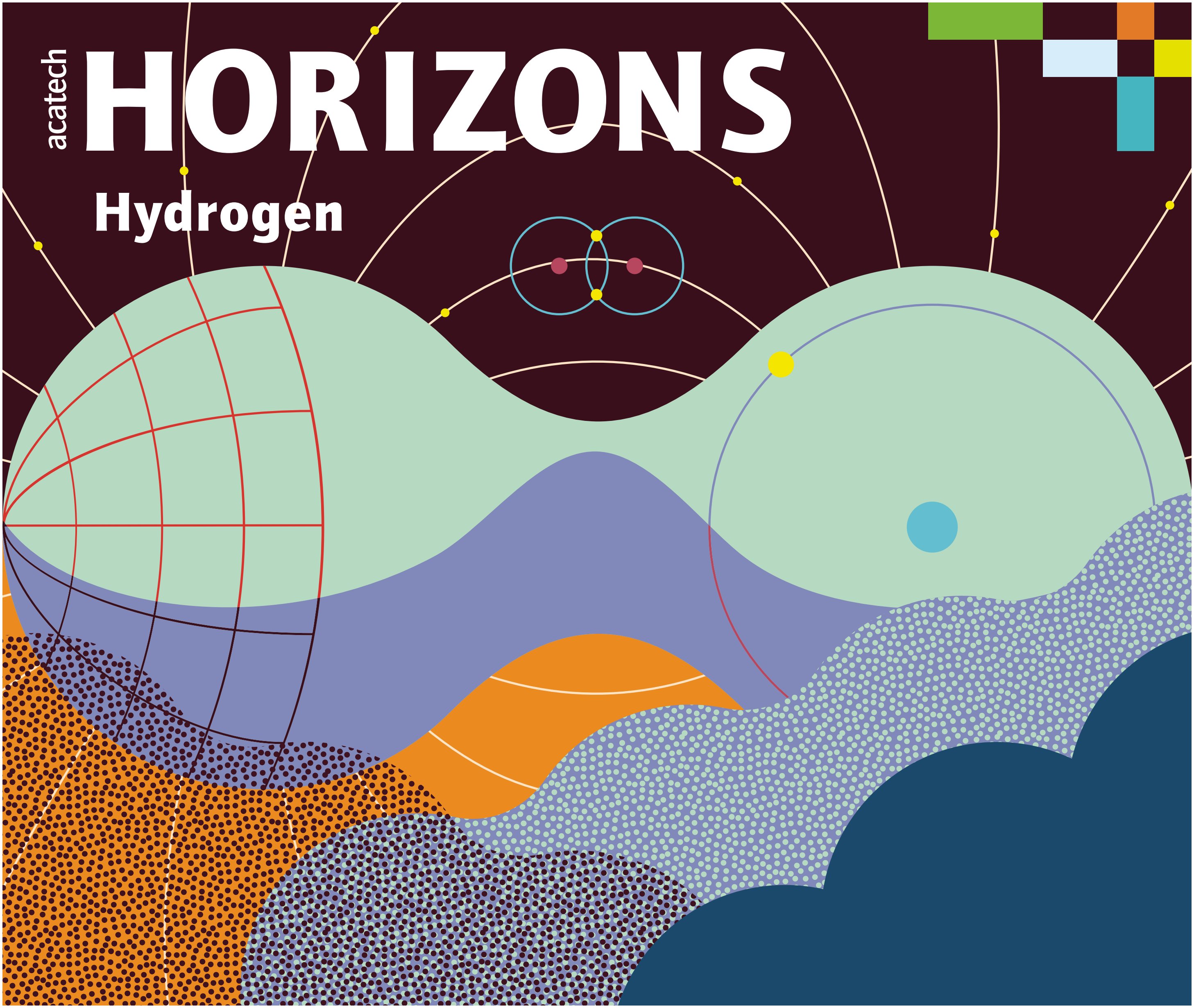
acatech

HORIZONS

Hydrogen



What is hydrogen and why is it important?

What's already possible today? Where do we want to get to?

So, how and where from? The global perspective

What needs to happen now?

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NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

The acatech HORIZONS series makes hot topics in technology accessible to anyone who's interested. Each issue is dedicated to a field of technology which opens up new horizons, is economically significant and enables societal change. Drawing on the latest research, acatech HORIZONS take a well-founded and clear approach to these fields of technology, explaining the facts and addressing societal, macroeconomic and political issues as well as options for the future.

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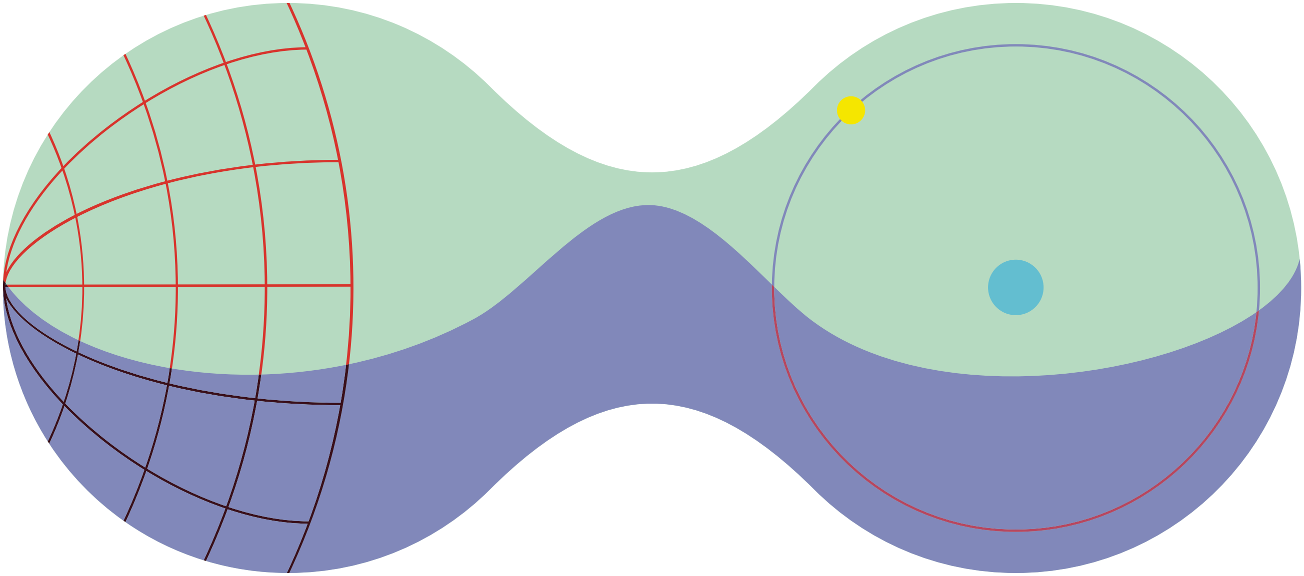

Contents

Eight facts about hydrogen

1. Hydrogen has existed since roughly three minutes after the **Big Bang** and is the most abundant element in the universe. On earth, hydrogen mainly exists not in pure, but in bound form, such as in water.

2. If we want to make use of hydrogen, we must *convert it into pure form*. It is only truly **climate-friendly** if we use renewables such as wind and solar energy to do this. This is what is known as "green" hydrogen.

3. Hydrogen affects us all and is **key** to Germany's **energy transition** and **climate targets**. It is *the* opportunity to leave fossil fuels such as natural gas, coal, and oil behind once and for all.

4. The possibilities are huge. We can use hydrogen to transport renewable energy from A to B, to manufacture climate-friendly steel in future, ship goods more cleanly or to fly in a more climate-friendly way. It is, therefore, also **key** in the **future of the European industry**.

5. Green hydrogen has the advantage that it can be produced anywhere where there is plentiful availability of land, wind, and sunlight. However, Europe and particularly Germany do not have enough of these resources, which makes us **dependent on imports.**

6. At the same time, we *now* have the opportunity to **reshape the energy map** after decades of dependence on oil and natural gas. This means forging new **trust-based energy partnerships** on an equal footing with as many different regions of the world as possible and **diversifying energy imports through a variety of routes.**

7. Hydrogen can not only help achieve climate goals, it is also a **huge business opportunity**, from which all countries can benefit. Europe is *still just* in the race as we are still at the technological **forefront**. We have to maintain our **know-how** and stay in the race once **hydrogen** really takes off: the race against time has begun.

8. If we[a] get it right, in the coming years we will be able to **export cutting-edge European technology and know-how** and **import climate-friendly hydrogen**, while more jobs, progress and **environmental prosperity** will be created in the **Global South**. Hydrogen is, thus, also a real opportunity to distribute **prosperity more *fairly* around the world**.

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a Who is meant by "we"? For ease of understanding, this issue of HORIZONS makes frequent use of phrases including "we", such as "we have to get going" or "we are at the technological forefront". This is also common in political discourse and facilitates reading and debate. At the same time, it is possible to have a negative view of such "we" phrases. For instance, they could give the (erroneous) impression that all stakeholders, whether they be policy makers, businesses, societal players, or even nation states, might be willing to pull in the same direction when it comes to overcoming global challenges. The realities of a decentralised market economy mean that corporations have their own economic interests and do not necessarily act in the interest of the common good. At global level too, nation states have their own vested interests. Using "we" might lead to an idealised view of the feasibility of the reform and transformation processes involved, for instance, in the energy transition and climate targets. Of course, acting as "we" in these contexts is highly desirable but doing so requires great effort and will not always meet with success. It is important for us to make this distinction because acatech's goal is to provide policy makers and society with independent, fact-based information on a non-profit basis.

1 What is hydrogen and why is it important?

Welcome to the fascinating world of hydrogen. Why is everyone talking about it? Does it have anything at all to do with me as an ordinary citizen? What potential does hydrogen have for the environment and the climate? Find out more in our first section of this issue of HORIZONS.

Do you have any idea where all the hype about hydrogen is coming from? Scientists and politicians from all over the world have been racking their brains about it lately, the media are reporting on it, and industry wants to produce it and put it to use as quickly as possible. Yet the element hydrogen has been around for a very long time and is even **older than the history of humanity!** Hydrogen is being hotly debated today and ever more countries are considering their own hydrogen strategies, because it will play a very significant role in our future. But it's not that simple, we're only at the beginning and **many issues remain to be clarified**. Our **first illustration** shows what we mean when we talk about hydrogen.

Why is hydrogen so important? Does it have anything at all to do with me?

The possibilities for making use of climate-friendly hydrogen are huge: we can transport renewable energy from A to B, manufacture climate-friendly steel in future, meet global food needs with climate-friendly fertiliser or ship goods more cleanly (see section 2). So, when we talk about hydrogen, we mean a whole **family of climate-friendly technologies and solutions** which leave the **smallest possible carbon footprint.**

Hydrogen is, thus, becoming a **key factor** in the **energy transition and climate targets.** It is the opportunity to **leave fossil fuels** such as natural gas, coal, and oil **behind once and for all**. At the same time, it is key to the **future of the European industry** and, therefore, to our jobs, too. So, this much is clear: hydrogen **affects us all.**

"Hydrogen is not a hype topic - it's essential to securing energy supplies and achieving climate targets. I can't see a future without hydrogen."

"The elephant in the room when it comes to the current debate is the challenge of volume: the quantities of hydrogen we need are vast."

European Green Deal: on the way to the first climate-neutral continent?

You will most likely have heard about the European Green Deal. It's a kind of roadmap for a sustainable EU economy, defining a new strategy to help **Europe achieve an environmentally friendly, resource-efficient and competitive economic model**, which is designed to be fair and inclusive for all. So, quite a tall order! The ambitious goal is to be **greenhouse gas-neutral by 2050** and, thus, become the world's first climate-neutral continent. Germany is even going one step further and wants to achieve this by 2045. Moreover, as part of the Green Deal, the EU set out its own **hydrogen strategy** in 2020.[1]

You are probably wondering how far we've come already? Well, we're still pretty much at the beginning. The illustration What is an electrolyser? shows that obtaining hydrogen in pure form does not involve any technical wizardry. Nevertheless, **we will first have to build the infrastructure**, in some cases from the ground up, including electrolysers, hydrogen terminals and pipelines, in order to produce[2] and transport the **huge quantities**[b] **of hydrogen** which will be required (see section 2, illustration Storing and transporting energy with hydrogen). We'll also need **many raw materials** to do this (see section 3, illustration Where can we get the raw materials for an electrolyser?) and vast amounts of renewable energy. Europe in particular will have to forge new partnerships with other regions of the world which have plentiful raw materials, wind, sunlight and open spaces because Germany and Europe do not have enough (see section 3). It will probably be **a decade** until we have this infrastructure in place and are producing hydrogen in large quantities and transporting it worldwide. **A hydrogen economy** is the goal all countries are pursuing (see section 4).

"The energy transition is actually not a difficult task. We're just making life difficult for ourselves because we want to dot every "i" and cross every "t".But we can't go on researching until we understand everything; we didn't start with the iPhone X when it came to smartphones either. We just have to start."

We don't have much time; **climate change isn't waiting** for anybody. We're already experiencing extreme weather such as heat waves, floods, and droughts with increasing frequency around the world. We need to ***get going*** *now* and move forward as quickly as possible. The good news is that every tonne of CO_2 we save today won't have to be extracted from the atmosphere later. The **costs** we're paying today for the **energy transition** and to develop the hydrogen economy, **we will save later,** when the damage is so great that we will no longer be able to repair the **consequences of climate change**.

Henry Cavendish discovers "inflammable air"

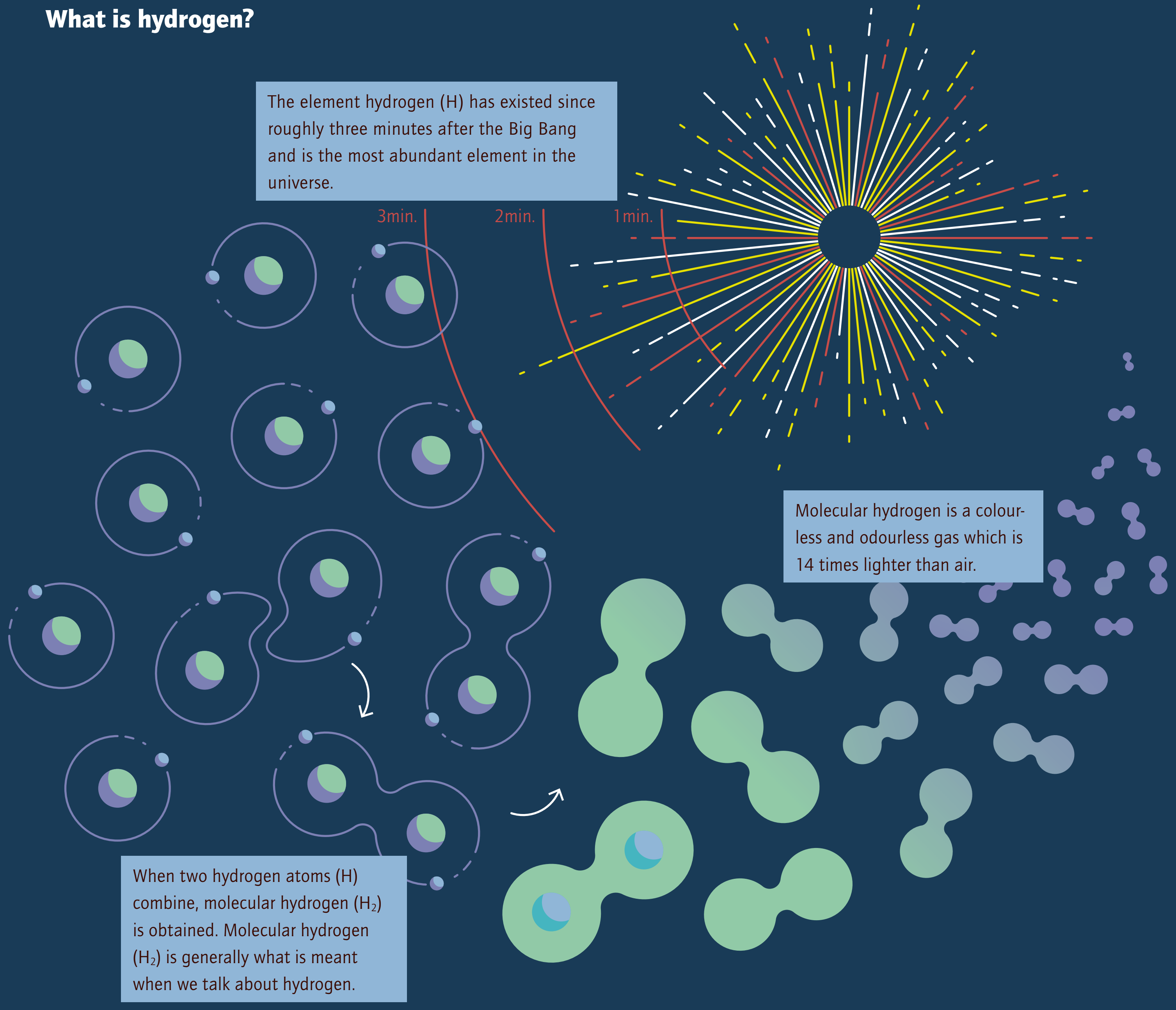
In the 18th century, the British nobleman Henry Cavendish wanted to know what happens when metals react with acid. His experiment produced **a gas that burned very well**. He, therefore, called the gas **"inflammable air"**. As you may well have guessed, this inflammable air was hydrogen. Cavendish demonstrated that **burning hydrogen produces only water.** But hydrogen is becoming so important today because burning **it releases energy which we can use.** Unlike oil, natural gas or coal, this process **does not release environmentally harmful CO_2, but water.**

Fun fact: energy transition

Did you know that it was in Germany where the concept of the energy transition originated back in 1980? Since then, other countries have adopted the idea and, in specialist circles, sometimes even use the German term "Energiewende".
Germany faces the challenge of simultaneously **phasing out nuclear energy and fossil fuels,** which is a particularly **difficult task for an industrialised nation.** This makes hydrogen all the more important!

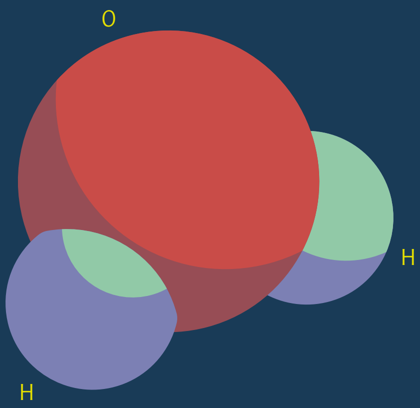
b What are huge quantities? According to calculations for the German federal government's hydrogen strategy, Germany will have an estimated annual hydrogen requirement of 90–110 terawatt-hours (around 3.4 million tonnes) by 2030. It is still unclear how much of this Germany will have to import. Studies have calculated that annually between 50 and 90 per cent of Germany's requirements for hydrogen and its synthesis products, such as ammonia or methane, will have to be purchased from other countries.[2]

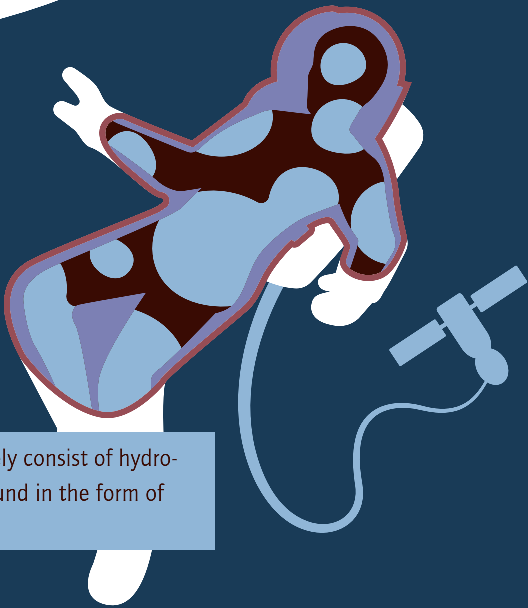
What is hydrogen?



Source: own illustration

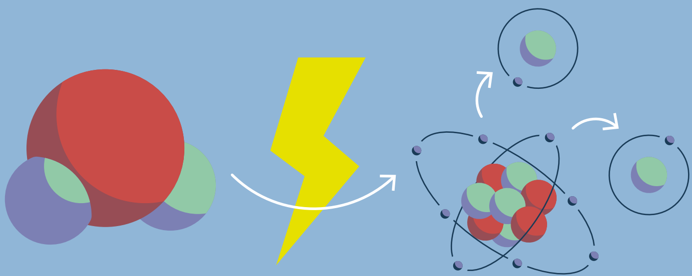
On earth, hydrogen is mainly not in pure, but in bound form, for instance combined with oxygen (O) to form water (H_2O).



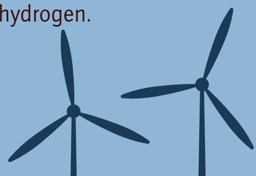


Our bodies largely consist of hydrogen which is bound in the form of water.

If we want to use hydrogen, we first need to obtain it by splitting water into its components, hydrogen and oxygen, a process which requires electricity.



Only if the electricity is obtained from renewable energy sources is the hydrogen known as climate-friendly, "green" hydrogen.



There's no ideal solution to the energy policy triangle and we, the people, will have to decide

Wouldn't it be great if we could meet all three goals, **environmental and climate compatibility, security of supply and affordability, simultaneously and equally well?** The theory of the energy policy triangle explains how things unfortunately look in reality: the closer we get to one goal, the further away we move from another. If we opt for environmental compatibility, i.e. climate-friendly hydrogen, we have to pay more because hydrogen is currently more expensive than fossil fuels, while the latter take us closer to affordability, they take us further away from environmental compatibility, because they result in CO_2 emissions. Neither is security of supply assured in the event of war or political instability if we are always guided by the lowest prices. One last example: if we increase the share of renewables, we get closer to the goal of environmental compatibility but further away from the goal of security of supply, since wind and sunlight are not always available precisely when we need them. Consequently, there is **no ideal solution**. We have to **weigh up between these three goals.** Which way we want to go is a political decision, and we all have a right to shape the way forward together. Ultimately, **politics is a reflection of society** and, as **voters** and **citizens**, we can make a big difference. For instance, the **Fridays for Future** movement has helped push the issues of the **energy transition** and **climate targets high up the agenda of political parties in countries** around the world and even at the United Nations. This is an example of how a group of (young) **people** can start a worldwide political movement and help **shape political events**.
It is just as important for politicians to **inform the general public** and **include them in these considerations**, in order to create acceptance when it comes to the construction of new wind or solar farms, for instance. **Only if society goes along with and plays an active role in shaping the energy transition will it be a success**.

Incidentally, hydrogen is not only green, but multi-coloured, as shown by the following illustration The hydrogen colour spectrum: a typically European debate?

Hydrogen only counts as **green** and climate-friendly if we produce it in an electrolyser using renewable energy. Another route is to use a steam reformer to heat hard coal, brown coal or natural gas with water and so obtain hydrogen, which is then known as **black, brown** or **grey** hydrogen. The drawback is that climate-damaging CO_2 is released. **Blue** or **turquoise** hydrogen work in the same way, though with the difference that no CO_2 is released into the atmosphere but is put to further use or stored underground as solid carbon. **White hydrogen**, also known as natural hydrogen, occurs in natural deposits in molecular form but there is relatively little of it. **Pink hydrogen** is hydrogen produced using nuclear power. If biomass such as biowaste is used as the starting material, the product is known as **orange hydrogen**.

> "The pathway to green hydrogen is multicoloured."

Biotechnologists are working on other processes that are still at the test stage. In the future, what are known as cyanobacteria will be able to produce hydrogen from water via photosynthesis. This is a climate-friendly process which also consumes few resources.

The hydrogen colour spectrum: a typically European debate?

Hydrogen is an odourless and colourless gas which can be produced in various ways. Each one is labeled with a different colour.

How's it been done so far? Hydrogen has for many years been produced using fossil fuels such as coal and natural gas. This leaves a large carbon footprint and harms the environment.

The goal: To achieve climate targets. In the long term, Germany and Europe are backing green hydrogen from renewables.

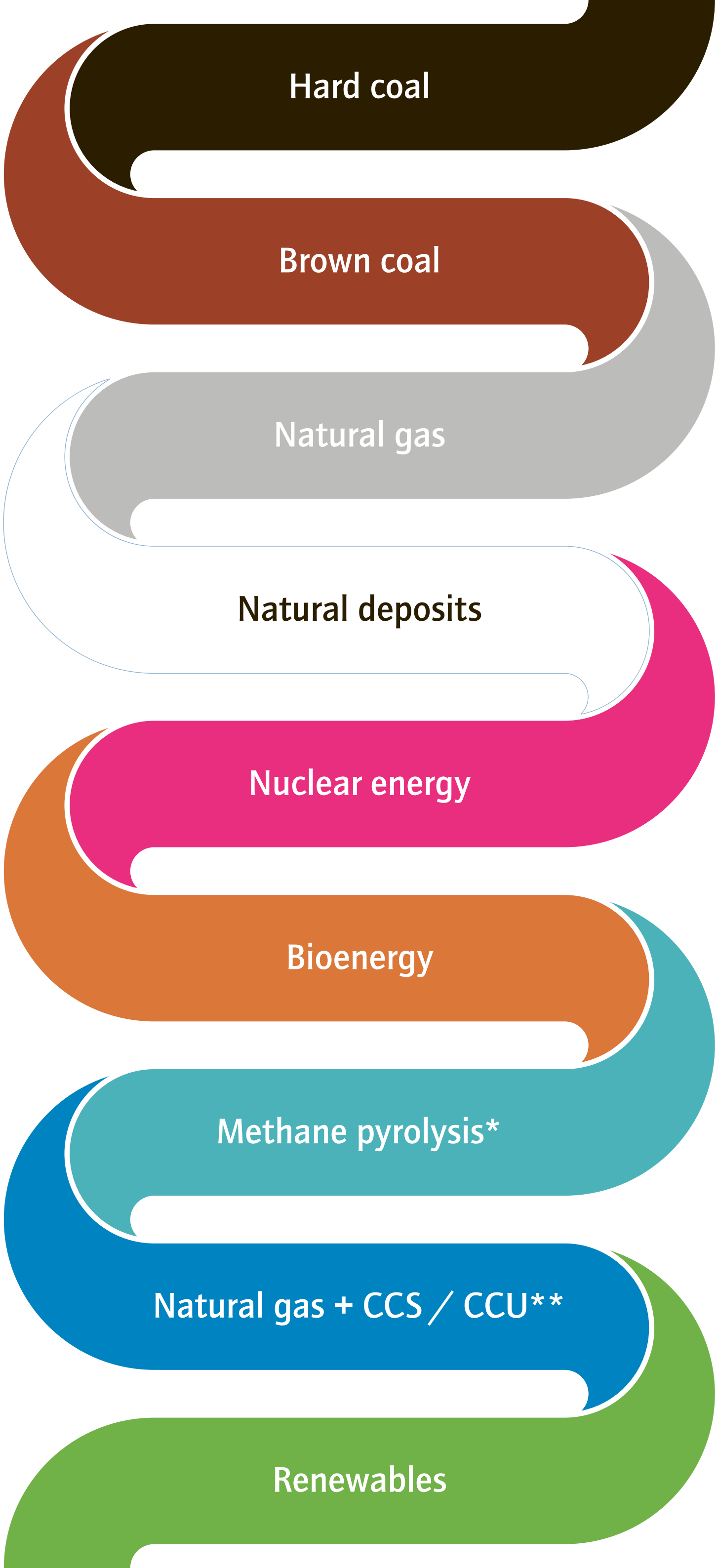
The problem: It will take many years until we have the infrastructure in place and are able to manufacture the vast quantities required.

Getting there: Interim solutions, such as blue hydrogen obtained from natural gas, in which CO_2 is not released into the atmosphere but instead stored, will enable us to reduce the carbon footprint progressively during the transitional phase.

Good to know: Not all countries are debating whether hydrogen is pink, turquoise, blue or green. All that matters is: it's hydrogen. In Europe, however, the colour spectrum is being hotly debated.

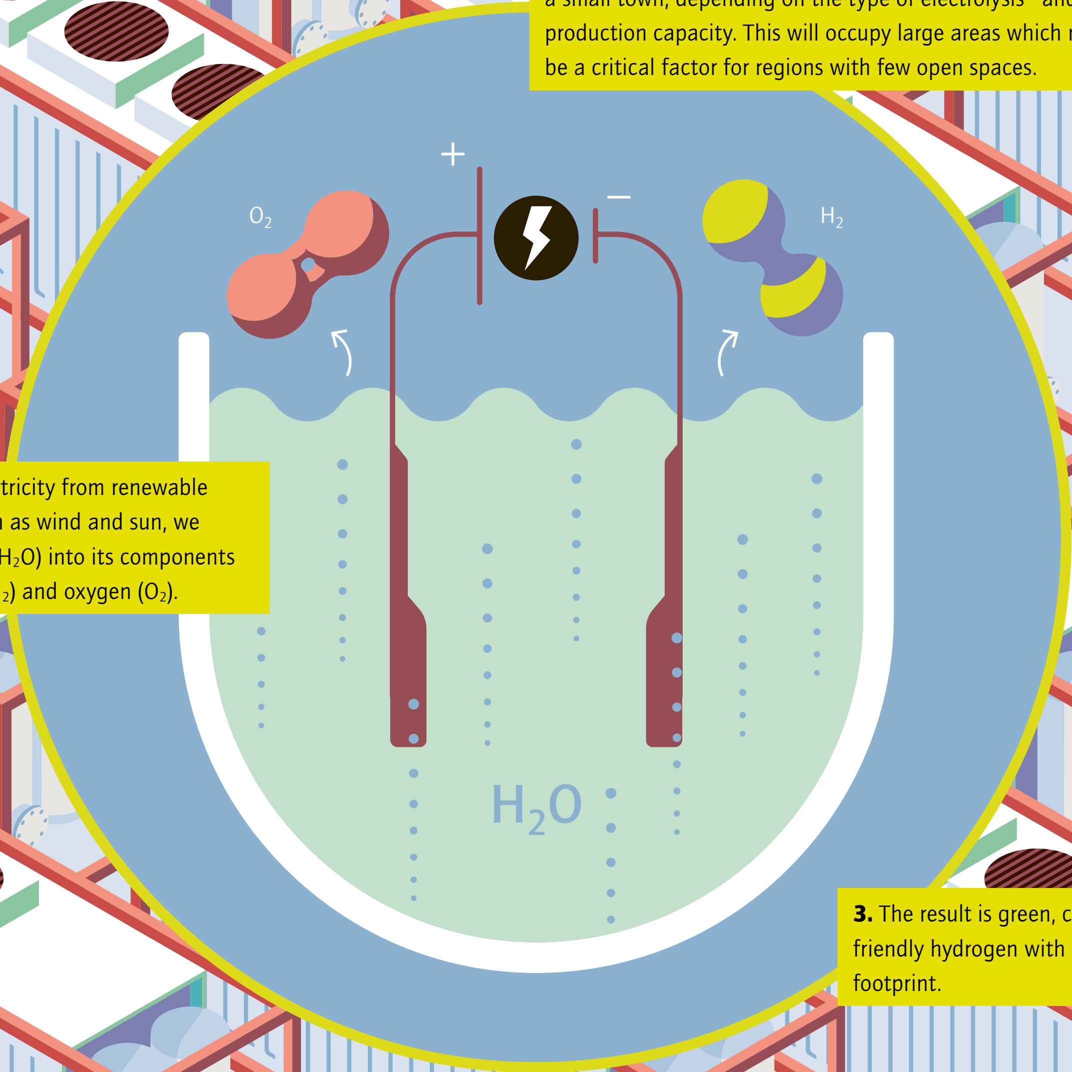
*In the case of turquoise hydrogen, methane from natural gas is split into hydrogen and solid carbon.

**In the case of blue hydrogen, natural gas is split into hydrogen and CO_2. The CO_2 is stored or put to further use so that it is not released into the atmosphere (CCS/CCU = Carbon Capture Storage/Utilisation).



What is an electrolyser?

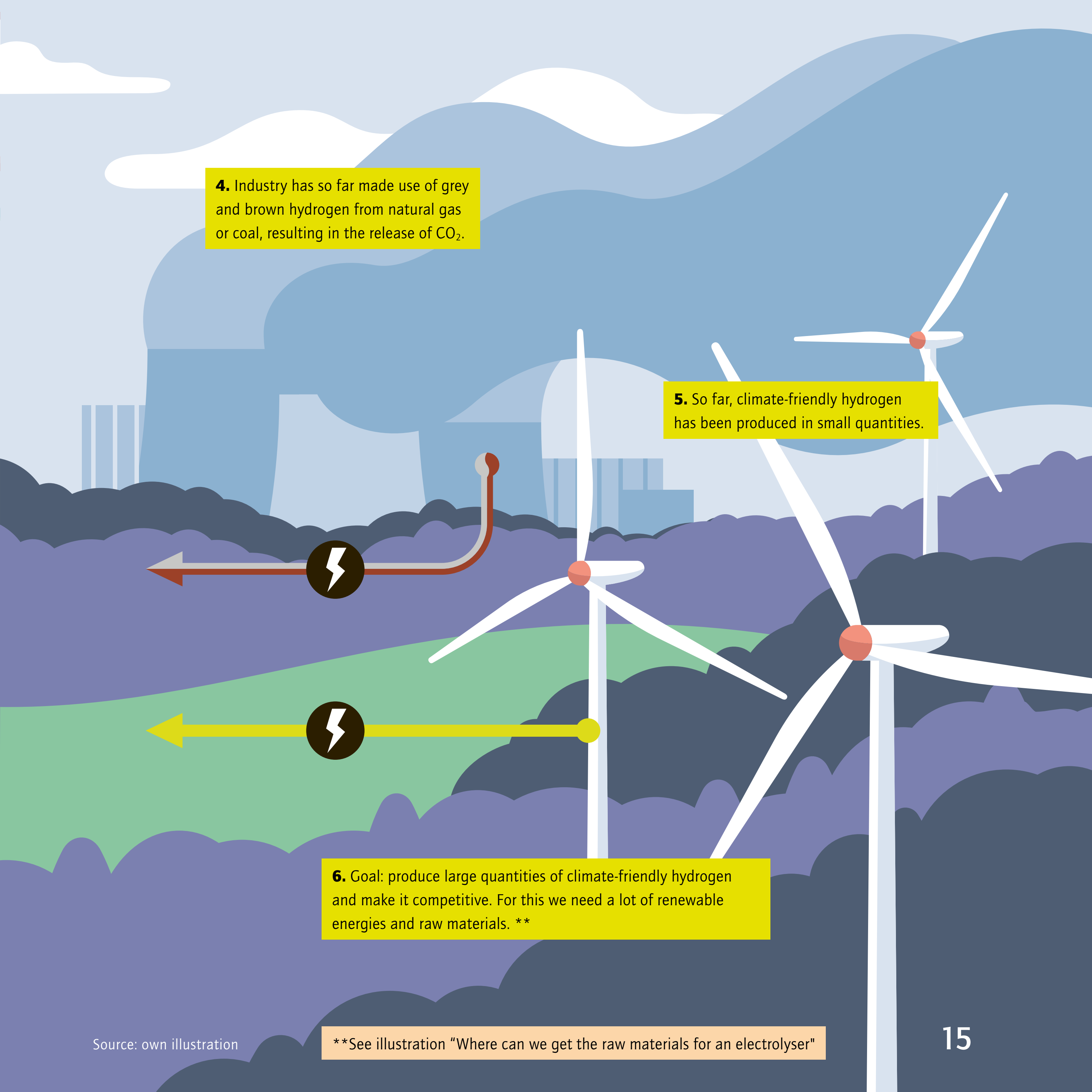
1. Electrolyser: produces hydrogen. In the future, large industrial plants will consist of multiple electrolysers, tanks, pipelines, wind, and solar farms. They may be as large as a small town, depending on the type of electrolysis* and production capacity. This will occupy large areas which may be a critical factor for regions with few open spaces.



2. With electricity from renewable sources such as wind and sun, we split water (H_2O) into its components hydrogen (H_2) and oxygen (O_2).

3. The result is green, climate-friendly hydrogen with no carbon footprint.

*We have shown an alkaline electrolyser by way of example. This is just one of several technologies. In the meantime, research on other electrolysers is ongoing, each with their strengths and weaknesses.

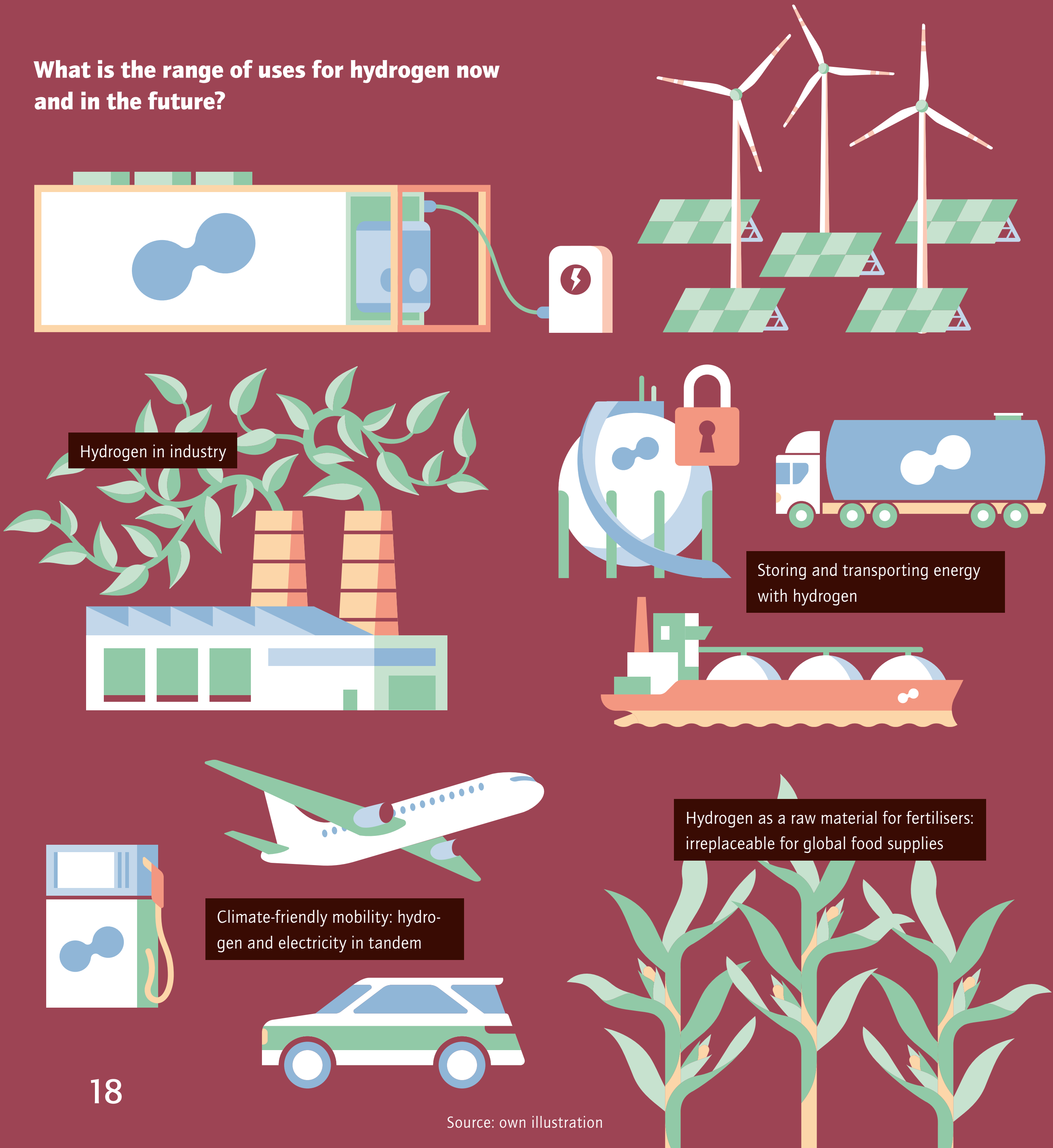


Source: own illustration

2 What's already possible today? Where do we want to get to?

Whether as raw material for industry, as an energy storage medium or in transport applications, we can't get by without climate-friendly hydrogen. What's technically possible today? What are the obstacles and where do we want to get to? Section 2 illustrates where hydrogen can be put to use today and in the future; four different areas are shown in the following illustration.

What is the range of uses for hydrogen now and in the future?



Source: own illustration

Hydrogen in industry

Hydrogen is the oldest element in the universe. **Humans have been using hydrogen for about a hundred years**, but so far almost no climate-friendly hydrogen. Industry mainly makes use of grey hydrogen obtained from natural gas. Hydrogen is used here as a **raw material**, for instance to produce steel, cement, fertilisers for agriculture, plastics, or adhesives for electrical appliances. Industry also uses hydrogen to generate process heat, for example, for melting metals or plastics. The snag is that **grey hydrogen results in the release of CO_2**, which is harmful to the climate.

If we want to achieve **climate targets**, we can't get by without climate-friendly hydrogen, which leaves no carbon footprint. This will entail entirely restructuring a **large part of our industry**, which is still dependent on **fossil fuels** such as coal, natural gas or oil. Particularly countries, that are dependent on manufacturing, such as Germany, Japan, China and the USA, need very large quantities of hydrogen to keep their factories running. Hydrogen is, thus, **becoming an important key for the survival of German and European industry**, and consequently also for our jobs and prosperity (see section 4).

The **steel sector**, which still largely uses coal and, therefore, has particularly great leverage, has **recognised the potential of climate-friendly hydrogen** and is working flat out to completely **transform its production model** and **make Europe fit for a green future**. The following illustrations, Hydrogen as a raw material in industry and What will the steel manufacturing of the future look like?, provide an overview.

"Oil and gas must stay in the ground!However, that will prove difficult while there's still a lot of money to be made extracting them.

So, the faster we get going, the faster hydrogen will become competitive and fossil fuels less profitable."

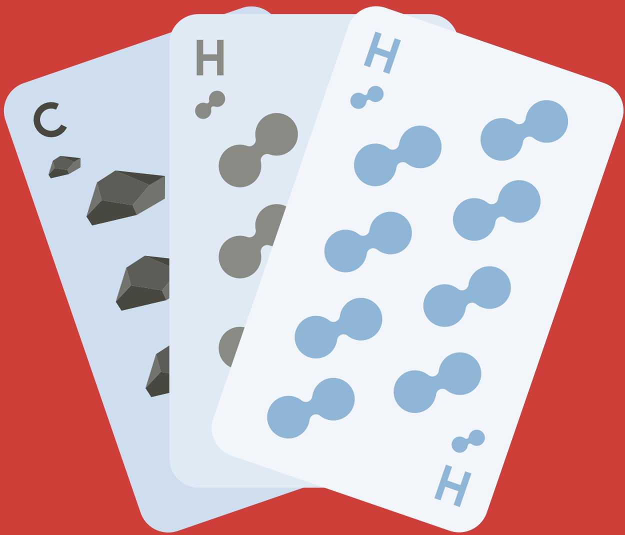
Hydrogen as a raw material in industry

1. German industry, specifically the steel and chemicals sectors, accounts for nearly a quarter of Germany's carbon emissions. So, there is huge potential to make these sectors climate-friendly.

2. Steel is needed everywhere: in construction, rails, trains, cars and wind turbines.

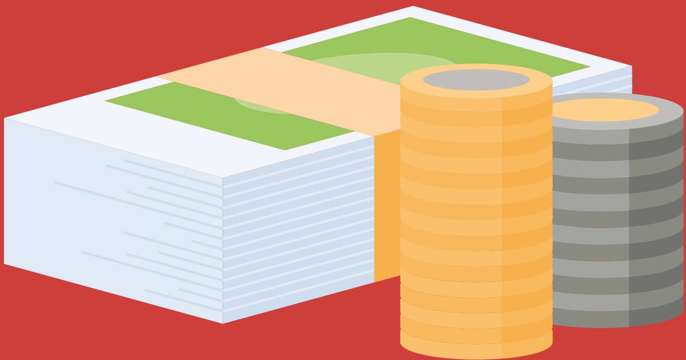
3. Until now, the steel industry has not been clean. For over 200 years, coal has been burned to turn iron ore into steel.

4. Today, we can replace coal with hydrogen, which may initially also be grey or blue hydrogen from natural gas. The goal is to reduce the carbon footprint progressively and to produce only climate-friendly hydrogen by 2045.



5. What do we need? Vast quantities of hydrogen from renewables, much of which we will have to import. New or upgraded ports, ships and pipelines will also be required.

6. What else? Completely new production plants capable of using hydrogen, which will require billions of euros in capital investment.



7. So, what's next? Technology must be scaled up as quickly as possible to make European climate-friendly steel competitive.

Source: own illustration

What will the steel manufacturing of the future look like?

In a traditional blast furnace, coal and iron ore are heated to produce pig iron, which is used to make steel.
This process has been in use for over 200 years but suffers from the drawback of releasing CO_2 into the atmosphere.

In the blast furnace of the future, hydrogen rather than coal will be added to iron ore (Fe_3O_4), i.e. the raw material for steel. In the future, green electricity will also be used to melt the iron.

This no longer results in releases of climate-damaging CO_2 but climate-friendly H_2O, which disappears into the atmosphere as water vapour. The final result: climate-friendly steel!

But it is not all that simple! The process for completely CO_2-free steel production is to be used in industry as of 2045. Until then, the industry is working with bridging solutions to reduce the use of coal and the CO_2 footprint step by step.

Source: own illustration

Storing and transporting energy with hydrogen

Generating green electricity from sunlight and wind is a great way to achieve climate targets. If we want to put it to **direct use**, however, it meets its **limits** because wind and sunlight aren't available on demand whenever we might want them.

You're probably wondering: **why can't green electricity simply be stored in batteries?** This works to a certain extent, for instance in a mobile phone or e-car battery. However, if we want to achieve the climate targets and completely transform all sectors, i.e., industry, transport, or heating, and make them climate-friendly, we will need huge numbers of very large batteries using many different raw materials from all over the world. This would be unaffordable and would have an impact on the environment.

This is where hydrogen comes in. We can use it to temporarily **store electricity and transport it from A to B** so that it can subsequently be converted back into electricity or used as a raw material in industry - where and when we need it. This provides much greater flexibility in terms of timing of use, so that not immediately used electricity is not wasted. **We can think of hydrogen metaphorically as a kind of "battery"[c],** as the following two illustrations Storing and transporting energy with hydrogen show in overview.

"It makes little difference whether the ship travels two thousand or twenty thousand kilometres because it is running on hydrogen."

However, there is one drawback: every time we convert electricity into hydrogen and then back again, some of the stored energy is lost. **Scientists** are researching how we can make **more efficient use of hydrogen**. Once we have enough hydrogen and the associated global infrastructure is in place, the question of efficiency will probably no longer be of such great significance. This is because **renewables** have the **massive advantage of being available to us in virtually limitless amounts.**

Our goal is therefore a climate-neutral future in which **hydrogen and electricity work together in tandem with their complementary pros and cons.**

How can we get the hydrogen to Germany?

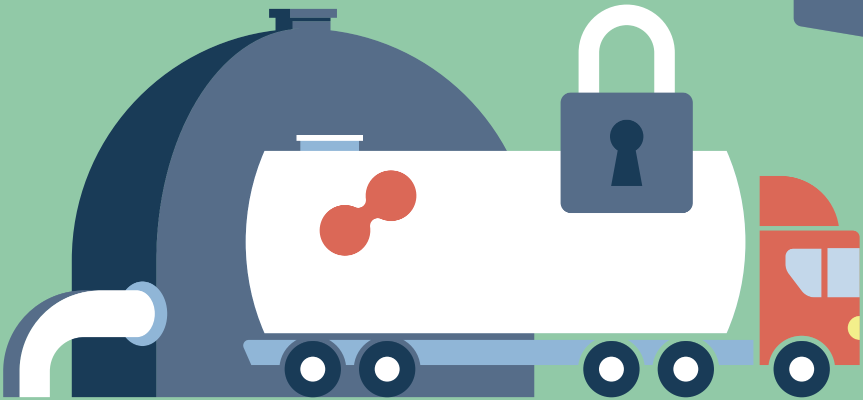
Germany will probably only be able to meet its hydrogen needs by imports from EU and non-EU countries. Which options are suitable for transporting hydrogen? What are their pros and cons? What are the barriers to building trade relationships? These questions have been addressed by a working group of the Project Energy Systems of the Future (ESYS) which acatech is coordinating. Want to find out more? Then take a look at the analysis *"Options for the import of green hydrogen to Germany up to 2030."*[2]

c This is just a metaphor to provide a simpler image of hydrogen. Strictly speaking, a battery is an energy storage device, while hydrogen is an energy source. In the case of a battery, I can use the stored electricity directly by connecting the battery to a consumer. If I want to use the energy stored in hydrogen, I have to convert the hydrogen first, for example in a fuel cell. Hydrogen is also known as a chemical storage medium.

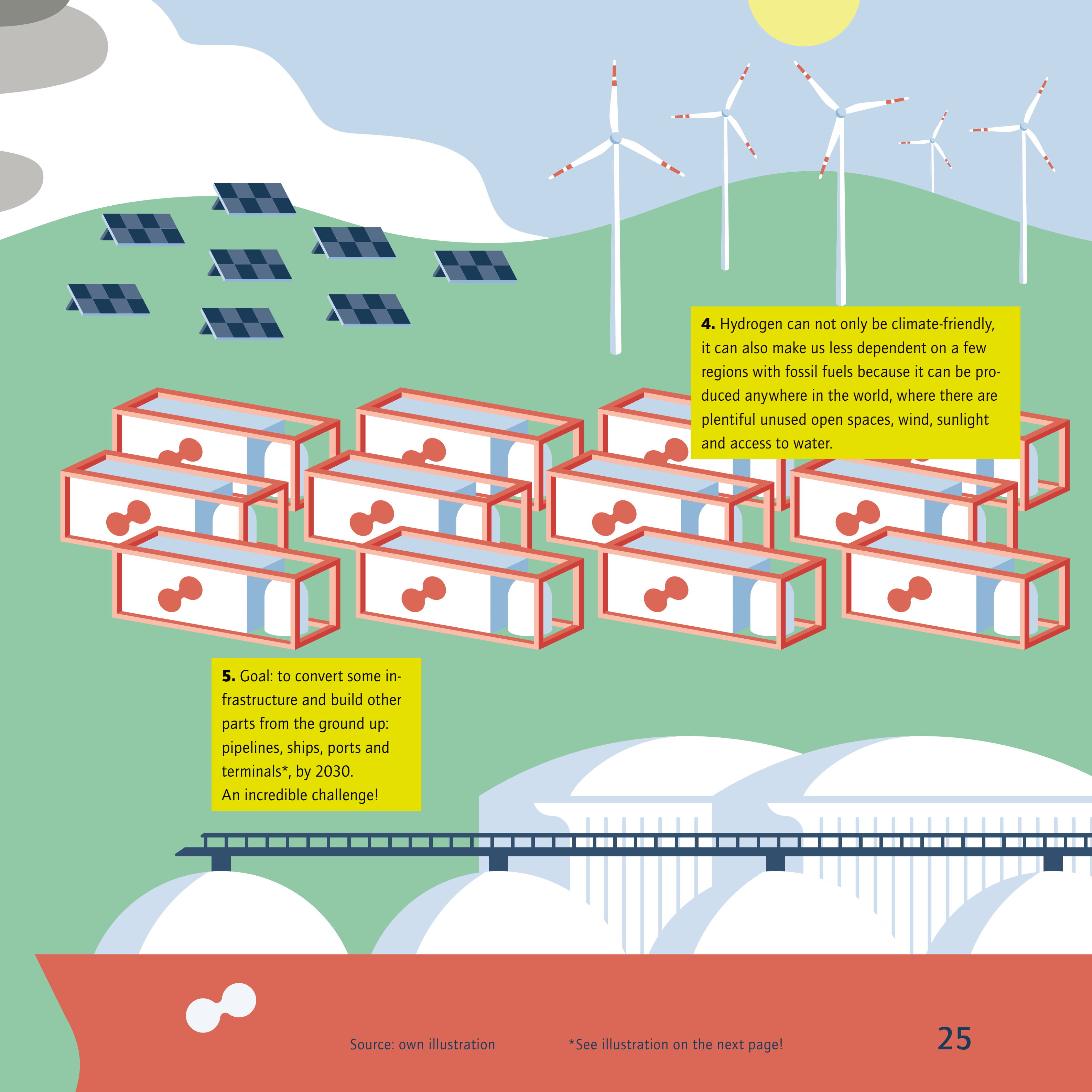
Storing and transporting energy with hydrogen

1. Green electricity is important for achieving climate targets. However, wind and sunlight are not available on demand. If we don't use the electricity immediately, it goes to waste.

2. Why not batteries? These work to a certain extent, for instance mobile phone batteries. If we wanted to replace the energy available around the clock from natural gas and coal with renewable electricity, we would need an unrealistically large number of batteries.



3. This is where hydrogen comes in. It can temporarily store energy and transport it from A to B so that it can be converted back into energy or used as raw material wherever and whenever needed.



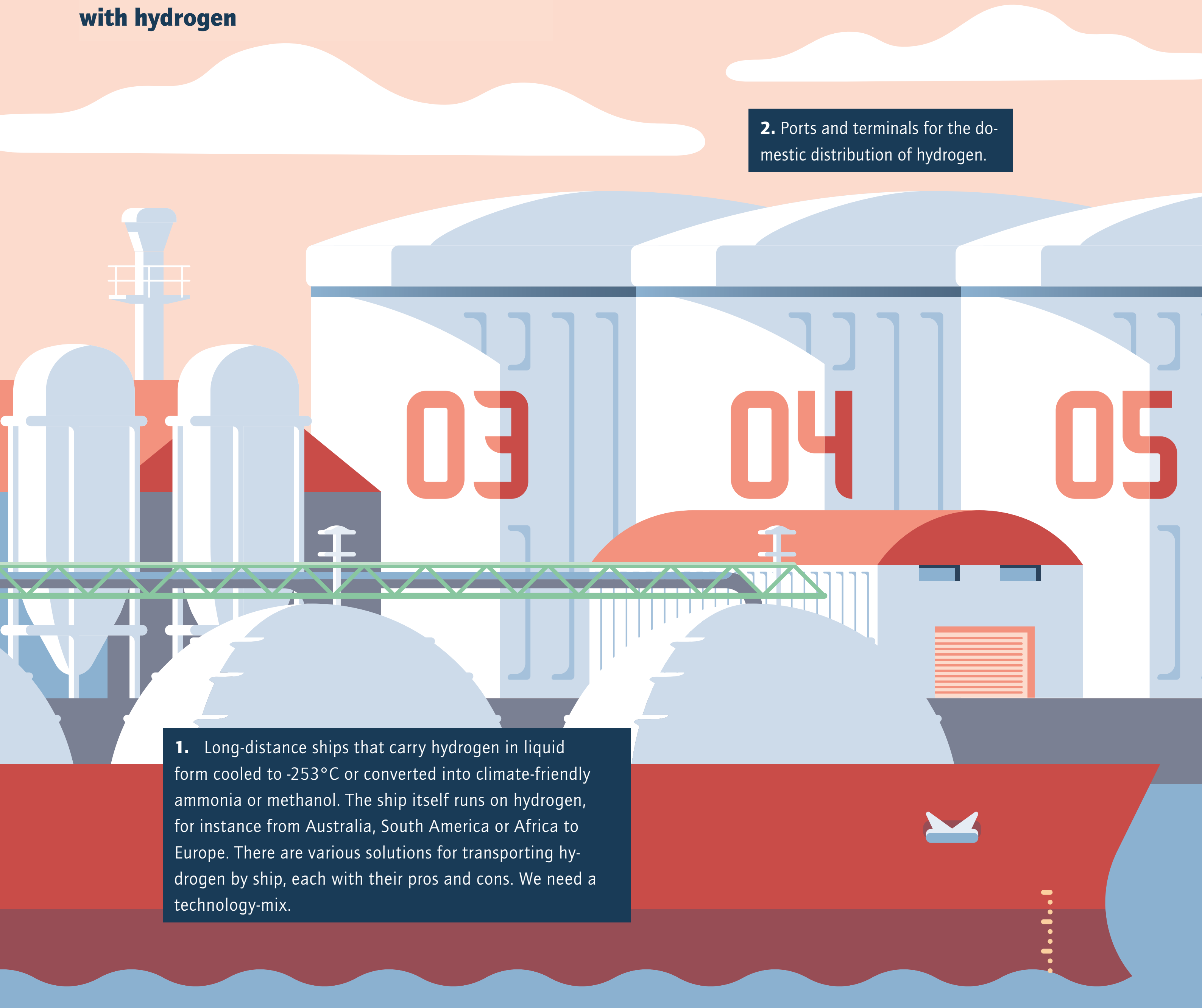
4. Hydrogen can not only be climate-friendly, it can also make us less dependent on a few regions with fossil fuels because it can be produced anywhere in the world, where there are plentiful unused open spaces, wind, sunlight and access to water.

5. Goal: to convert some infrastructure and build other parts from the ground up: pipelines, ships, ports and terminals*, by 2030.
An incredible challenge!

Source: own illustration

*See illustration on the next page!

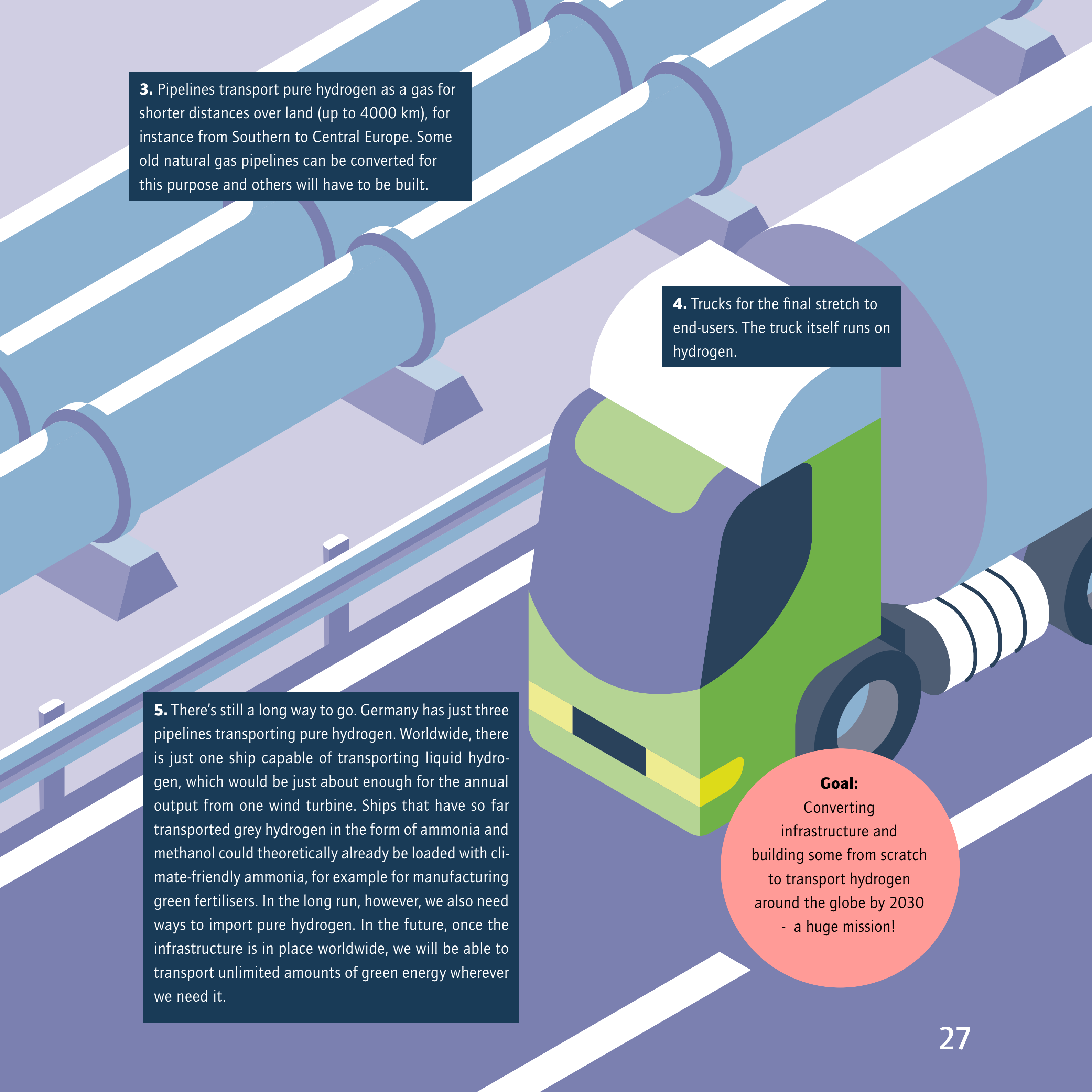
Storing and transporting energy with hydrogen



2. Ports and terminals for the domestic distribution of hydrogen.

1. Long-distance ships that carry hydrogen in liquid form cooled to -253°C or converted into climate-friendly ammonia or methanol. The ship itself runs on hydrogen, for instance from Australia, South America or Africa to Europe. There are various solutions for transporting hydrogen by ship, each with their pros and cons. We need a technology-mix.

Source: own illustration



3. Pipelines transport pure hydrogen as a gas for shorter distances over land (up to 4000 km), for instance from Southern to Central Europe. Some old natural gas pipelines can be converted for this purpose and others will have to be built.

4. Trucks for the final stretch to end-users. The truck itself runs on hydrogen.

5. There's still a long way to go. Germany has just three pipelines transporting pure hydrogen. Worldwide, there is just one ship capable of transporting liquid hydrogen, which would be just about enough for the annual output from one wind turbine. Ships that have so far transported grey hydrogen in the form of ammonia and methanol could theoretically already be loaded with climate-friendly ammonia, for example for manufacturing green fertilisers. In the long run, however, we also need ways to import pure hydrogen. In the future, once the infrastructure is in place worldwide, we will be able to transport unlimited amounts of green energy wherever we need it.

Goal:
Converting infrastructure and building some from scratch to transport hydrogen around the globe by 2030 - a huge mission!

"Renewables are like flat rates. Solar energy can meet the people's energy needs ten thousand times over. We've just never had the technology before."

Hydrogen to feed the world

For millennia, humans have been fertilising fields with manure or slurry to help crops grow better. We still need to fertilise agricultural soils to **feed the world's growing population.** We still sometimes use manure as fertiliser but we also manufacture large quantities of **synthetic fertilisers**. But why do we have to fertilise more and more?

One of the most important fertilisers is based on nitrogen. Nitrogen is necessary for fruit, vegetables, cereals, or rice to grow. It forms a large proportion of the air but **plants cannot directly absorb this atmospheric nitrogen**. However, there is also nitrogen in the soil, which plants can absorb through their roots. In nature, plants die and rot where they have grown. This way, the nitrogen stored in the plant returns to the soil and the next generation of **plants absorbs this nitrogen back up through its roots**, so closing **nature's nitrogen cycle**. Though, this is **not the case in agriculture**, where **humans harvest plants before they rot.** Since agricultural soils lose nitrogen to the crops and no new nitrogen is added naturally from decaying plants, **we must add nitrogen via fertilisers**. Only this way can plants continue to grow in the future.

Is that really the only way? Not entirely. We are facing the question of **how to adapt our agriculture and food supply in future.** This includes consuming more sustainably, throwing away less food and, consequently, needing less land. Also, we would not always have to harvest all the land, but could leave some of the plants to perform their natural cycle, and consequently reduce fertiliser use.

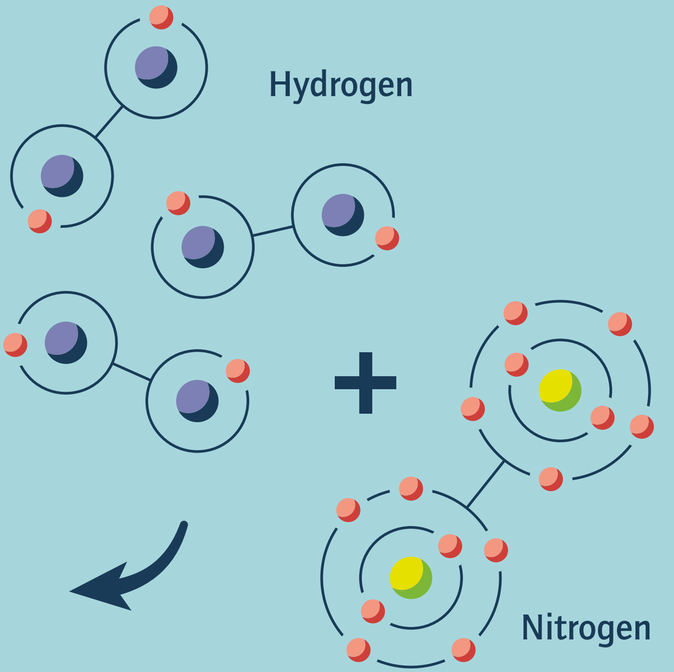
What does this have to do with hydrogen? The **starting point for fertiliser manufacture is ammonia**, a nitrogen compound of **hydrogen** and elemental nitrogen. At the beginning of the 20th century, the German chemists Fritz Haber and Carl Bosch succeeded in producing ammonia from hydrogen and atmospheric nitrogen in what is known as the Haber-Bosch process. This allowed humans to harvest more crops to feed a growing population. **Ammonia** and, consequently, **hydrogen** are an **important component of our current food supply**.

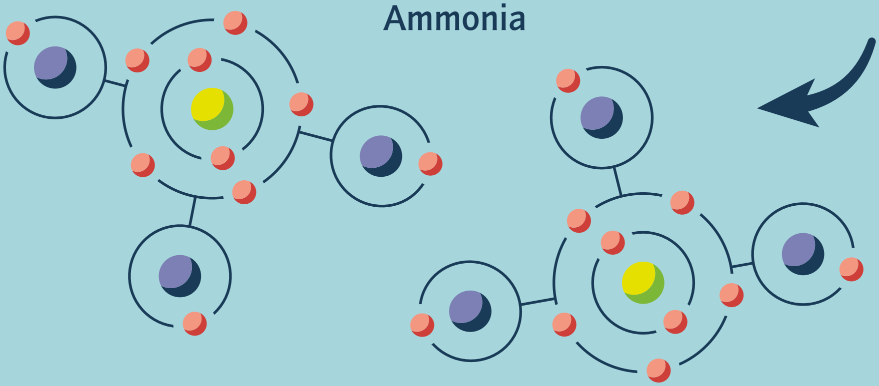
What's the problem? Between the 20th century and now, we have **mainly been manufacturing ammonia using hydrogen from natural gas or coal**, and so releasing very large volumes of CO_2 into the atmosphere. Since we cannot do without ammonia because our agriculture is very dependent on it as a fertiliser, it is important to produce ammonia in the most climate-friendly way possible. So here, too, **climate-friendly hydrogen is our only option**.

The following illustration Hydrogen as a raw material for fertilisers: irreplaceable for global food supplies provides an overview.

Hydrogen as a raw material for fertilisers: irreplaceable for global food supplies

If we are to feed the world's growing population, we need crop fertilisers for agriculture. Hydrogen comes into play here too - it is an important raw material in fertiliser production. This infographic explains the interrelationships between plants, hydrogen, fertilisers and ultimately our food supply.

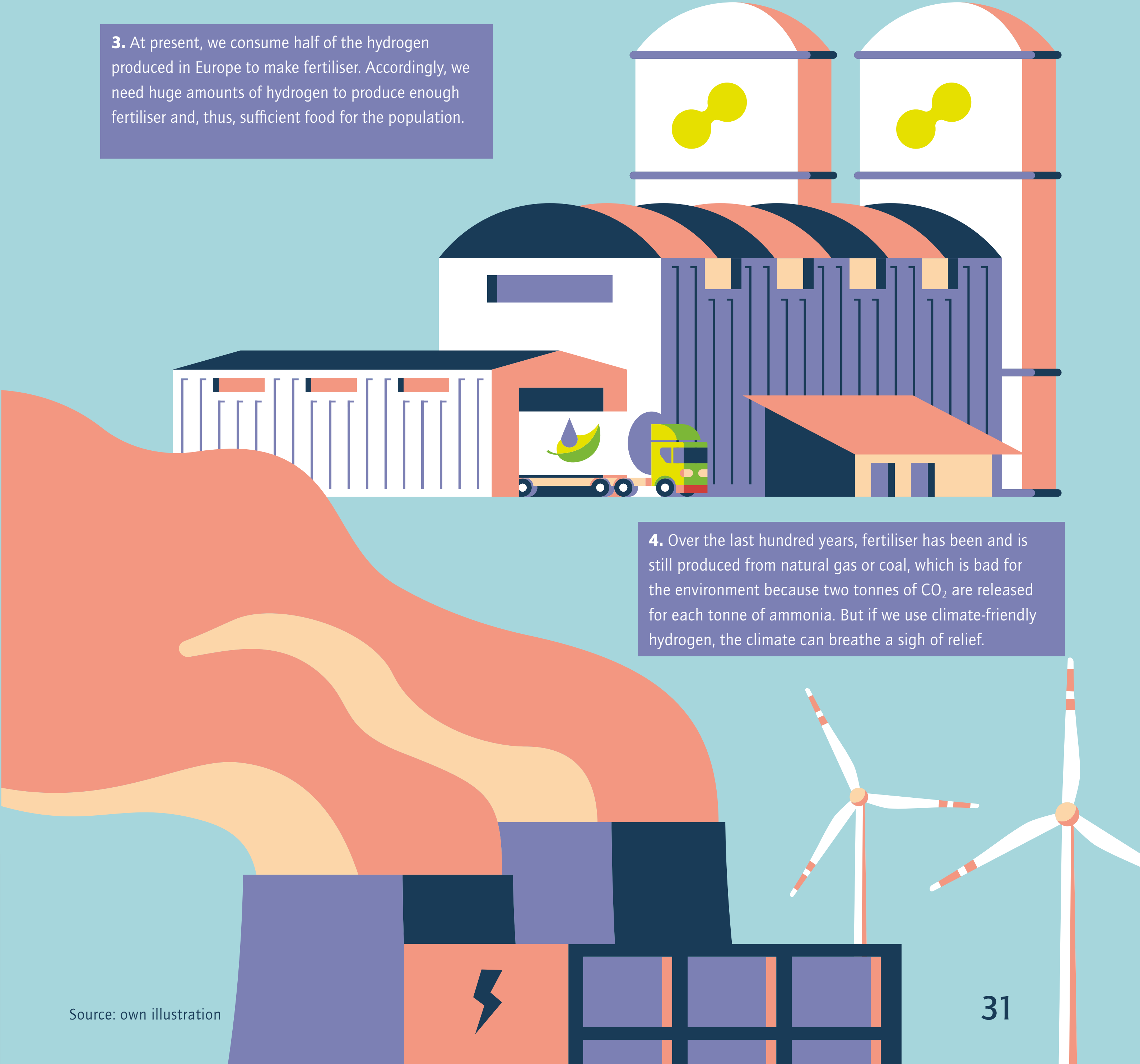




2. What does hydrogen have to do with it? If we want to produce fertiliser, we need hydrogen as the Haber-Bosch process produces ammonia (NH_3) from hydrogen and atmospheric nitrogen. Ammonia is the starting product of fertiliser production.

1.What are fertilisers?
Plants such as cereals or maize need certain nutrients in order to grow in the fields. The most important nutrient is nitrogen (N_2) which farmers apply to the fields in the form of fertiliser.

3. At present, we consume half of the hydrogen produced in Europe to make fertiliser. Accordingly, we need huge amounts of hydrogen to produce enough fertiliser and, thus, sufficient food for the population.



4. Over the last hundred years, fertiliser has been and is still produced from natural gas or coal, which is bad for the environment because two tonnes of CO_2 are released for each tonne of ammonia. But if we use climate-friendly hydrogen, the climate can breathe a sigh of relief.

Source: own illustration

"Hydrogen is becoming part of our everyday life: I can imagine that in the future we will buy fruit and vegetables, which a hydrogen-fuelled truck has brought to the supermarket. The truck will be made with green steel, which is, in turn, made with hydrogen from green electricity."

Climate-friendly mobility: hydrogen and electricity in tandem

Transport leaves a significant carbon footprint. Batteries in e-cars are one solution for emission-free driving but they have their limits: a truck, a ship or an aircraft would need such large and heavy batteries that they would not be able to travel very far at all and would require very large quantities of raw materials. Currently the lightest electric aircraft has a battery which accounts for sixty per cent of its total weight. This aircraft could carry at most nine passengers just six hundred kilometres, which means it can manage a distance from Los Angeles to San Francisco or London to Paris.[3]

This is where hydrogen comes into play again because it can **store electricity from renewables,** with **hydrogen being converted back into electricity in the car or aircraft.** The exhaust fumes do not contain any climate-damaging gases but virtually only water.

Several countries including Korea, China, USA, Japan, France and even Germany already have hydrogen vehicles and hydrogen fuelling stations. The technology works, but we are still in the early stages. **So, the debate is not between hydrogen or battery, we need both.** Only this way can we make mobility sustainable and achieve climate targets. The illustration Climate-friendly mobility: hydrogen and electricity in tandem provides an overview.

How much hydrogen does a hydrogen bus need?

The German Federal government expects annual hydrogen demand to reach 90–110 terawatt-hours by 2030. This is probably just a number for most people, so a hypothetical comparison might be helpful. This amount of hydrogen could theoretically fuel Germany's entire bus fleet for seven to eight years.[d] In reality, however, it is still unclear how hydrogen will be distributed between sectors, such as industry or mobility.

Is hydrogen dangerous?

Like all flammable gases, hydrogen can explode. Safety must be considered when storing and transporting gas. To prevent a pipeline or gas tank from bursting in the event of an accident, there are safety valves to ensure that the hydrogen is vented and does not explode. **Tests with hydrogen cars have shown that hydrogen is no more dangerous than fossil fuels**. The chemicals industry also has years of experience with hydrogen which industry and academia can now build on for climate-friendly hydrogen.

A socially just energy transition for all?

How can we **combat climate change and shape the energy transition in a socially just wa**y, i.e., such that **living standards and opportunities are approximately equal for everyone in society?** Ideally, everyone's outlooks and differing requirements will be considered. Significant differences can arise along many dimensions, for example **gender, ethnicity, age, religion, disability, or sexual orientation.** In the context of climate change, energy, and hydrogen, for example, the **EU Commission** directly addresses the **equality of women** by taking the different life circumstances of men and women into account in its European Green Deal.
This is because women and men are not equally affected by climate change measures. For instance, **women** are at **greater risk of falling into energy poverty**. This is because women more often have difficulty paying the bills for their energy costs, such as electricity or gas, since they often still earn less than men.[4] Rising energy prices due to the war in Ukraine (as of September 2022) and the **shift to renewables**, which are currently more expensive than fossil fuels, mean **this gender gap is widening.** It is right for policy makers to take proper account of these inequalities as we transition to a hydrogen economy.
But the gender gap in energy poverty is by no means the whole story because men still dominate the upper echelons of energy companies.[5] Globally, men hold 94 per cent of ministerial posts with responsibility for national energy policy. In 2019, only four countries in the European Union had female energy ministers.[6]
It's a good thing, that the EU already has this on its radar. It has developed **a strategy for gender equality**[7] and backed it up with concrete measures which it intends to implement by 2025.

d Own calculation

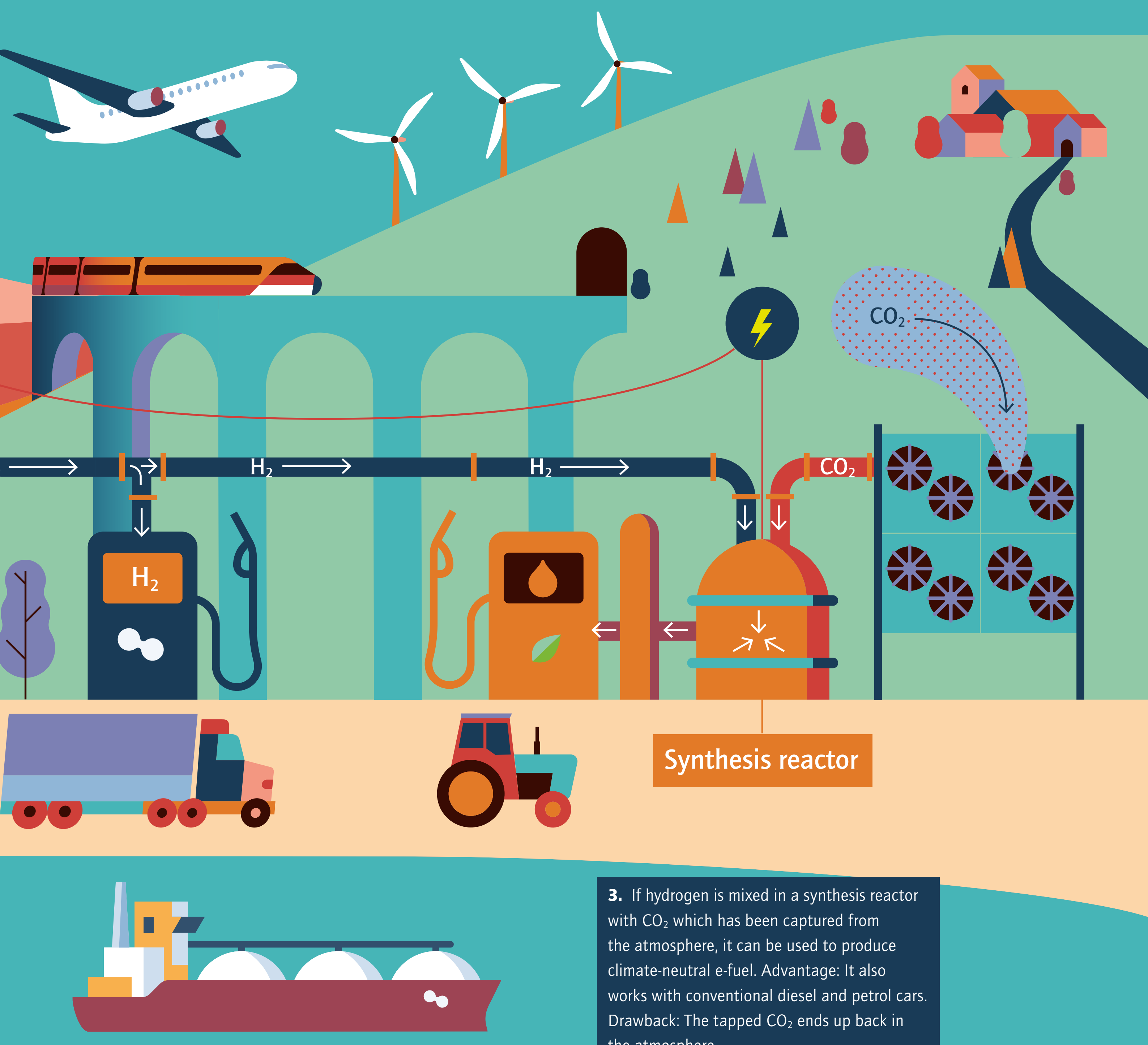
Climate-friendly mobility: hydrogen and electricity in tandem

Transport leaves a significant carbon footprint, but mobility can also be more climate-friendly. Here, too, hydrogen is key.

1. Batteries are one solution for emission-free driving but they do have their limits: heavy vehicles, trains, ships or aircraft would need such large batteries that they would not be able to travel very far.

2. Hydrogen comes to the rescue. It is obtained from water in the electrolyser and subsequently converted back into water in a fuel cell in the car, truck or aircraft, as a result releasing energy. The advantages are less noise, fewer wear parts and no exhaust fumes.

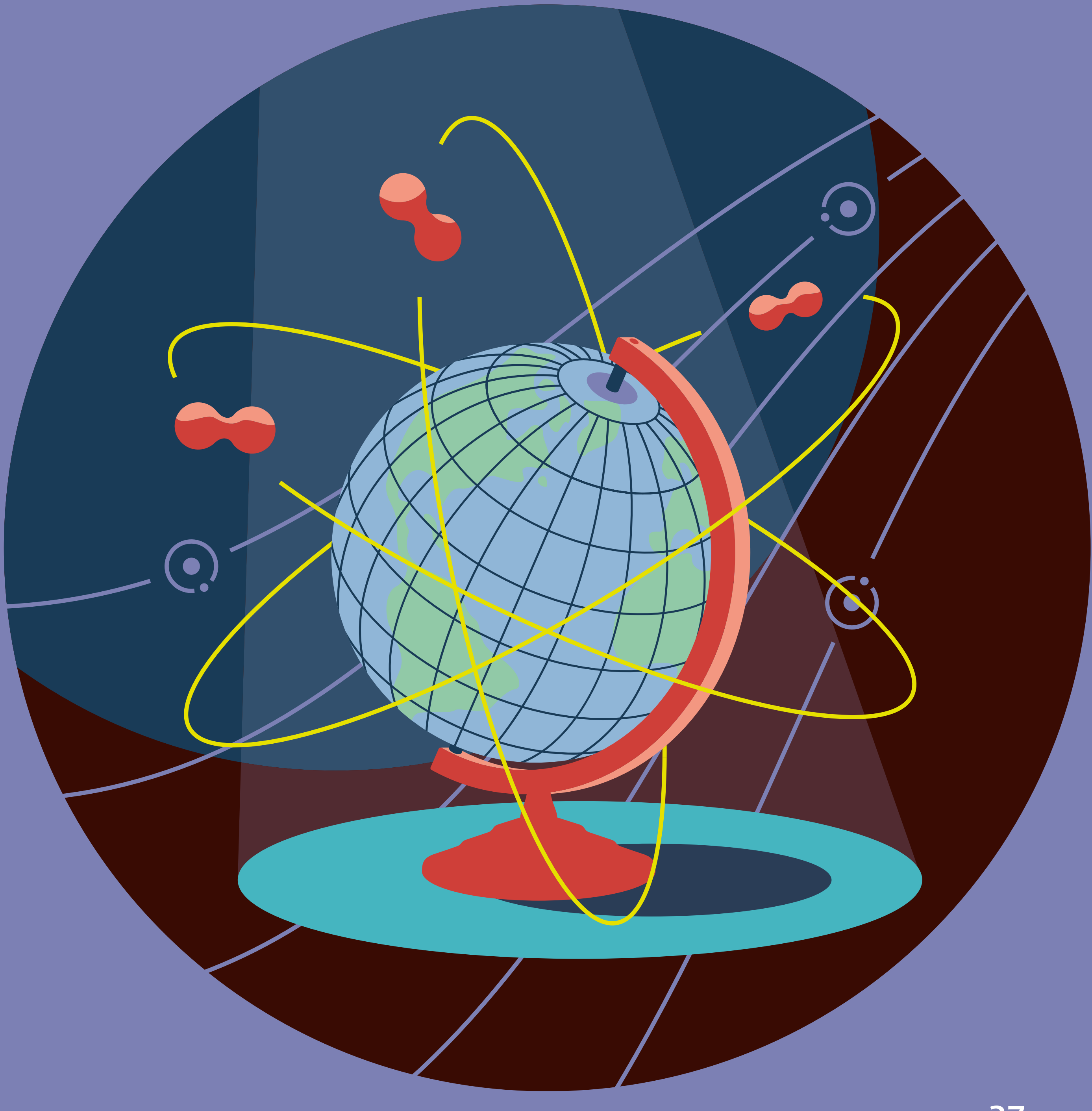
Source: own illustration



3. If hydrogen is mixed in a synthesis reactor with CO_2 which has been captured from the atmosphere, it can be used to produce climate-neutral e-fuel. Advantage: It also works with conventional diesel and petrol cars. Drawback: The tapped CO_2 ends up back in the atmosphere.

3 So, how and where from? The global perspective

For a while now, many countries have recognised the environmental and industrial potential of hydrogen. But where will the hydrogen come from and who will get it first until there is enough for everyone? Section 3 provides an overview.



"Studies have shown that, using solar and wind power, we could produce huge amounts of climate-friendly hydrogen with just two per cent of Australia's land area.[8] Theoretically, that might even be enough to meet Germany's needs several times over."

Hydrogen can only be a global solution: we can try as hard as we want in Europe and transform our lives to climate-friendly solutions, but **only if all regions and countries join in** and bring about a **global reduction in the carbon footprint will we achieve the climate targets**. CO_2 takes no notice of national borders. If only some countries opt for climate-friendly hydrogen, while others continue to burn oil, coal and natural gas, the climate benefits will only be slight.

We are, thus, **all in the same boat** and are dependent on each other. For instance, in Europe and above all in Germany, we will have to i**mport climate-friendly hydrogen from other regions** because we cannot produce enough ourselves. Why? Our **industry needs very large quantities of hydrogen** and at the same time a lot of people live within a comparatively **small area**. This area will not be enough even if we build wind and solar farms on every open field and roof.

So, we are **dependent on regions with plentiful sunlight, wind and open spaces** such as Australia, Africa, South America or Southern Europe, to name just a few. At the same time, this also holds an opportunity for all parties. Actively **promoting new hydrogen projects in different regions of the world** over the coming years will ideally also create new job opportunities in these regions in the field of renewables and environmentally friendly technologies. However, we must be careful to **ensure good and fair environmental and working conditions.** We must avoid creating any new conflicts, for instance by using a desert country's water for the electrolysis process and so depriving the local population of water for drinking or irrigation.

However, if we get it right, in the coming years we will be able to export cutting-edge technology and know-how from **Europe and import climate-friendly hydrogen**, while in **the Global South**[e] more **jobs and prosperity** will be created, a **win-win** for everyone. If we also succeed in creating the right **investment opportunities** and i**ncentives**, environmentally friendly development will ideally be just as worthwhile for the countries of the Global South as development with fossil fuels currently is. The goal is an energy partnership on an equal footing, a partnership from which both sides benefit equally.

And there's more good news - hydrogen is more than just an important building block for achieving climate targets and creating new jobs. I**n comparison with fossil fuels, it also makes us less dependent on the few countries** which have deposits of natural gas and oil. This is because we, the global community, can **produce hydrogen from renewables anywhere in the world** with plentiful open spaces, wind and sunlight.

We are, therefore, faced with the huge opportunity of a fresh start. After decades of dependency on oil and natural gas, we now have a chance to **redraw the energy map** by forging new long-term, **trust-based energy partnerships** with many regions of the world and **diversifying energy imports across various routes**. Diversification is important because in the event of war, pandemic, political instability or raw material shortages, we always need a plan B to avoid overnight energy shortages (see section 1, box There's no ideal solution to the energy policy triangle).

Then, what's the problem, why isn't everything already up and running? Although the **world theoretically has unlimited supplies of wind and sunlight**, we don't yet have the hydrogen. First of all, **we have to convert some parts of the global infrastructure and build other parts from the ground up** in order to produce, store and transport hydrogen (see section 2, illustration Storing and transporting energy with hydrogen). So, **we should get going right now!** Only those who jump on the hydrogen bandwagon now will play a role in the creation of the anticipated **vast new hydrogen market!**

"From a geopolitical perspective, we have a huge opportunity to completely rethink our connections with other regions of the world."

We cannot yet answer the question of where hydrogen will come from and where it will go in the coming years because it's still unclear **which countries and regions will be the first to get their hands on hydrogen and profit from the hydrogen market.** For a while now, countries such as Australia, Japan, South Korea and China have recognised the enormous potential of hydrogen for the environment and industry and are making great strides forward. These countries approach the hydrogen colour spectrum with more flexibility than Europe (see section 1, illustration The hydrogen colour spectrum – a typically European debate?). This is also making it easier for them to get started now and invest in hydrogen projects based on coal, natural gas or nuclear energy, for example, even if they are not truly climate-friendly. All that matters is hydrogen. Hydrogen is, thus, becoming a geostrategic issue. Cooperation with other regions is important but at the same time, we must ensure that everyone gets a fair slice of the hydrogen pie.

"How should we distribute the hydrogen? Where the greatest carbon savings are made or where the best price is paid? The question is, what will help the planet the fastest?"

e The term Global South replaces the previous term, which is perhaps perceived as derogatory, of emerging and developing countries. The global North, on the other hand, denotes the industrialised nations.

Electrolysers: capacities and raw material requirements

How much hydrogen will Germany be able to produce by 2030? What impact might the Russian war of aggression in Ukraine have on German electrolyser production, given that many raw materials required for manufacturing electrolysers come from Russia? You can find out more about this in the studies **Raw materials for electrolyser production**[9] and **How large are electrolysis capacities?**[10] acatech and DECHEMA jointly authored these studies as part of the H2-Compass project and the results are incorporated into the federal government's hydrogen roadmap.[11] The goal of the roadmap is to bring data and facts together in a process of dialogue in order to demonstrate progress in hydrogen innovations.

Apart from the raw materials for building electrolysers, the production of hydrogen requires one thing above all - **water**. This raises the question as to **whether the hydrogen economy could lead to water shortages**. A comparison is helpful here: if we want to produce the quantities of green hydrogen that Germany has set as a target for 2030, the volume of water amounts to just 0.2 per mil of the volume flowing from the Rhine into the North Sea.[g]

Is this just a meaningless number to you? If so, don't worry because the important thing is that electrolysis consumes only a fraction of the water consumed by nuclear, gas, and coal-fired power plants. **So, if fossil fuels are eliminated in the future, we will actually save water overall!** The situation is different in regions that are already suffering water shortages. While seawater can be desalinated, it costs additional energy and can have a negative impact on the environment.

Moreover, if we want to produce hydrogen, we do indeed initially need to extract water, for instance from groundwater or a river; but as soon as we use the hydrogen to release energy, for instance, in a car or factory, pure steam is obtained. Therefore, the water is not lost, it passes into the atmosphere and ends up back in a river or lake in the form of rain.

"Building the hydrogen economy is about collaboration with trusted partners, not just buying and selling."

The illustration Where can we get the raw materials for an electrolyser? gives you an idea of the regions where we can find the raw materials for building electrolysers[f]. The illustration also shows that many electrolysis projects do not originate in Europe, **despite a large proportion of the world's electrolysis companies being European**. This is also because the projects go where there is the most renewable energy and the cheapest green electricity.

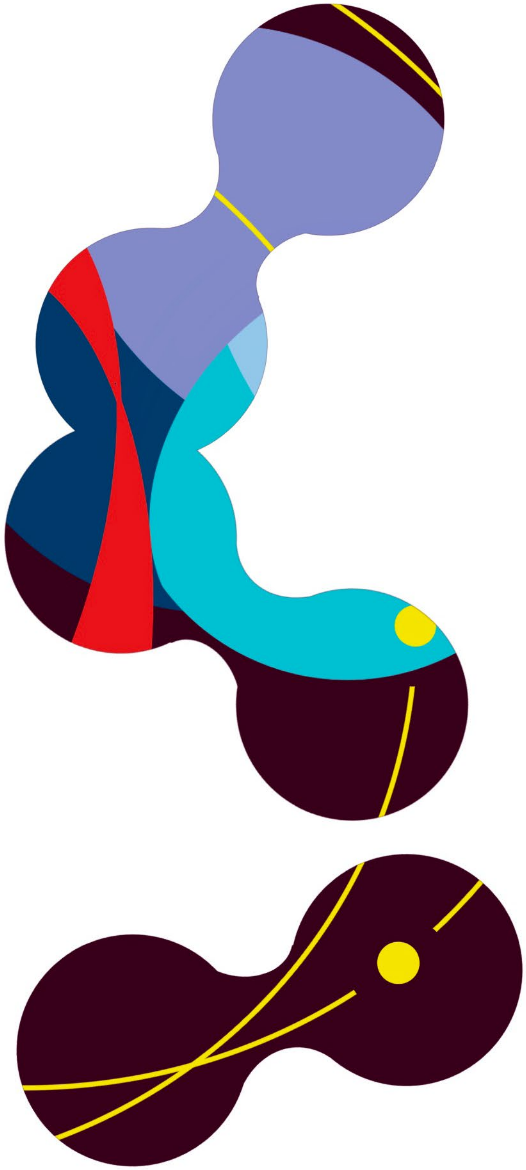
In the future, **entire branches of industry could increasingly migrate** to locations with not only a lot of renewable energy but also important **raw materials** which we have so far been importing to Europe, such as iron ore for steel production. Section 4 describes what specifically needs to be done.

"When it comes to renewables and raw materials, other regions have an advantage. There is also a risk that we will lose our lead in technological know-how and the industry will migrate. So, we need to be quick off the mark - the world is not waiting for Europe."

Cleanly recycling raw materials with urban mining

Electrolysers, wind and solar farms, and batteries for e-cars - we need **raw materials** everywhere. However, the earth's resources are finite. If we use them wastefully, our planet will not be able to cope in the long run. Nevertheless, a lot of things today are worn out after a short time and end up in the bin. This is precisely where urban mining comes in: **instead of mining more** and more raw materials, we could **reuse** existing **secondary materials** which have previously lain **unused in cities and populated areas.** Curious? Find out more in our HORIZONS publication **Urban Mining.**[12]

Still, not everything ends up in the bin. For instance, we already recycle raw materials such as platinum, which is needed for catalytic converters and electrolysers. After all, platinum is a precious, valuable metal that costs about sixty times as much as silver. Moreover, metals such as gold, silver and platinum suffer absolutely no loss of quality when recycled and can, therefore, be **infinitely recycled!**



f There are various electrolysis technologies, some already on the market, others still in the test phase. Depending on the electrolyser, different raw materials are required, some of which are critical. The European Commission defines raw materials as critical if they are of great economic significance but are not available in Europe in sufficient quantities and mainly have to be imported.

g Own calculation

Where can we get the raw materials for an electrolyser?

We already have the technology* for climate-friendly hydrogen. However, we first need to produce electrolysers and we need various raw materials for that which are not available in Europe. The carbon footprint of these raw materials depends on how cleanly we extract, transport and recycle them. Even green hydrogen is not (yet) one hundred per cent climate-friendly. The illustration shows some of these important raw materials. It also shows that green hydrogen is mostly produced not in Europe, but in other regions with plentiful open spaces, wind, and sunlight. This makes global cooperation more important than ever!

*See illustration "What is an electrolyser?".

** Rare earth element

Source: own illustration based on acatech, DECHEMA 2022[9], DERA 2022[13] and Wappler, Unguder, Lu, Ohlmeyer, Teschke, Lueke 2022[14]

Selection of important, potentially critical raw materials for constructing electrolysers:

Palladium (Russia, South Africa, USA)
Cerium** (China, USA, Australia)
Scandium (China, Russia, Philippines)
Titan (China, Japan, Russia)
Nickel (Indonesia, Philippines, Russia)
Iridium (South Africa, Russia)
Platin (South Africa, Russia)
Yttrium** (China, Myanmar)

Selection of announced projects for green and other types of clean (white, pink, orange, turquoise and blue) hydrogen (2022):

: Canada, USA, Colombia, Brazil, Netherlands, France, UK, Norway, Finland, Poland, Czech Republic, Hungary, Ukraine, Kazakhstan, Egypt, Mauritania, Saudi Arabia, Oman, Namibia, South Africa, Russia, China, South Korea, Australia

: Chile, Portugal, Spain, Morocco, Italy, Germany, New Zealand

4 What needs to happen now?

What else can policy makers, business, academia and society do to make the quickest possible start with the hydrogen world? The final section provides some food for thought.

Markets and governments moving towards the hydrogen economy

We saw in section 3 that a large proportion of hydrogen projects are migrating into regions where there are plentiful raw materials, open spaces, wind and sunlight, and these are mainly outside Europe. **Those who get left behind**, and are not quick enough off the mark, could in the worst-case scenario **lose entire industries**. It could be that the **steel industry** will completely migrate to a region where there is plentiful climate-friendly hydrogen as well as the raw material iron ore which is necessary for steel production. This would allow companies to **produce steel locally, instead of importing raw materials and hydrogen to Europe** over long distances by ship and pipeline. The same could happen with the **chemicals industry** which also needs hydrogen as a raw material for medicines, adhesives for electronics, or fertilisers and could manufacture locally instead of importing the hydrogen to do so. Since these are hugely important, **major industries**, which act as big employers in Europe, the stakes are very high.

"Lurking behind hydrogen is the greatest business opportunity of the century - I reckon it's as big as oil and gas put together."

The fact that the industrial landscape will change is probably unstoppable, and the European industry is well aware of it. What's important is for a **significant proportion of value added[h] to remain here and for European companies to continue to be leaders in technological know-how.** This is something that many stakeholders in politics, business and society in Europe have understood and it is why **Europe is already moving towards a hydrogen economy**. However, we cannot afford to lose a single second in this **race against time**.

Europe remains **the technological leader in electrolysis**.[i] A large proportion of **electrolysis companies** around the world come from Europe. However, the **fewest major hydrogen projects** are being **implemented in Europe**. European companies are indeed global market leaders in technology and are selling high quality electrolysers everywhere, but **we can only set up our own electrolysers in Europe to a limited extent**, to produce hydrogen for our own needs. Instead, **we have to import a large proportion** of the **necessary hydrogen**.

Though, this is not only due to the limited areas of land for renewables and low availability of raw materials, but also due to a **strict regulatory framework**: experts from industry and academia are repeatedly complaining that it is currently very **complicated to invest in hydrogen in Europe**. Compared to other regions in the world, European rules are less flexible and highly bureaucratic; this makes it more attractive for investors and companies to go somewhere else, where it is easier and quicker to set up an electrolyser and produce hydrogen. European policymakers have already taken some important steps to simplify the rules for green hydrogen so that European manufacturing companies can remain competitive. So, what´s next?

"Technological know-how is our last card and we simply must play it."

h Value added is the economic output produced in economic sectors or companies, i.e. the value of the product manufactured or the service provided there less the value of the intermediate inputs required for this purpose.

i Experts consider that Europe is currently (still) the front-runner in all areas of electrolysis manufacturing: technological know-how, intellectual property, production capacity, transport, safe handling of large-scale plants, investment and legal certainty, infrastructure and very highly trained specialists.

Greening hydrogen

We cannot conjure up raw materials and open spaces but we can **adapt the conditions** and **give companies the investment security** so that a **hydrogen market can also flourish in Europe. This is where government, both nationally and at the European level, must get involved.** What does this mean?

In simple terms, **broad-brush regulations and standards** must be defined **without making things too complicated and without planning every single detail.** Companies must be able to see a way through the bureaucratic jungle and have the certainty that they will subsequently be able to sell the climate-friendly hydrogen they produce in their costly plants. Only then will a company take the risk of investing millions or billions of euros in hydrogen.

"Today's economy has not in any way been planned out in detail. Similarly, we cannot in 2022 plan every single detail of the hydrogen economy for 2030."

What do we mean by broad-brush regulations and standards? Governments must define just what **green, climate-friendly** hydrogen is and standardise **"greenness"**, so to speak. This includes the **entire carbon footprint** which is left by **the production, transport and consumption** of hydrogen. Just as we have defined quality standards for toys and food, companies must also know what criteria they can use to produce and sell hydrogen while consumers must at the time of purchase be able to see whether these criteria have been met. This is where things get difficult because these standards should ideally **apply worldwide.** It would make little sense if companies in every country were to follow different standards. No one would be able to keep track of everything and we would not make any progress. This makes **global cooperation** more important than ever.

"A global hydrogen market must come into being as quickly as possible, which means having standards for climate-friendly hydrogen that are accepted worldwide. This can't be achieved by being pushy - collaboration is the only way forward."

Hence, broad-brush regulations and standards for "greenness". At the same time, industry needs the freedom of action and latitude for different electrolysis technologies to develop in the market. No one can predict when which technology will come out on top. It, therefore, always makes more sense to take a multipronged approach and remain technology-neutral. Only then will hydrogen have a chance to move from the pilot phase to scale and only then will we reach our goal - the **hydrogen economy**.

"Technically, almost anything is already possible today. We've got on top of the pilot plants and testing, so now we need to get a move on with scale-up."

What do we still need the government to do? **Hydrogen imports** from other regions must be **boosted**. The government must make it possible for sufficient hydrogen to come to Europe and gain a foothold here.[j] **European policymakers are** already working on **forging energy partnerships worldwide** (see section 3) – **on an equal footing** and with as many countries and regions as possible. Both sides benefit from such partnerships, and we all have a plan B in the event of a crisis, or bottleneck. How the imported hydrogen is then distributed among the different sectors - such as industry, chemistry, and transport - should be left to develop independently. **Only if policy remains flexible and includes all technologies and sectors will a hydrogen market be able to flourish.**

Small players need hydrogen, too

Experts do not expect **significant volumes of climate-friendly hydrogen to be available until 2030.** Until then, we will have to think carefully about how to use the limited quantities of hydrogen which, in the coming years, we will produce ourselves in Europe, or import from other regions. Even if the intention is for the market to develop freely without excessive government intervention, we must ensure that small and medium-sized enterprises also get a chair at the table. Both large and small companies and start-ups should be able to benefit from government and European funding and enter the hydrogen economy. It would be great if everyone could harness this **enormous potential!**

So long fossil fuels, welcome climate-friendly hydrogen

What's the goal? We want to achieve climate targets. And we just can't get by without climate-friendly hydrogen.
The problem is that it still costs more than fossil fuels or grey hydrogen produced using natural gas.
The short-term solution is to make carbon and natural gas more expensive and create incentives for climate-friendly hydrogen, making it more profitable.
In the long term, companies will manage to scale hydrogen so that it remains competitive even without incentives, and displaces **fossil fuels forever.**

"Most industries need hydrogen for trial use in their plants. If we cut these industries off from hydrogen now because it's still in short supply, they will miss out on the learning phase. And once climate-friendly hydrogen is available, they won't have the experience to make use of it."

"Businesses are allowed to take risks sometimes, so technologies can reach the point of no return and really take off."

j In the start-up phase of the climate-friendly hydrogen market, it may also be necessary for the government to give companies a helping hand to get the necessary investments in hydrogen technology underway.

"Even in the medium-term, many things will become significantly cheaper again. I think the coming years are set to see massive cost reductions for climate-friendly hydrogen."

Communicating science

Research, research, research! This is the only way to **progress**, whether in medicine or in climate research. Scientists around the world are researching more efficient electrolysis technologies that produce climate-friendly hydrogen, the raw materials we need for electrolysers, and how we can store hydrogen efficiently and transport it safely. **Science produces knowledge**, creating the basis for innovation and technological progress. Though, it also has to share the knowledge it produces with other parts of society, i.e., with **policymakers, industry and us citizens and present complex knowledge in a simple and understandable way, making it accessible to all.** This is where science communication comes in. How else are people supposed to know that hydrogen is important for our future, what role it can play in the energy system, and what needs to be done now? Only with **support from a population** which **understands, accepts and trusts what is, after all, a new technology**, does the energy transition have a chance at succeeding.

Science, thus, **contributes to democracy**, with all people informed and jointly making decisions about our future **founded on scientific knowledge**.

"The energy transition will only succeed if science, business and politics cooperate and society comes along."

Cooperating with academia, business and policymakers: HySupply

The hydrogen economy is fundamentally collaborative, because while one party may have plentiful sunlight and raw materials, the other has the specialists and technological know-how. It, therefore, makes sense for different countries to cooperate with each other and **share expertise and knowledge**. Ideally, if the conditions are right and there is agreement, **long-term energy partnerships** are established.

One of many examples is the HySupply project, which is co-supported by acatech and involves **experts from academia, politics and business** from **Germany** and **Australia** cooperating to develop new knowledge and, thus, pave the way for a trust-based **energy partnership**. Find out more from the study "HySupply – German-Australian Feasibility Study of Hydrogen produced from Renewables".[15]

Climate-neutral prosperity for society

What can I do as an ordinary citizen? We have the great fortune to live in a democracy: we always have access to information, can form our **own opinion, go to the polls with this knowledge and decide for ourselves**. This is a luxury that not many people in the world enjoy.

And that's what it's all about - broadening our own perspective, using knowledge, and thinking globally. **Do we want to make the energy transition a reality, achieve climate targets, and live on a planet worth living on in the future?** If so, the only way this is possible is for us to **think globally and involve everyone**. It is of little help to our planet if only some countries opt for climate-friendly hydrogen while in other countries oil and coal continue to be burned for industry and heating, or forests are cut down on a massive scale.

"As customers we can demand that the energy transition becomes a reality. This really works - otherwise there would be no market for organic vegetables. If we demand that cars are produced only with green steel, that's what will happen."

So, what's next? Section 3 showed us that hydrogen isn't just about buying and selling, but about long-term, trust-based partnerships with as many countries in the world as possible. It's about the question of how we can enable **environmentally compatible progress and development in the Global South** to better **distribute the growing prosperity around the world**. This truly affects us all.

"I think that hydrogen is an essential part of a future where we can maintain our quality of life while doing something good for the environment."

Would you have thought at the beginning of this HORIZONS issue that hydrogen was about such fundamentally important things? Hydrogen is indeed the oldest element in the universe and involves much more than just technology. Anyone who deals with hydrogen quickly comes up against the philosophical question: **How do we want to live in the future?**

Hydrogen is a **huge opportunity to make the energy transition a reality, achieve climate targets, and distribute prosperity more fairly.** It's about giving something back to all of us - clean air to breathe, a healthy planet, more recreation, more time, a greater quality of life: a more **climate-neutral prosperity.**

"I'm completely convinced that we are heading into a hydrogen world."

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Contributors

Hydrogen project group

The project group defined the content of this publication, with the acatech Office interviewing experts from academia, business, and society. acatech's Executive Board would like to express their sincere thanks to the project group for their input:

Prof. Dr. Robert Schlögl, **Head of project group,** President of the Alexander von Humboldt Foundation, Director of the Inorganic Chemistry Department, Fritz Haber Institute of the Max-Planck-Society

Prof. Dr. Christoph Schmidt, President, RWI – Leibniz Institute for Economic Research

Martina Merz, CEO Thyssen Krupp AG

Prof. Dr.-Ing. Karsten Lemmer, Member of the Executive Board DLR, German Aerospace Center

Dr. Wiebke Lüke, Founder & Managing Director WEW GmbH

Nikolas Iwan, Managing director H2 MOBILITY

Philip Green, Australian Ambassador to Germany

Interviewpartner

Prof. Dr.-Ing. Dr. h. c. Albert Albers, Institute management spokesperson for IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT)

Prof. Dr.-Ing. Jürgen Fleischer, Director of Machines, Equipment and Process Automation, Karlsruhe Institute of Technology (KIT)

Storytelling, text and graphics, interviews, research

Christina Müller-Markus, acatech Office, HORIZONS, **lead author**

Marco Mitrovic, acatech Office, HORIZONS

Assisted by:

Dr. Sandra Fendl, acatech Office, HORIZONS

Dr. Doerthe Winter-Berke, aacatech Office, HORIZONS

Nardine Abdelmessih, acatech Office, HORIZONS
Social media communications

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National Academy of Science and Engineering

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PUBLISHER:
acatech – German Academy of Science and Engineering

OFFICE ADDRESSES
Munich Office
Karolinenplatz 4
80333 München
T +49(0)89 / 520309-0
F +49(0)89 / 520309-900

Berlin Office
Pariser Platz 4a
10117 Berlin
T +49(0)30 / 2063096-0
F +49(0)30 / 2063096-11

Brussels Office
Rue d'Egmont / Egmontstraat 13
B-1000 Brüssel
T +32(0)2 / 2 13 81-80
F +32(0)2 / 2 1381-89

horizonte@acatech.de
https://en.acatech.de/project/acatech-horizons-overview/

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You may still vaguely remember hydrogen from your first chemistry lessons. If you burn it, energy is released. Its advantage is that this releases only water, not environmentally harmful gases. If produced in a climate-friendly way, it can help us turn our backs on fossil fuels such as coal and natural gas once and for all and finally make industry, transport and energy supply sustainable.

But how does this work and what technologies are already available? Where will the hydrogen come from? What is conceivable in the future and what still needs to happen? If this has piqued your curiosity and you've been on the lookout for a fact-based yet easy-to-understand overview of hydrogen for a while then you're in the right place!