrogen bus of Van Hool

In the fuel cell, hydrogen protons pass through a membrane that the electrons cannot. The electrons must instead leave the cell through an external circuit, creating electricity. There are no harmful emissions, and the only by-product is water vapor.

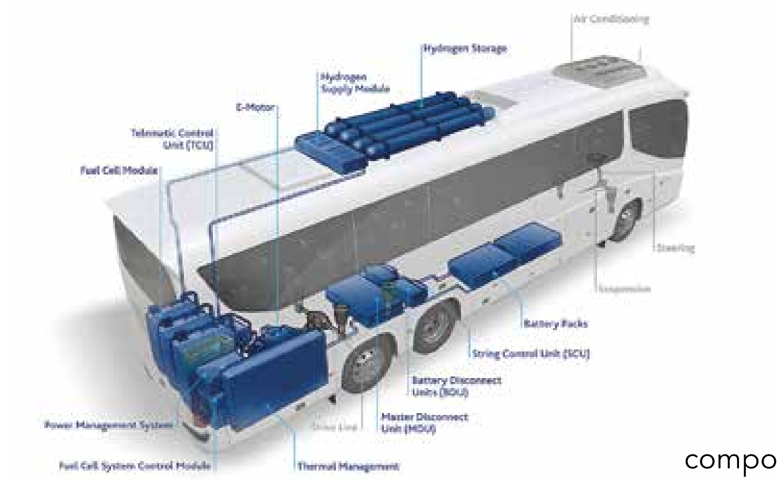


Illustration of key components in a hydrogen bus

In 2021, Van Hool delivered its first hydrogen bus to the MIVB (Brussels Public Transportation Agency). They would like to test this bus for 2 years in as many lines as possible to measure the performance at different locations and weather conditions.
In 2022, 10 new hydrogen busses will start driving in public transportation in Emmen, The Netherlands. These A330 busses will go on the road as part of the JIVE2 (Joint Initiative for hydrogen Vehicles across Europe). It's a plan to let 152 hydrogen busses - plus fuelling infra-structure - drive in 14 European cities.

The advantages of a hydrogen bus versus an electrical bus is that you can drive 400 km without refuelling. To achieve that with an electrical bus you would need 5,000 kg of batteries; whereas the hydrogen bus can handle it with 40 kg of hydrogen.

Forklifts & Vans

Another interesting application of fuel cells is in material handling trough forklifts. The American company Plug Power has joined forces with Walmart, one of the biggest retail companies in the US, to supply not only fuel cell units, but also the infrastructure to supply hydrogen. A research at Walmart showed that hydrogen-powered forklifts could move more goods with fewer vehicles compared to electrical forklifts. Plus, their refuelling stations, took up less space and were easier to scale up. And last but not least, hydrogen refills take up less time than battery recharging. As they say in America "time is money".

Not only US is investing in hydrogen forklifts. Already back in 2019, retail distribution centers from Carrefour in France, Colruyt Group in Belgium and Norgesgruppen/Asko in Norway, were operating on industrial trucks powered by hydrogen.

Since the COVID-19 pandemic, the interest in hydrogen forklifts for distribution companies has risen even more, as with the rise of e-commerce, the demand for emission free and highly reliable forklifts has risen equally. The hydrogen fuel cell forklift market is growing at a faster pace with substantial growth rates over the last few years, and it is estimated to continue this path in the coming years.

DHL is also using the hydrogen technology, but they show a wider interest than just the forklifts and started buying also hydrogen fuel cell vans to its fleet to cut carbon emissions. Again, hydrogen vans show faster refuelling time and longer range than battery-electric vehicles can offer. Initially, DHL deployed 100 "H2 panel vans" in 2020, but they expect to expand their hydrogen fleet up to around 500 hydrogen vans.

DHL fuel cell van & fuel cell forklifts - Photo courtesy of DHL

Cars

If you compare hydrogen cars with electrical vehicles, hydrogen comes out superior in most aspects.

To start with, “the only exhaust of a hydrogen car is water, either as water vapor or droplets, so you have no CO_2, no NOx, no particulates”, as quoted by Robin Hayles, manager of sustainable fuel development at Hyundai.

Hydrogen has the same advantages as petrol and diesel when it comes to range, performance and refill times, without the huge disadvantage of having a detrimental impact on the environment. At the same time, it has the same smooth drive of an electric vehicle, zero emissions and instant torque. But whereas charging an electrical battery takes a minimum of 30 minutes, a hydrogen vehicle can refuel in 3 minutes, like a regular fuel stop.

When we zoom in on range, there is a significant difference between hydrogen cars and electric vehicles. Whereas the average range of an electric car is between 250 and 350 km, a hydrogen car can cover +700 km like a petrol fueled car.

In Asia there is a lot moving with regards to hydrogen cars. Major car manufacturers like Toyota, Honda and Hyundai have been leading the race to introduce the next-generation zero-emission hydrogen vehicles. Neil Spires, Mirai product manager for Toyota, believes that electric vehicles are perfect for inner city use, but that the future belongs to hydrogen cars.

Today Toyota has its 2022 Mirai which does not only work with the hydrogen technology but is as smooth and luxurious as a Lexus or any other high-quality car. Moreover, "Mirai" means "future" in Japanese language. The South Korean Hyundai company, produces the Nexo: a unique SUV with a hydrogen fuel cell that combines advanced technologies to a futuristic design and a driving range of up to 700 km.

Hyundai Nexo - Photo courtesy of WaterstofNet

Mercedes-Benz GLC F-CELL - Photo courtesy of Fuel Cell and Hydrogen Joint Undertaking

As in petrol cars, the range depends on the fuel in the storage tank. Hydrogen stores under 700 bar in pressure and 0.5 – 1.0 kg of hydrogen is consumed per 100 km.

In Germany, Mercedes and BMW have been playing with the idea of hydrogen cars for years, but now they are almost there. Mercedes-Benz Group AG has developed several fuel cell electric vehicles, based on their Mercedes-Benz A-Class, B-Class and GLC-Class. Its first generation of the F-Cell was already introduced in 2002. The BMW X5 Hydrogen was first shown at the 2020 Frankfurt motor show. BMW aims to make its fuel cell technology available on a broader scale by introducing a production model around 2025, provided there will be enough demand and the market conditions will allow it. Toyota is also involved in the project, as the two companies have been collaborating on fuel cell powertrain systems as well as scalable, modular components for hydrogen fuel cell vehicles since 2013.

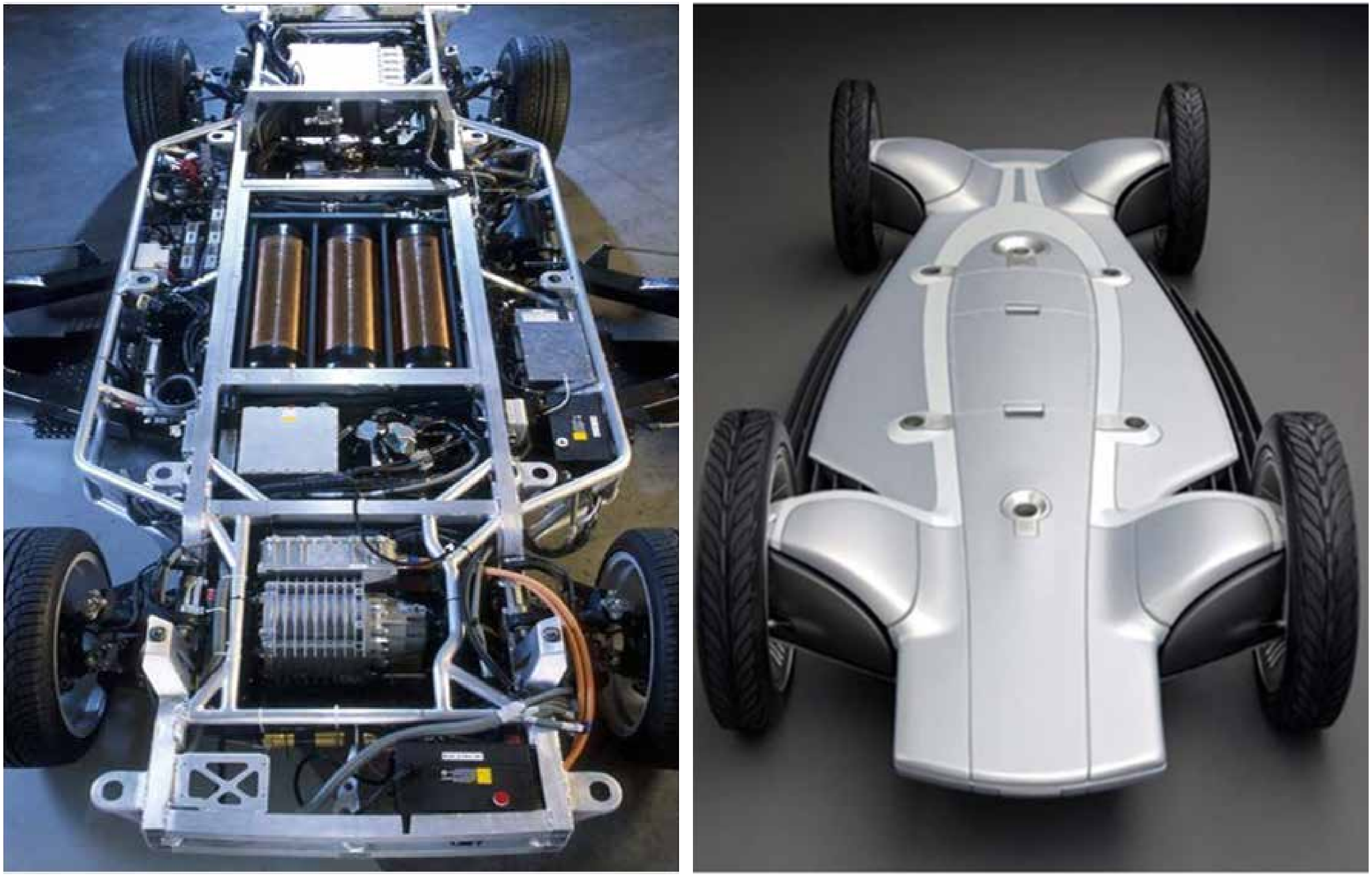
Back in January of 2002, General Motors introduced a vehicle that was powered by hydrogen fuel cells and used a drive-by-wire system, controlling the vehicle entirely via computer. It showcased an entirely new architecture of vehicle manufacturing, wherein multiple different vehicles could be successfully built using a single common chassis thanks to its innovative parts. At about twice the efficiency ratings as a standard internal combustion engine, a fuel cell vehicle could in theory provide about twice the fuel efficiency of a comparably sized vehicle, emitting only water from the tailpipe.

There were no pedals. No instrument cluster. No steering column. The driver was free to sit anywhere within the vehicle, on top of a chassis that allows for hydrogen storage fuel-stacks to store and distribute fuel from all around the vehicle, eliminating the spaces required to house a fuel tank, drivetrain, engine and traditional seating layouts. Today, GM is still investigating in the potential of fuel cell technology, now together with Toyota.

The HyWire has a so-called "skateboard chassis". The control and propulsion systems are all placed in the 11 inch skateboard, allowing GM to maximize the interior space and also making it possible to quickly alter the look of the car with a different bodywork.

The hydrogen tanks themselves are made from composite materials. Three of these units are used in the chassis and have a total weight of 75 kilos (165 pounds). They store gaseous hydrogen at a pressure of 350 bars.

General Motors - Hy-Wire



GM’s HyWire - Photo courtesy of GM

Hydrogen infrastructure

Refuelling stations

In 2018, Belgian-Dutch organisation WaterstofNet started with a project to build 8 refuelling stations for cars within the Benelux: 4 in the Netherlands, 3 in Belgium and 1 in Luxemburg. The project was called H2Benelux. It was funded by the European programme "Connecting Europe Facility" and supported by the Flemish, Walloon, Dutch and Luxemburg government. In the meantime, there are 9 stations available in the Netherlands to refuel your car, spread over the entire Dutch territory. In Belgium there are currently only 4: in Zaventem, Antwerp (2) and Halle.

The hydrogen fuel station in Zaventem, Belgium - Photo courtesy of Air Liquide

‘You’re not going to be selling energy in the future, you’ll be selling life!’, Dr. Hugo Vandenborre

Piping network

In Belgium we have one of the longest hydrogen pipelines. It is about 650km long and belongs to Air Liquide. Important nodes are around the ports of Antwerp and Ghent.

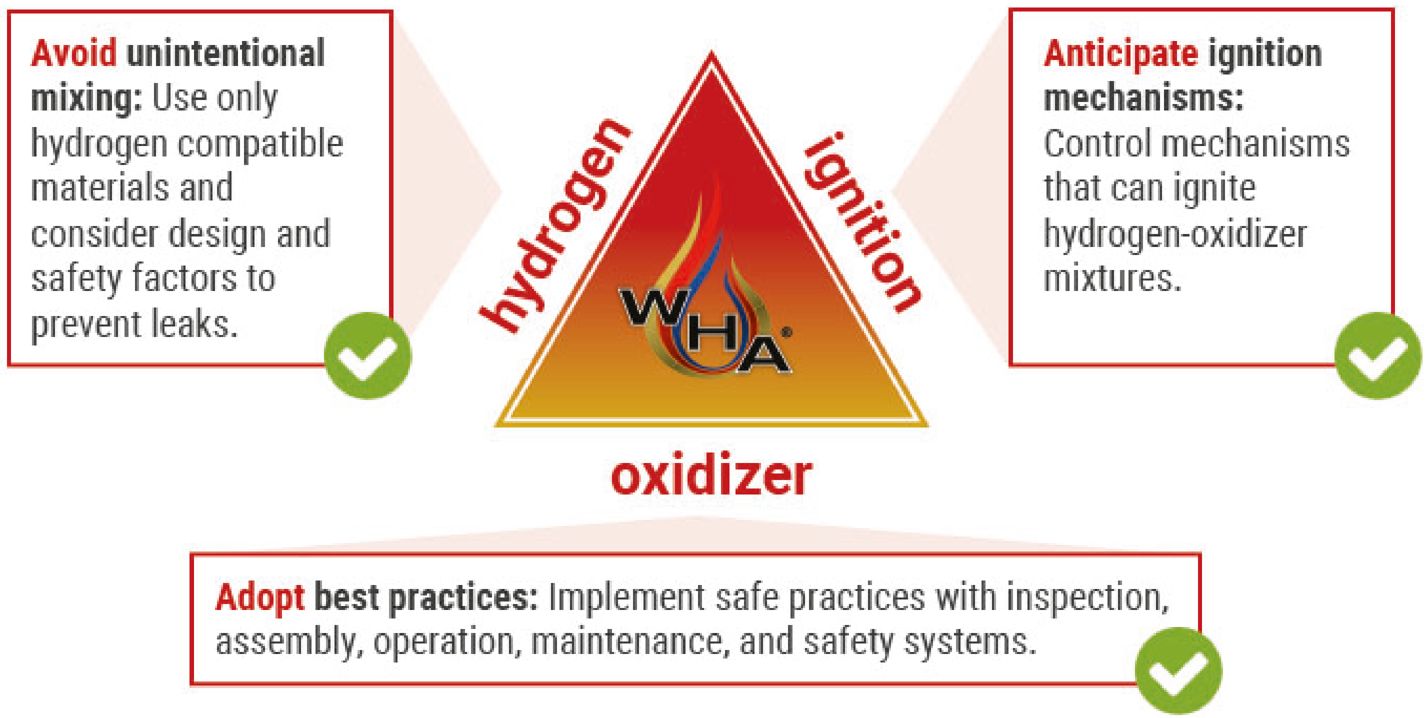
In Germany there is 375km, in the Netherlands around 360 km. France only has about 300 km and Great Britain as little as 40 km of piping. In the entire United States, there is approximately 1,200 km of hydrogen piping, especially in Texas and Louisiana.

The hydrogen piping network in Belgium and its neighbouring countries - Photo courtesy of Air Liquide

Safety

Like any other fuel, the right safety regulations must be observed when using hydrogen. Hydrogen is highly inflammable and very explosive. Hydrogen ignites with a 4% concentration in air and is explosive at 18%.

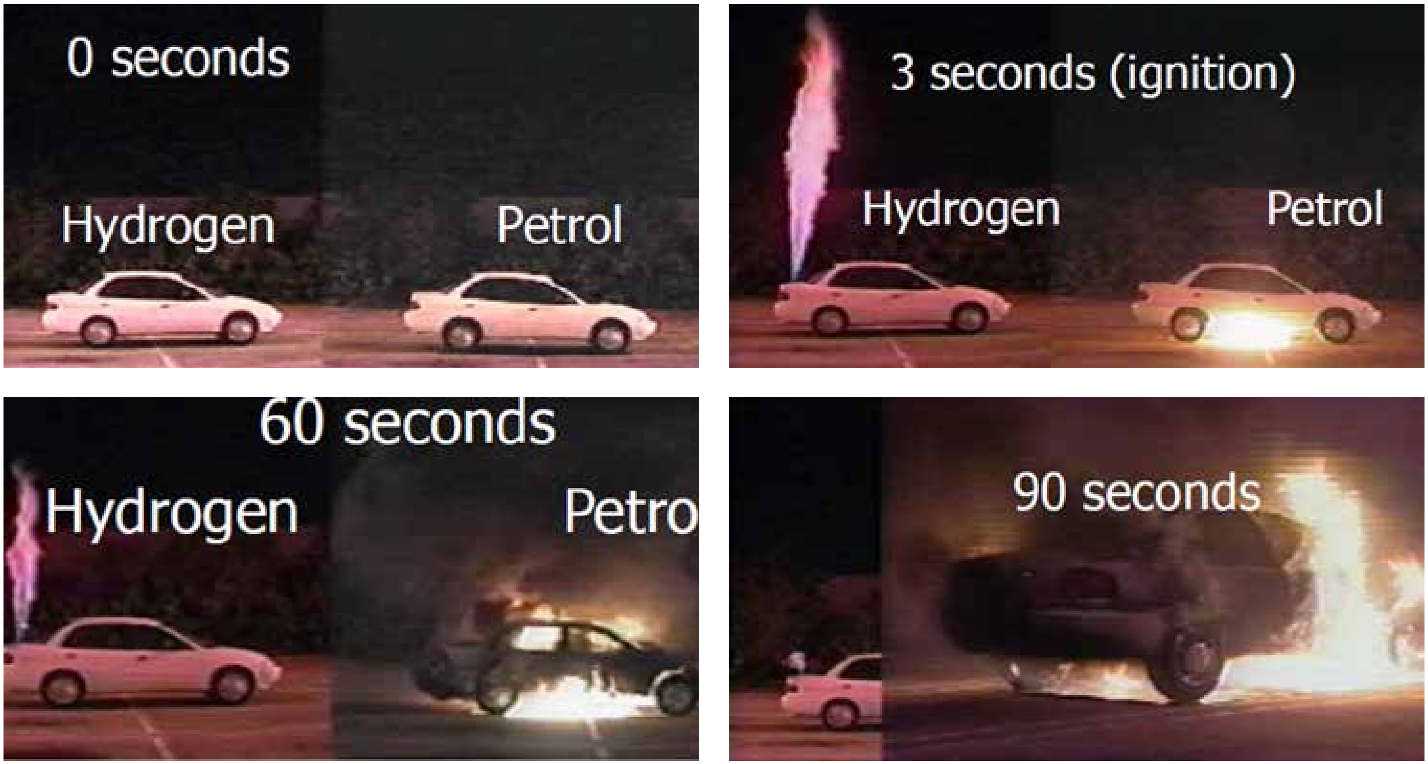
Safety, as for any combustible substance, means that users must be aware of the so-called fire triangle. For combustion, three elements are necessary: the fuel, an oxidant and ignition.



The safety triangle - Photo courtesy of WHA

Fire only occurs if all three elements are present. The oxidant is usually common oxygen that already accounts for 20% of the air. Safety preferably means excluding two of these elements, e.g. no smoking when refuelling or handling hydrogen; and avoiding contact with air. Most companies working with hydrogen will have a hydrogen detection system that will give an alarm as soon as the sensors detect hydrogen. Also, a ventilation system can be added that comes into action as soon as the sensors notice a minimum of hydrogen. In any case, if the correct precautions are taken and measurements are followed up, there is no reason at all to be afraid to use, store or work with hydrogen.

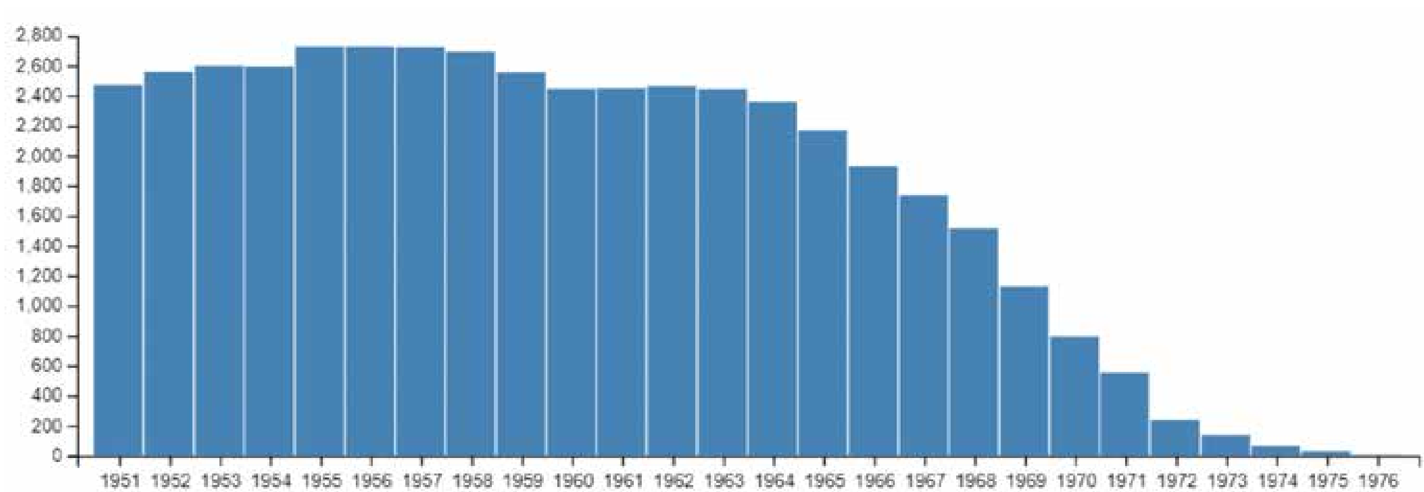
Also, let us not forget that we use gasoline, diesel or other fossil fuels every week, if not every day. It has become routine, and we do not dwell on the fact that 40 litres of gasoline has as much energy as 300kg of TNT. “If we compare the safety of gasoline to that of hydrogen, hydrogen actually comes out better”, as quoted by Ford motor company. Hydrogen gas of course is more flammable and more explosive than gasoline, but it is also much more volatile. In the most exceptional case of a fire in the gasoline tank, the gasoline will spread underneath the car, because it is heavier than air. Gasoline also burns longer than hydrogen and produces suffocating gasses.
To conclude, safe storage of hydrogen is absolutely necessary, preferably under pressure, to prevent mixing with air.



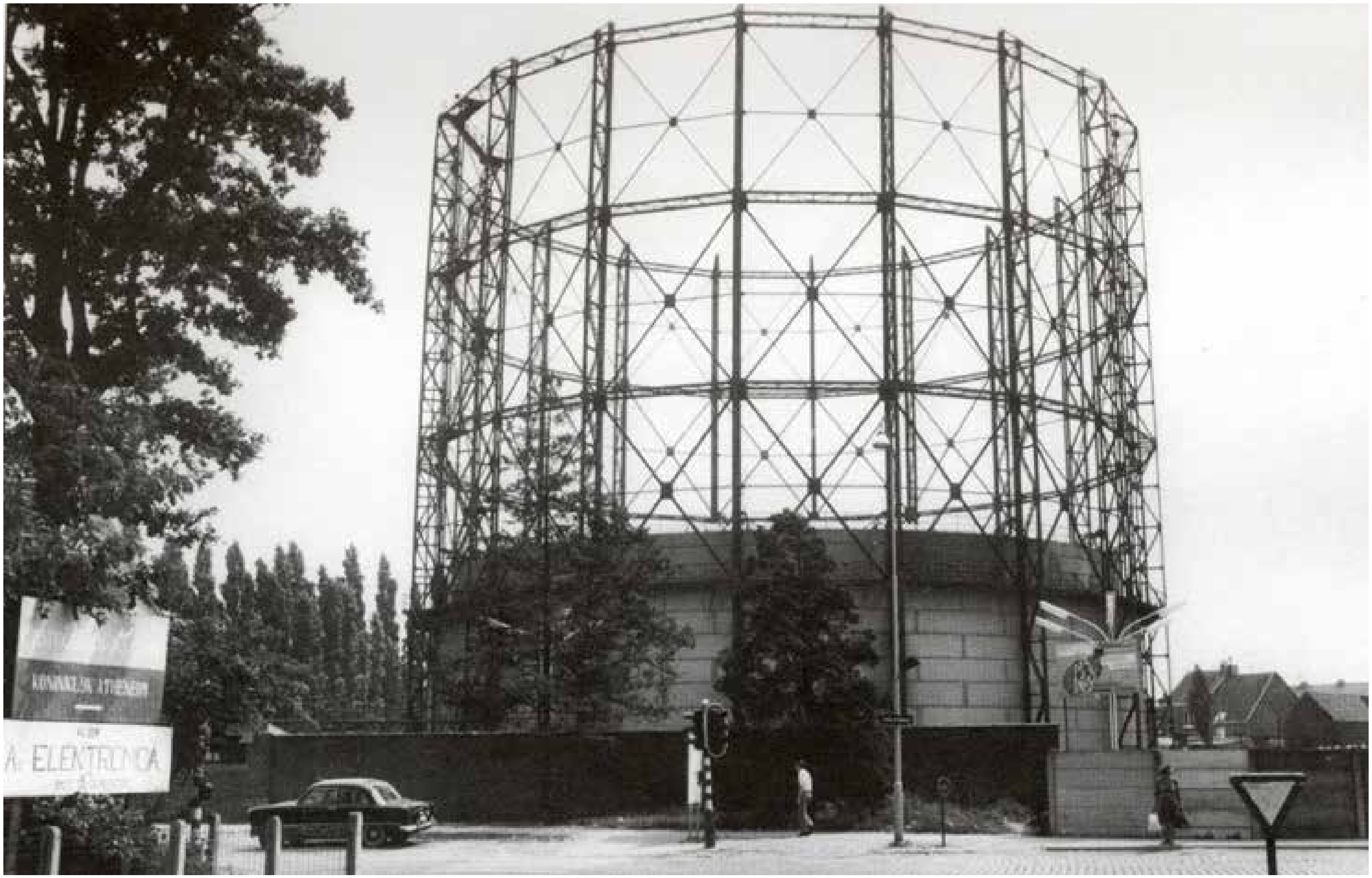
Experiment at the University of Miami, Florida, showing the difference of what happens to a hydrogen car and a petrol car x number of seconds after ignition.

Town Gas

Most people might not know it, but hydrogen is already actively in use for over 100 years. The so called "town gas" was commonly used to heat homes until the first half of the 20th century. Town gas or coal gas made from coal, was a mix of around 60% hydrogen mixed with methane, carbon dioxide and carbon monoxide. The gas was used for heating and lighting people's homes before the supply and transmission of natural gas became widespread. In the UK, town gas was used throughout the 19th century for street lightning. Between 1962 and 1976 the UK experienced a decline of coal as a feedstock for town gas. This gas was sometimes also used for a more ill-fated purpose namely, to commit suicide. However, hydrogen was not to blame, they died from carbon-monoxide poisoning.



Coal-based town gas production, millions of therms - British Gas (1980)



Picture of a town gas installation in Belgium

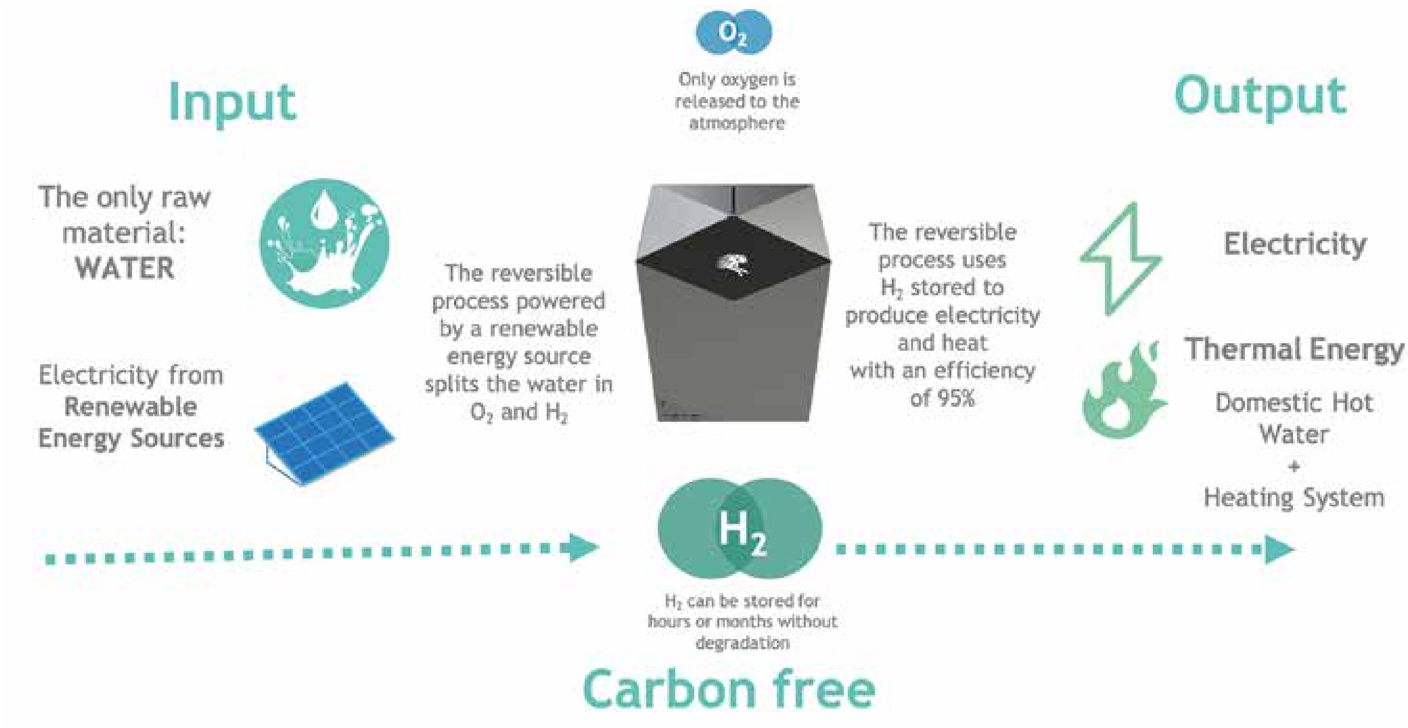
Energy storage - Powerbox

It is clear that hydrogen fuel offers the largest potential benefits in terms of reduced emissions of pollutants and greenhouse gases. But the development of a hydrogen infrastructure is often seen as a technical and economic barrier. A widespread hydrogen distribution infrastructure does not currently exist, although the technologies to produce, store and distribute hydrogen are commercially available today.

But imagine that in the future, you could drive your hydrogen car into your garage and gas it up at your own home hydrogen fuel station. Solenco Power - a start-up I founded in 2015, is focusing on making this concept a reality. The Solenco Powerbox does not only refuel a hydrogen car, but it can also power a home through electricity and heat.

This is how it works. Solar panels act as the sole source of energy input. Electricity needs are covered by the solar panels during daytime and only the surplus is sent to the Solenco Powerbox. This unit then splits the water molecules and produces hydrogen. The latter is stored as a pressurized gas. When there is no sunshine, electricity is produced from the stored hydrogen and at the same time heat is produced together at 95 % efficiency.

The heat covers hot water needs for heating and sanitation. In the framework of a demonstration project financially supported by the European Commission, a few systems of the Powerbox were installed in Belgium during 2021 and are now a fully certified product ready for commercialization.



Reversible Fuel Cell process

Excess renewable energy is used to generate green hydrogen.
It stores energy for long term (from hours to seasons)

It assists the hot water needs for heating and sanitary water.
If production of heat would be higher than requested, heat is stored in a hot water tank

The Powerbox is a triple- zero-carbon system. Production, storage, and usage are free of greenhouse gases.

Solenco Powerbox

Hydrogen storage

The Powerbox has the following integrated components that work seemlessly together and are controlled via a cloud enabled software platform:

- Electrolyser mode
- Fuel cell mode
- Power electronics and AC/DC rectification and conversion
- Water treatment system
- Hot water tank and cooling loop
- Safety system
- Smart energy software control system

The hydrogen compression and storage is not integrated and is done in gas vessels that are certified for high pressure hydrogen storage.
The Powerbox can be delivered for indoor or outdoor applications.

Monitoring & control software

Solenco's developers environment will use all the data acquired to generate software updates. The results of 1) data analytics, together with 2) energy profiles, 3) user behaviour, 4) weather data and 5) existing prefab models, will provide insights in how to optimize the operation of each installation based on machine learning, towards virtual power plants.

Personal thoughts

The Stone Age did not end because the stones ran out

For decades we have exhausted and polluted the earth with fossil fuels. Today we are faced with an evolution comparable to the transition from horse and carriage to an internal combustion engine-powered car.

That evolution - which took place over a hundred years ago - was surrounded with many doubts about the safety of the fuel and its availability. In the beginning, there was no fuel infrastructure and fuel had to be taken from the pharmacy - as it was seen as very toxic.

Critics denounced the loss of jobs in the horse-breeding and cart-building sectors. But gasoline and diesel vehicles prevailed and quickly they fundamentally changed our transportation system and our way of living and working.

Nowadays, we are equally aware of the disadvantages of a transportation system based on fossil fuels - our towns and our environment have been seriously damaged. Moreover, the earth's oil reserves are not infinite and are often located in political flash points, which makes price and availability very unstable.

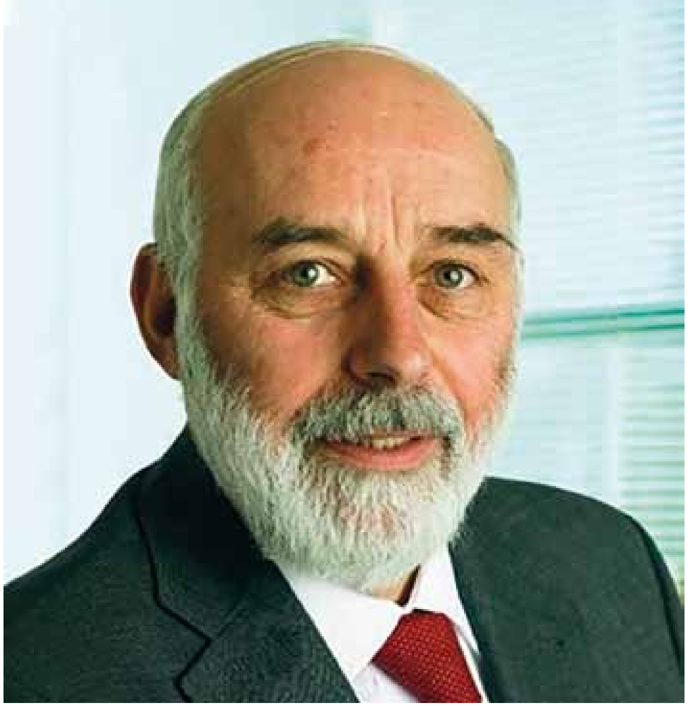
Hydrogen and Fuel Cell Technology offer us a new approach to the supply of energy. It does not make sense to try and resolve the major environmental crisis with binding emission targets. We need a new development paradigm, a development model that will lead to a healthier world.

I do hope that large-scale implementation of state-of-the-art hydrogen and fuel cell technology combined with future developments will lead us to a world based on a green (sustainable) and blue (water) energy system. Solenco Power and myself will keep contributing to this goal with the roll out of the new products, Powerhub and Solyzer. Together, we will discover these products in the upcoming volumes as part of this series of books.

Jonas Vandenborre, the youngest heir of the family, looking into a bright hydrogen future

Useful links and relevant websites

Energy Hydrogen Alliance: http://www.h2euro.org
Fuel Cell & Hydrogen Energy Association: http://www.fchea.org
Fuel Cell and Hydrogen Joint Undertaking: http://www.fch.europa.eu
Fuel Cell Today: http://www.fuelcelltoday.com
Hydrogen and Fuel Cell Safety: https://www.hydrogenandfuelcellsafety.info
Solenco Power: https://www.solencopower.com
Solenco Power GmbH: https://www.solencopower.de



Dr. Hugo Vandenborre is President and CEO of Solenco Power NV - a new venture he founded in 2015. With the help of joint shareholders VINCI Energies SA, Giacomini SpA, Energiek BV, Joris Van Dyck and HESTIA Holdings NV, the company focuses on residential, community, commercial and industrial energy storage based on hydrogen technology.

Among various other positions, Dr. Vandenborre was Chairman of the European Electrochemical Engineers and the International Hydrogen Energy Association. He is a founding member of HYNET, the European Thematic Network on Hydrogen; Marine Hydrogen & Fuel Cell Association; Joint Undertaking of the European Commission and Masterplan & Implementation WaterstofNet.

He was part of various European and International Committees and was selected as one of the 12 members of the High-Level Group who wrote the pathway towards Hydrogen and Fuel Cells for former European President Romano Prodi.
He was Chairman and Executive VP of Stuart Energy, a public company listed on Toronto Stock Exchange. After a merger, he became co-founder and vice Chairman of Hydrogenics Corporation, a NASDAQ listed Company (HYGS).

He obtained his Doctorate of Science in Physics (maxima cum laude) at the University of Leuven, Belgium after completing his studies at the Institute of Science in Jülich, Germany and Brookhaven National Laboratory, New York, US.

He was keynote speaker at various international hydrogen conferences and has published over 200 international articles. He has over 85 patents to his name. He recently (2021) was honoured by King Filip for his vision and pioneership on hydrogen and he is now a member of the Order of Leopold, the oldest (1832) and most distinguished Order in Belgium.

In 1969, he married Grete Van den Troost. He has three children - Bieke, Hans and Dorien. He has two sons-in-law - Nico and Manu -,
a daughter-in-law Kathie and eight grandchildren. He was born in Kampenhout and lives in Kasterlee, Belgium.