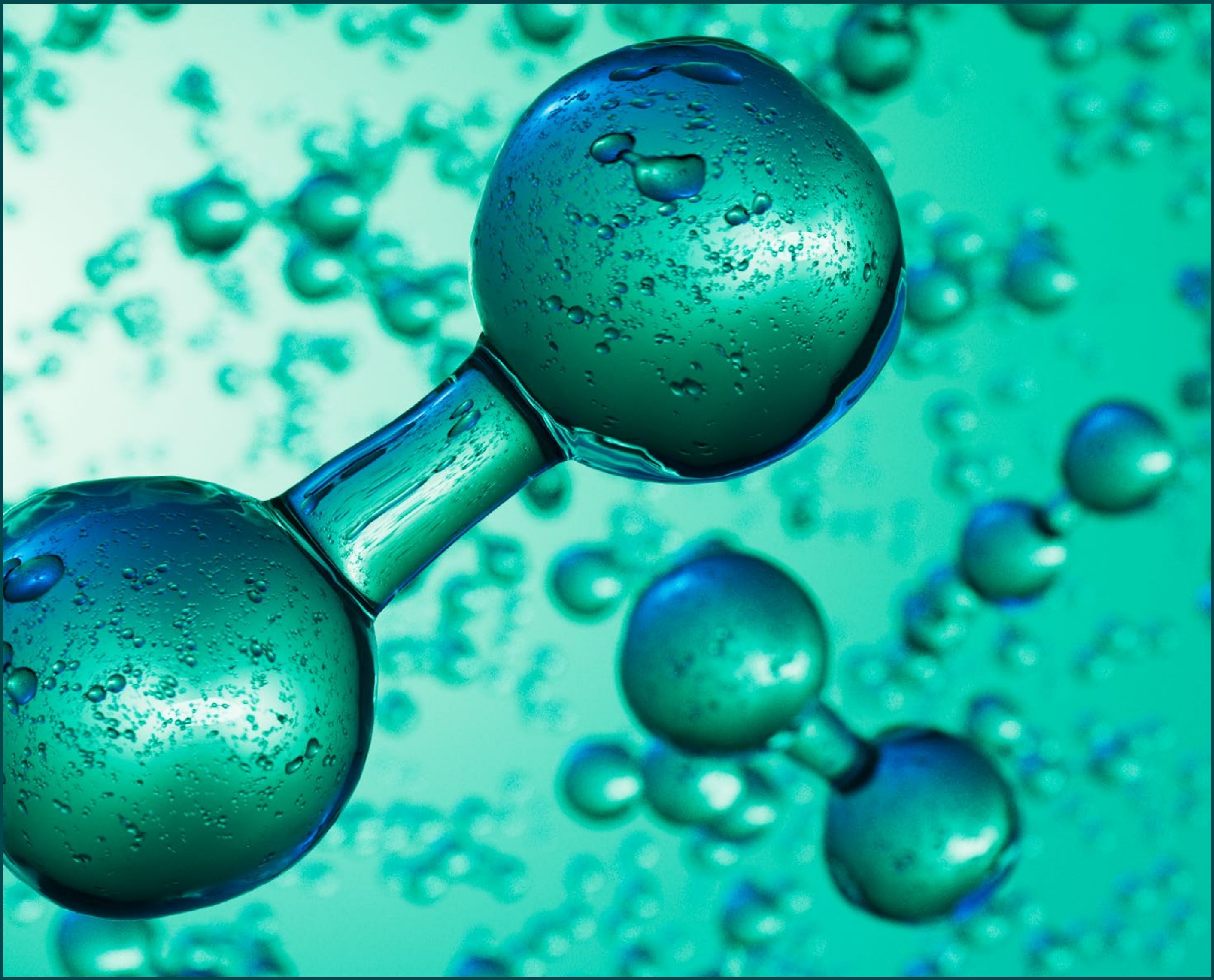
Energy Compass PSI

Navigating the energy transition
#1 / 2026

Hydrogen and the energy puzzle

What is the role of low-carbon molecules on the road to climate neutrality?



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Editorial

The lightest and simplest chemical element in the universe, hydrogen will be an important energy carrier for the energy transition. It is not free of controversy, though. Hyped by some as the “Swiss army knife” of the energy transition, a one-size-fits all solution to all imaginable energy system challenges, it is regarded by others as too expensive, inefficient, and dangerous to play a significant role. The reality lies between these two extremes, as we examine in our second issue of the PSI Energy Compass.

Hydrogen has numerous advantages. Its use releases no greenhouse gas emissions, it can be stored, and it can fulfil a variety of functions across the economy, from motive power to high temperature heat. A further advantage of hydrogen is the derived energy carriers that can be produced with it, including so-called synthetic fuels, such as methanol and ammonia.

Hydrogen also has downsides. It is expensive to produce sustainably. The tiny molecule can easily leak out of infrastructure designed for storing and transporting fuel such as natural gas. Any leakage would indirectly increase the atmospheric concentration of known greenhouse gases like methane and ozone. Furthermore, whilst the energy density is quite high per unit of mass, it is relatively low per unit of volume – meaning it takes up a lot of space, not ideal for applications like aviation. Hydrogen also tends to cause embrittlement of steels used for pipelines, which reduces their lifetimes compared to their use for other gases. It is more explosive than other gases, which can present a safety hazard, and in turn may result in lower acceptance from society. Finally, the manufacture of hydrogen via sustainable pathways is more energy and resource intensive than alternatives such as electrification.

Despite these disadvantages, there is an emerging scientific consensus that hydrogen and hydrogen-based fuels make sense in several specific sectors. But even these limited applications will require a massive scale-up of hydrogen production and imply numerous trade-offs, as we explore in the coming pages. Meanwhile, advancing policy to support production and adoption of hydrogen and hydrogen-based fuels is hindered by the complexity of the options, the sheer number of actors involved, and the long-term implications of technological choices that will define the energy system for decades to come. In this issue, we examine the potential roles of hydrogen and its derivatives, along with the opportunities and challenges they bring for a net-zero future.

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Cover photo
Hydrogen molecules
Photo: Monika Blétry, PSI

Kicking the carbon habit

A sustainable energy system must abstain from oil, coal and natural gas. Alternatives are needed. Could hydrogen be an option?

The goal is clear: to stop emitting greenhouse gases by the middle of this century. This is necessary to limit global warming to two degrees Celsius or less – in line with the climate targets in the Paris Agreement. But the way there is still long and unclear. Minimising emissions of the most important greenhouse gases, CO_2 and methane, means that oil, coal and natural gas will no longer have a place in our energy supply. Despite all climate protection efforts, these fossil fuels still meet more than 80 per cent of the world's primary energy demand. In Switzerland, this figure is significantly lower at just under 50 per cent, thanks to electricity from hydroelectric and nuclear power stations. Nevertheless, replacing oil and natural gas for heating; petrol, diesel, and kerosene for transport; and natural gas for industrial processes with sustainable alternatives is a mammoth task in this country too.

But what alternatives are actually available?

Firstly, electricity from renewable sources and nuclear energy, as these cause hardly any greenhouse gas emissions. In many cases, electricity can directly replace fossil fuels if suitable technologies such as battery electric vehicles or heat pumps are available.

Secondly, hydrogen (H_2) – but only if produced sustainably. It can be used directly or combined with carbon dioxide (CO_2) to produce synthetic hydrocarbons such as kerosene, methane, diesel or petrol.

Using pure hydrogen directly is not straightforward. Special technologies and processes are required, such as fuel cell vehicles instead of combustion engines. Transporting and storing hydrogen is anything but trivial because hydrogen must be highly compressed due to its low energy density (see Figure 1). This requires either high pressure or low temperatures and, in both cases, suitable materials such as carbon fibre tanks or pipelines made of special types of steel. Compression and cooling also require a lot of energy, which, like the special materials, leads to high costs.

Synthetic hydrocarbons, on the other hand, have a wide range of applications. Kerosene, methane, diesel or petrol produced from hydrogen and CO_2 can replace the fossil fuels used today on a one-to-one basis, and can be transported, stored, and used with the same infrastructure.

Hydrogen and greenhouse gas emissions

Like electricity, hydrogen is a so-called secondary energy carrier – one that has to be produced, just like electricity. There are many ways of doing this. A colour scheme is often used to distinguish between the different types of hydrogen production, which are associated with different levels of greenhouse gas emissions (see “The hydrogen rainbow”).

In order for hydrogen to contribute effectively to climate protection, its production must be associated with very low emissions. This is measured across the entire value chain, from the extraction of resources to their conversion into hydrogen.

Green and pink hydrogen best meet the requirement for low greenhouse gas emissions. Blue and turquoise hydrogen can also meet this requirement, but only if methane emissions from natural gas supplies are low and if most of the carbon released during hydrogen production from natural gas is permanently stored. No colour has been assigned to hydrogen produced from biomass yet, but it could well become an important means of producing hydrogen with very low emissions. Brown and grey hydrogen currently account for around 85 per cent of global production, but they have no place in tomorrow’s hydrogen economy if we are to achieve our climate targets, as they simply cause too many greenhouse gas emissions.

Today, there is little sign of a switch to green and blue hydrogen – less than one per cent of hydrogen is currently produced in this way. This is mainly due to the high costs, which are not likely to decrease any time soon. It is therefore foreseeable that hydrogen will remain a scarce and expensive commodity that must be used as wisely as possible.

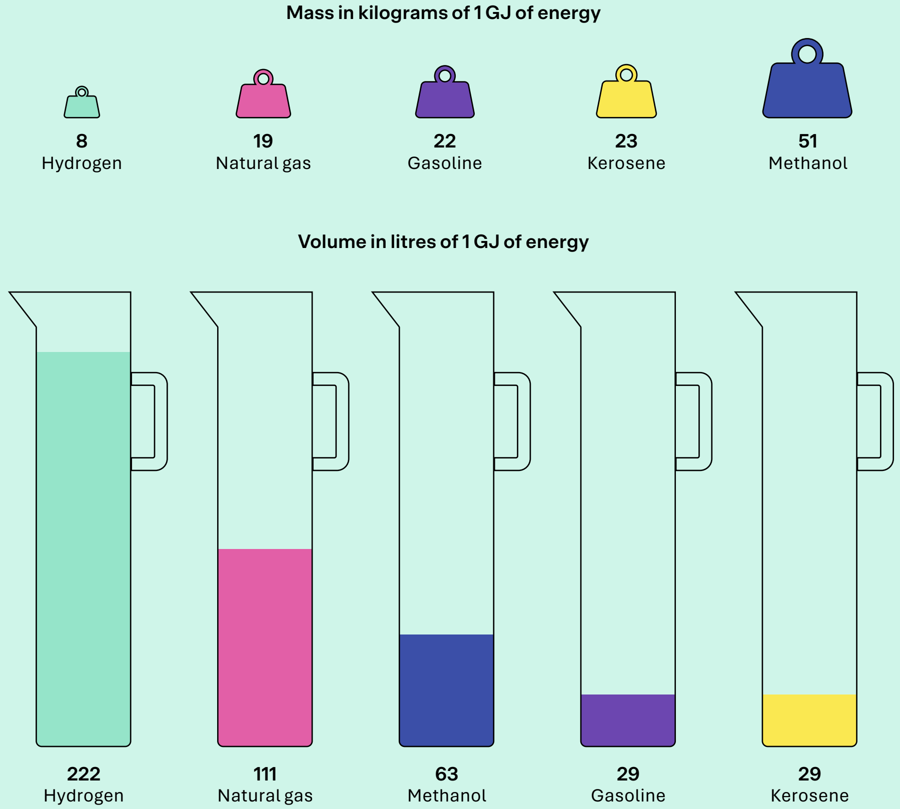


Figure 1: **Inverse gravimetric (top) and inverse volumetric (bottom) energy densities of selected fuels**

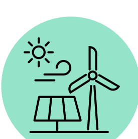
The figure shows the mass in kilograms of fuel corresponding to 1 gigajoule (GJ) of energy (top), and the volume in litres for the same amount of energy (bottom). Hydrogen has a high energy content per mass but, due to its low energy content per volume, takes up much more space compared to liquid hydrocarbons such as kerosene or gasoline. The volumes shown assume typical storage conditions: compressed hydrogen at around 700 bar, compressed natural gas at roughly 250 bar, and gasoline, kerosene, and methanol as ambient-temperature liquids.

The hydrogen rainbow

Hydrogen can be produced in a variety of ways, each associated with different environmental impacts. To distinguish among these production routes, a colour-based naming convention is commonly used, although it is not standardised.

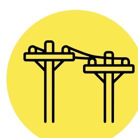
One key differentiator is the amount of greenhouse gas emissions generated on a life-cycle basis. Some of these production routes employ Carbon Capture and Storage (CCS), which involves capturing carbon dioxide (CO_2) and storing it underground. As shown in Figure 2, this can even deliver negative emissions, effectively removing CO_2 from the atmosphere. However, nearly all of the 97 million tonnes (Mt) of hydrogen produced globally today comes from fossil fuels, resulting in around 920 Mt of CO_2 emissions annually.

Green



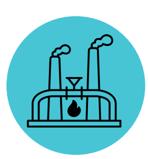
Green hydrogen is produced by using renewable electricity – such as wind or solar power – to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) through electrolysis. This pathway is virtually emissions-free. Its main drawbacks are its relatively high cost and the need for substantial renewable energy and water resources in order to scale.

Yellow



Yellow hydrogen refers to hydrogen produced through electrolysis powered by grid electricity. While this method is flexible and can leverage existing power infrastructure, the amount of greenhouse gas emissions it produces varies with the carbon intensity of the local grid. In regions where the grid includes a high share of fossil fuels, the emissions can be substantial, even exceeding those of grey hydrogen.

Turquoise

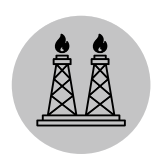


Turquoise hydrogen is made by converting methane into hydrogen and solid carbon via pyrolysis, a thermochemical process in which methane is broken down into its components in the absence of oxygen. If the process is powered by renewable energy and methane leakage along the supply chain is controlled, it can be a low-emissions pathway. The solid carbon by-product could be permanently stored or used in industrial applications. However, this technology is still in early development and not yet commercially deployed.

Pink

Pink, purple, or sometimes **red hydrogen** is produced through electrolysis powered by nuclear energy. This method offers low life-cycle greenhouse gas emissions; however, concerns include nuclear waste, safety risks, and high upfront costs.

Grey



Grey hydrogen comes from steam reforming of natural gas. In steam reforming, methane is converted into hydrogen and carbon dioxide with steam at high temperatures. This is the most cost-effective and established production process, but it causes high CO_2 emissions (see Figure 2).

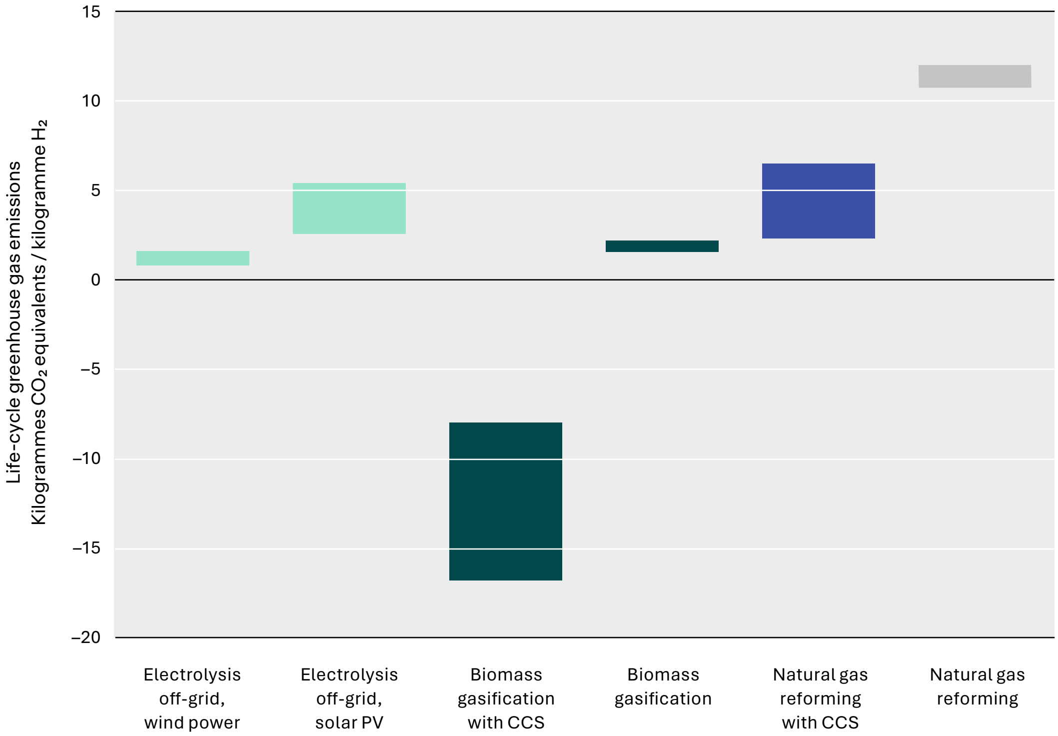


Figure 2: **Possible ranges of greenhouse gas emissions of selected hydrogen production pathways**

This figure compares the life-cycle greenhouse gas emissions of different hydrogen production pathways. Emissions vary widely: wind- and solar-based electrolysis (green hydrogen) result in low impacts, while natural gas reforming without CO_2 capture (grey hydrogen) is the most carbon-intensive option shown.

(Source: PSI Laboratory for Energy Systems Analysis)

Blue

Like grey hydrogen, **blue hydrogen** is produced via steam methane reforming, but with the addition of CO_2 capture and storage. This process can significantly lower the carbon footprint and makes use of existing natural gas infrastructure. On the downside, CO_2 capture and storage is energy intensive and does not capture all emissions.

Black/Brown

Black or brown hydrogen is produced by gasifying coal. During gasification, coal is converted into a gas mixture of hydrogen, carbon monoxide, and carbon dioxide under limited oxygen supply and high temperatures. This is one of the most carbon-intensive hydrogen production methods.

White

Naturally occurring **white hydrogen** is found in underground deposits. Exploration of this resource is still in the early stages, with only one operational plant, and uncertainties remain about the size and accessibility of global reserves, the economics of extraction, and possible environmental impacts of drilling and subsurface disruption.

Hydrogen from biomass (no colour yet)

Hydrogen can also be produced from biomass through thermochemical or biochemical processes. The greenhouse gas emissions associated with biomass-based hydrogen vary widely depending on the feedstock, land-use change impacts, and whether CO_2 capture and storage is applied. In some configurations, particularly when using waste biomass with carbon capture, this pathway may result in net-negative emissions, i.e., remove CO_2, which has been captured by the growing biomass, permanently from the atmosphere (see Figure 2). However, sustainability concerns can limit large-scale deployment.

Setting priorities

Low-carbon hydrogen will remain scarce and expensive in the coming years. That is why suitable applications must be carefully considered.

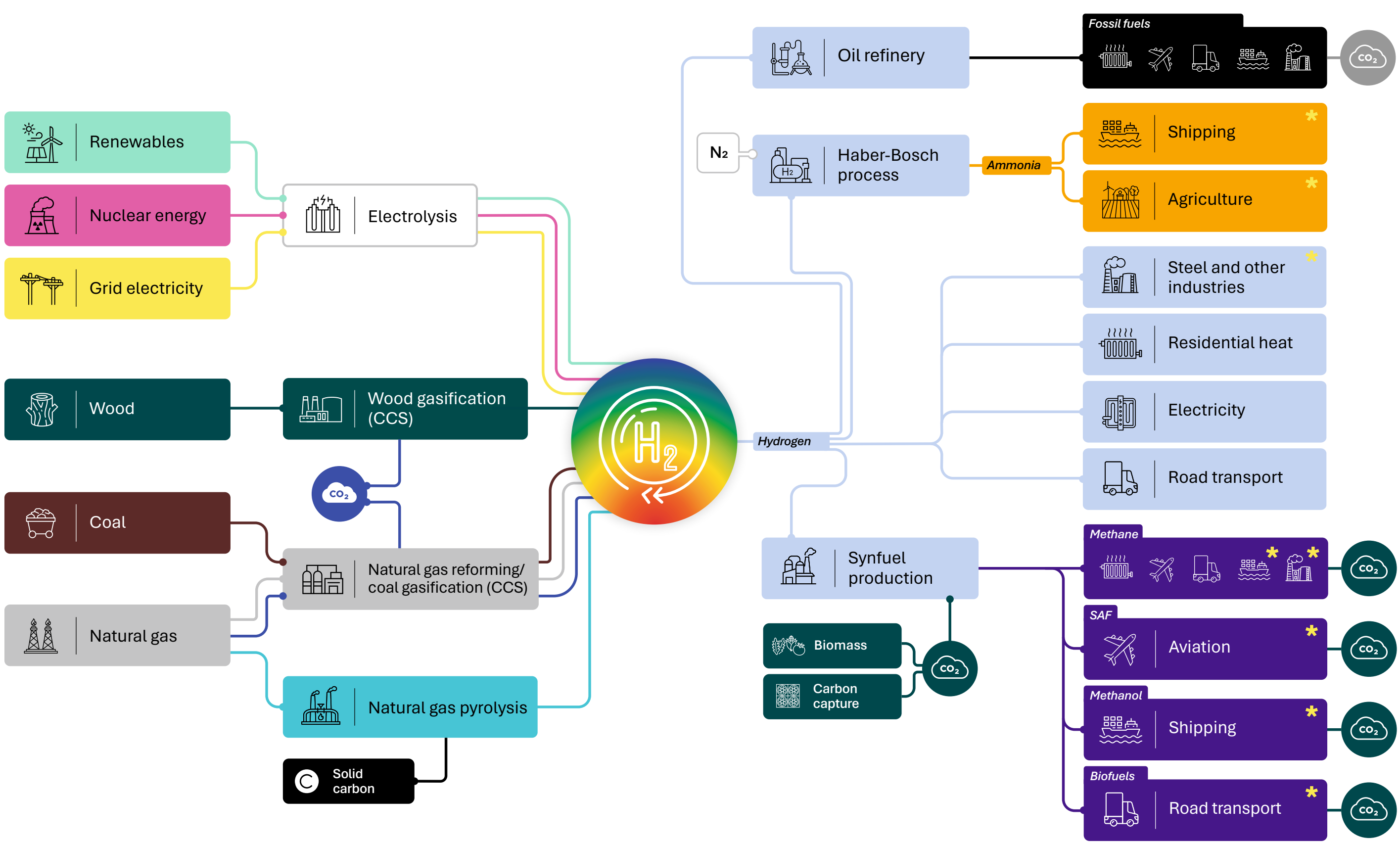
Hydrogen for cars? Probably not. For sightseeing boats? Also unlikely. For heating our homes? Definitely not. These much-cited applications of hydrogen make little sense, as more efficient, easier-to-use, and cheaper alternatives exist. Battery-electric vehicles and electric heat pumps, for example, are a more sensible option for cars and heating systems because they use electricity directly, thus avoiding conversion losses. A car running on synthetic petrol made from hydrogen and CO_2 needs around five times more electricity than a battery-powered car, while a heating system running on synthetic natural gas requires ten times more than a heat pump. In addition, battery-powered cars and heat pumps are even now hardly more expensive than fossil fuel technologies over their lifetime.

So, if these applications do not make sense, what is all the green and blue hydrogen used in scenarios that meet climate targets for? First of all, today's hydrogen demand of around 100 megatonnes per year must be met – in oil refineries, the chemical industry and fertiliser production. In addition, there are many applications for which there are no alternatives to hydrogen or energy carriers derived from it. These in turn differ in their additional costs and the extent to which greenhouse gas emissions can be reduced.

Our research shows that the largest reduction in greenhouse gas emissions can be achieved if coal is replaced by hydrogen in steel production. Hydrogen can also replace natural gas wherever very high temperatures are required, thereby reducing greenhouse gas emissions. Examples include glass production and metal processing. Significant emissions reductions can also be achieved in the production of ammonia and methanol if green hydrogen replaces the natural gas used today. Hydrogen-based synthetic fuels could largely replace heavy fuel oil in shipping and fossil kerosene as jet fuel (see “Decarbonising shipping” and “Will it fly?”). These hydrogen applications all have one thing in common: significant limits on the extent to which they can be electrified.

For all of these purposes, there is hardly any way around using hydrogen. Biomass-based fuels, such as aviation fuels made from waste oil or agricultural residues, are often a suitable supplement. However, the potential for sustainably usable biomass – preferably in the form of residues – is too low to replace hydrogen as a sustainable alternative to natural gas, coal and oil.

Given all the sensible applications mentioned, the crucial question is how high the demand will be. One thing is clear: these are not just niche applications on a small scale. On the contrary. Based on current demand for ammonia, methanol, aviation fuels, high-temperature heat and steel production, the future market for hydrogen and its derivatives will be huge, exceeding 100 million tonnes per year. From a business perspective, it therefore makes sense to prioritise these applications (see Figure 3).



Direct applications of hydrogen
Applications of synthetic fuels
Fossil fuels
Ammonia
CO_2 emissions from fossil fuels
Carbon stored underground
Biogenic CO_2 emissions
Application that should be prioritised

Figure 3: **Hydrogen production and application pathways**

(Source: PSI Laboratory for Energy Systems Analysis)

Green hydrogen means environmental trade-offs

Figure 4: **Production costs of green hydrogen in the most economical locations (2025)**

This map shows nine relatively low-cost regions for producing green hydrogen, along with the severity of water scarcity at each location, ranging from low (green) to severe (red).

(Source: PSI Laboratory for Energy Systems Analysis)

Global demand for hydrogen is expected to increase substantially to decarbonize diverse economic sectors. Green hydrogen requires significant amounts of water, materials, and electricity, resulting in environmental and economic trade-offs.

Hydrogen's primary applications are currently not as an energy source, but as a raw material in oil refineries and the chemical industry to produce ammonia, fertilisers, and methanol. However, as we just read, low-carbon hydrogen will be needed to substitute fossil fuels for a variety of applications to limit global warming, causing the global demand for hydrogen to soar. All of this hydrogen should be produced using processes with low embedded greenhouse gas emissions.

Scaling up production: geography matters

Finding suitable production locations is part of the challenge of scaling up green hydrogen production, as electrolysis requires sufficient available land, abundant fresh water, and renewable electricity. We have conducted a global analysis of where green hydrogen can be produced at the lowest cost – it shows that South America, Australia, the Midwest of the USA, and deserts in Africa and Asia rank highest. But even when considering location optimization and technological advancements, it will still take decades for the production costs of green hydrogen to come down to the current cost of hydrogen produced from fossil resources, as discussed in more depth in "Molecules in energy markets".

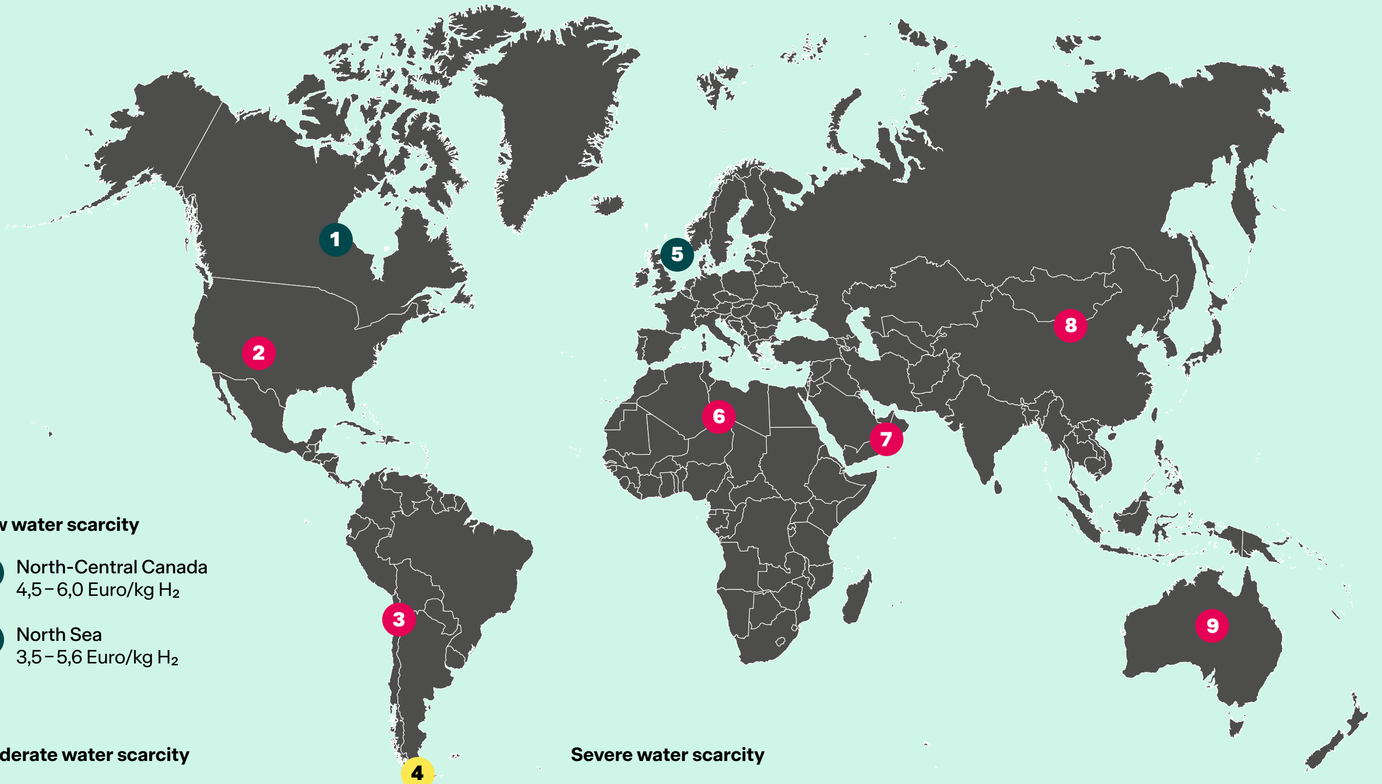
In addition, the cost of hydrogen and derived low-carbon fuels is location specific and strongly dependent on a country's investment risk. In fact, investment risk can be as much of a determining factor as the availability of renewable energy. Financial derisking, such as through subsidies and clear and consistent regulations, can attract more investment to countries that have promising natural resource potential but exhibit high investment risk, such as some countries in Africa.

Balancing opportunities and trade-offs

Although green hydrogen production causes low greenhouse gas emissions, scaling it up might still come with considerable environmental burdens. Water availability could pose a challenge, as electrolysers require purified water for the water-splitting process. More than 60 percent of the green hydrogen production potential we identified is in water-scarce areas (as seen in Figure 4). Additionally, the electricity requirements for grid-connected water electrolysis could burden power grids, as more renewable energy sources need to be installed.

The demand for critical materials could also become a problem. Hydrogen supply chains often rely on critical raw materials, such as iridium in some electrolysers, and rare earths, needed for the magnets used in wind turbines. The supply of these materials can come with serious social and environmental concerns, such as poor labour conditions, ecosystem degradation, and water contamination from mining. Furthermore, the extraction and refinement of critical materials is typically concentrated in China and a handful of other countries, posing potential additional risks to supply chain security.

Overall, the large-scale roll-out of hydrogen and hydrogen-based low-carbon fuels requires careful consideration of such economic and environmental criteria, and prioritization based on these trade-offs.



Low water scarcity

1 North-Central Canada
4,5 – 6,0 Euro/kg H_2

5 North Sea
3,5 – 5,6 Euro/kg H_2

Moderate water scarcity

4 Patagonia, Argentina/Chile
4,0 – 6,2 Euro/kg H_2

Severe water scarcity

2 Southwest/Midwest USA
3,8 – 5,2 Euro/kg H_2

3 Atacama Desert, Chile
3,9 – 4,1 Euro/kg H_2

6 Sahara Desert
4,6 – 6,4 Euro/kg H_2

7 Dhofar region, Oman
4,4 – 5,4 Euro/kg H_2

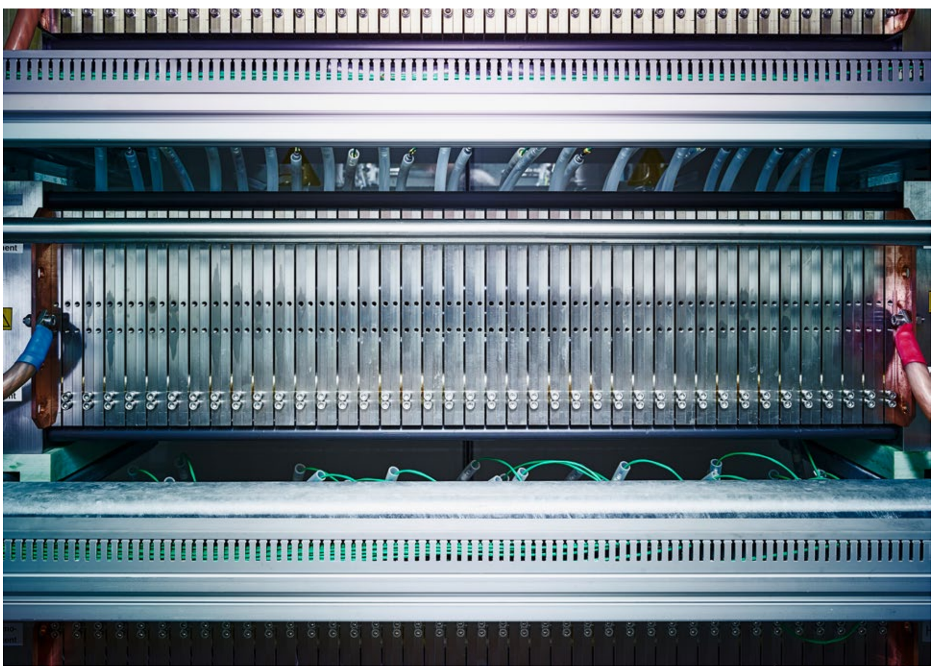
8 Gobi Desert, China/Mongolia
4,0 – 5,4 Euro/kg H_2

9 Central Australia
4,2 – 4,9 Euro/kg H_2

Solar farm in Central Australia

Putting the pieces together: hydrogen in the Swiss energy system

Molecular energy carriers, including hydrogen and synthetic fuels, are set to play a strategic role in Switzerland's decarbonisation. Our scenarios suggest they could cover around 15 percent of the country's energy needs by 2050 – largely through imports linked to European developments.



The electrolyser at PSI's ESI Platform

Hydrogen and synthetic fuels are beginning to take off as key options for cutting emissions in aviation, shipping, and heavy industry. However, their global use today is still below 1 million tonnes (Mt). For comparison, this is just 1 percent of current global oil demand. To limit overall warming to 1.5 °C, global use of low-carbon hydrogen for energy purposes should reach 44 Mt by 2030 and 280 Mt by 2050, according to the latest IEA Hydrogen Report, and up to 0.3 Mt by 2050 in Switzerland, according to our analysis.

Switzerland's hydrogen ambitions

The EU has placed hydrogen at the centre of its Green Deal, with regulations such as RefuelEU and FuelEU driving the uptake of e-fuels in planes and ships. In line with European ambitions, Switzerland published its own Hydrogen Strategy in 2024. The Swiss strategy sets a vision for CO_2-neutral hydrogen in alignment with EU sustainability rules. In contrast to the EU's strategy, it contains no binding targets for production or use, and does not provide a specific budget for hydrogen projects. Supported by federal decarbonisation and innovation programmes totalling 1.2 billion Swiss francs under the Climate and Innovation Act (KiG), Switzerland focuses on developing "hydrogen clusters", simplifying regulation, and enabling industry-led investment. Still, it adopts the mandatory requirement coming from the RefuelEU Aviation Regulation on blending targets for synthetic fuels.

Our energy systems and scenario modelling show that hydrogen can play a dual role in Switzerland's energy transition by providing:

a) clean fuel for hard-to-electrify sectors, such as cement, chemicals, and steel, and synthetic Sustainable Aviation Fuel (SAF) for aircraft fueled in Switzerland, and
b) seasonal balancing in the power system, storing surplus summer electricity for winter use.

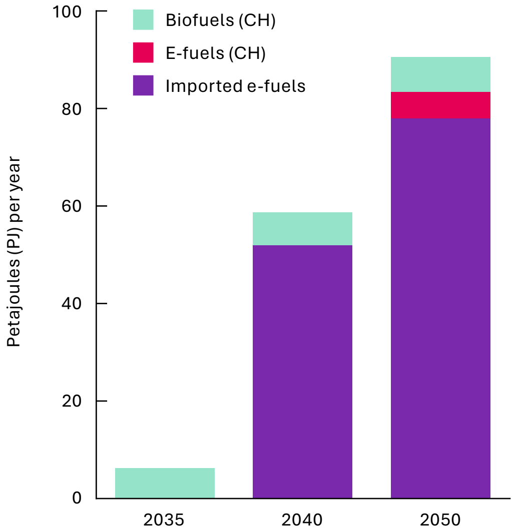


Figure 5: **Swiss domestic supply and imports of sustainable fuels through 2050**

In our net-zero scenario, domestic production of sustainable biofuels and e-fuels remains limited, with most future supply expected to come from imported e-fuels. By 2050, imported e-fuels dominate the mix.

(Source: PSI Laboratory for Energy Systems Analysis)

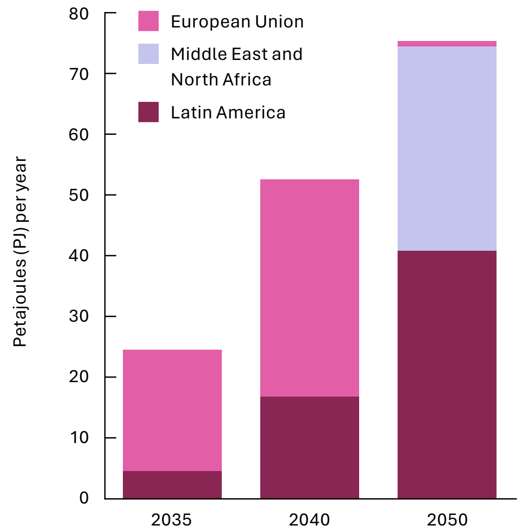


Figure 6: **Swiss e-fuel imports by origin through 2050**

In our net-zero scenario, Switzerland's e-fuel imports are projected to grow strongly, with the European Union providing the bulk of supply up to 2040. By 2050, Latin America and the Middle East and North Africa emerge as major exporters.

(Source: PSI Laboratory for Energy Systems Analysis)

In a cost-effective pathway to net-zero, hydrogen use in the Swiss energy system reaches up to between 0.2 and 0.3 Mt, or 24 and 26 Petajoules (PJ) per year. Additionally, aviation and industrial heating will depend on approximately 90 PJ of (mainly imported) synthetic fuels per year by 2050 (see Figure 5). Of this, Sustainable Aviation Fuel (SAF) demand alone accounts for 65 PJ (more on this topic in "Will it fly?"). Meanwhile, seasonal storage needs in Switzerland could reach 5 to 7 PJ. The Swiss energy provider Gaznat is planning to build lined rock caverns in Oberwallis with a 5.5 PJ capacity. For comparison, this is equivalent to 4 percent of Switzerland's current annual natural gas consumption.

Excluding hydrogen and e-fuels from Switzerland's energy mix, without considering international aviation, would raise the annual system costs by 200 Swiss Francs per capita for the next 25 years (that is, around 5,000 Swiss Francs in total per capita from 2025 to 2050) and make decarbonisation more challenging.

Scaling up from pilot projects

At present, Swiss hydrogen production is minimal. Installed electrolyser capacity is about 11 megawatts distributed across small projects in Dietikon, Reichenau, Uri, and Gruyère. Current domestic hydrogen output is far below 0.01 Mt/year. Looking ahead, our modelling suggests domestic production could reach 0.2 Mt/year from electrolysis by 2050, with an additional potential of 0.1 Mt/year from biomass gasification or methane reforming with carbon capture. Achieving this scale would require an estimated 22 billion Swiss Francs investment in production infrastructure alone. Such results underscore the magnitude of the challenge and the importance of clear long-term policy signals.

Even under high-domestic-output scenarios, over 90 percent of hydrogen and all e-fuels in Switzerland would be imported, mainly from North Africa, the Middle East, and Latin America (Figure 6). This highlights the need for Swiss links to European infrastructure, as with projects such as the European Hydrogen Backbone, an initiative from European gas transmission system operators to build dedicated hydrogen transport infrastructure across Europe. Long-term import contracts could also help keep costs stable and supply secure.

These fuels are not just energy carriers – they connect sectors, strengthen resilience, and help ensure a climate-neutral future. To prepare a hydrogen-enabled system in time to meet net-zero targets, Switzerland will need to build cross-border links, secure import partnerships, and send clear, long-term signals to investors. These steps would have to be taken now, to avoid being locked into more expensive, less adaptable pathways later.

Molecules in energy markets

Markets, technology, and ownership choices will shape hydrogen's role in a net-zero system – and Switzerland's energy future.

Turning hydrogen into a mainstream energy carrier will require an entire system of pipelines, storage facilities, and trading hubs, similar to the systems that underpin today's natural gas markets. Unlike methane, hydrogen has no dedicated grid or trading hubs, so deliveries typically rely on costly trucks. Today the hydrogen market remains small and expensive, with retail prices of around 8 to 10 Swiss francs per kilogramme according to the HYDRIX, a hydrogen index established in Germany in 2023. This corresponds to approximately five Swiss francs at the pump for petrol with equivalent energy content (and assuming a similar tax burden as for petrol). The high cost and lack of designated infrastructure are important reasons blending is considered an attractive option.

Challenges of blending and transporting hydrogen

Some countries have experimented with blending small amounts of hydrogen into the natural gas grid. Up to 15 percent by volume can typically be added without major technical issues. Higher shares are possible, but would require adjustments to valves, pipes, and appliances. And because hydrogen production from solar and wind tends to be intermittent, the resulting mixture would vary over time, raising both safety and reliability concerns. For these reasons, many experts believe that hydrogen will eventually need its own dedicated infrastructure if it is to play a significant role in the energy system.

Hydrogen storage: daily and seasonal uses

One advantage of hydrogen is that it can be stored for later use, either over hours, days, or even across seasons. This makes

it potentially valuable for balancing variable renewable electricity from solar and wind.

But storage comes at a cost. Hydrogen-based electricity storage – often called "power-to-power" (P2P) – involves converting electricity into hydrogen via electrolysis, storing it, and later turning it back into electricity using a fuel cell. This process is expensive, with costs of 330 to 500 Swiss francs per megawatt-hour of electricity delivered, which is much higher than today's electricity price span between day/night. To become competitive, a future cost reduction, as already experienced with PV panels, and improved efficiency would be required. Other options, such as pumped hydropower and batteries, are currently cheaper for daily storage cycles.

There is one area where hydrogen may offer a cost advantage: seasonal storage. Storing hydrogen in tanks or underground caverns over weeks or months could prove more economical than trying to scale up batteries or pumped storage for the same duration. However, Switzerland currently has no significant domestic gas storage capacity. It currently utilises three terawatt hours of storage capacity in the EU (mostly in France). It is unclear from a technical perspective whether this can be converted to hydrogen storage. Without building hydrogen storage facilities, hydrogen will provide only part of the needed flexibility. However, a viable hydrogen-based seasonal storage solution will require stronger seasonal electricity price signals than today, or supportive policies that reduce winter import dependence and enhance energy security.

Who should own the infrastructure?

The ownership of the electrolysers and the storage facilities can also shape market outcomes. If a large player controls a key part of the market, they might manipulate supply or demand to influence prices. This is known as market power.

Electrolysers use electricity, and most are owned by utilities that also generate electricity. If such a utility is large enough, it can affect both supply and demand and push electricity prices in its favour. Hence, it can exercise market power.

In a simplified model, we examined a case where a single power producer and a single electrolyser operator both have market power. If the same company owned both, the overall welfare – that is, the combined benefits to producers and consumers arising from the gap between market prices and actual costs of the system – improved, but only as long as the electrolyser capacity remained relatively small, as it is nowadays. However, as electrolysers increased in scale, keeping ownership separate tended to improve overall welfare.

These findings highlight how the distribution of capacity and ownership can influence market power. They also suggest that optimal market design may depend on the scale of green hydrogen production from electrolysis relative to electricity supply. Another important factor is risk aversion – preferring steady, predictable earnings rather than gambling on uncertain future highs that might also bring losses. Companies may prefer stable returns over maximum possible profits, especially in volatile energy markets. Viewed another way, risk-averse companies want to maximise their average profit and limit the risk of low profits. Using our modelling, we found that in such a context, when storage is operated by an energy consumer (rather than a producer), the system tends to make better use of the storage, leading to higher overall welfare. With well-designed financial contracts, though, it's possible to align incentives between different owners.

Looking ahead

Aside from the potential domestic production of e-fuels such as Sustainable Aviation Fuel (SAF), hydrogen's role in Switzerland hinges on seasonal storage. The ownership of electrolysers and hydrogen storage matters to ensure a well-functioning future hydrogen market. At the same time, market rules would have to prevent large players from distorting prices and ensure that even risk-averse companies make full use of storage capacity.

Will it fly?

While sustainable aviation fuels derived from hydrogen will play an important role en route to climate neutrality, only replacing the fuel will not be enough.

Carbon neutral by 2050 – many airlines have set themselves this goal. However, reducing climate impacts in the aviation sector is particularly challenging. Unlike other sectors, it is not feasible to directly electrify most aircraft. While battery electric drivetrains work well in cars, batteries are too heavy for planes, especially on longer routes. And unlike for trucks and heavy-duty road vehicles, there are no planes running on hydrogen planned in the foreseeable future. This is mostly due to hydrogen's low energy density per volume (see Figure 1), which would either require a total redesign of the plane, or a significant reduction in seating capacity.

In contrast, Sustainable Aviation Fuels, or SAF, are a plausible low-carbon replacement for conventional kerosene. SAF is a certified class of jet fuel that can either be made from biomass (bioSAF), or by combining hydrogen and non-fossil carbon dioxide (synthetic SAF). Both bioSAF and synthetic SAF are central to the blending mandate the European Union put into force in 2023, which stipulates that, by 2050, jet fuel should contain at least 70 percent SAF (and of that, half should be synthetic SAF).

Complicating factors

At first glance, synthetic jet fuel might seem like an elegant climate solution for the aviation sector. However, research from our lab paints a more complicated picture.

While synthetic SAF could drastically reduce fossil CO_2 emissions, two-thirds of aviation's warming impact today are due to so-called 'non-CO_2 effects'. These are the climate impacts caused by processes and emissions other than carbon dioxide. They include condensation trail (contrail) cirrus cloud formation, nitrogen oxide emissions, and high-altitude water vapour, which all have a net warming effect.

Synthetic SAF burns more cleanly than fossil jet fuel, which helps reduce contrails. However, growing air traffic erodes climate benefits of SAF. Sustained increases in air traffic would still lead contrails to cause over 50 percent of aviation's total warming impact in the future. Although non-CO_2 effects are often short-lived, more flying means more non-CO_2 effects, which ultimately leads to continued warming. In other words, non-CO_2 effects cannot be avoided just by switching jet fuels; we also need to fly less and reroute aircraft to reduce contrails.

Another complicating factor is the staggering energy and resource requirements of producing the volume of synthetic SAF needed. At the current rate of air traffic growth, if Europe's demand for jet fuel were to be satisfied using only synthetic SAF, Europe's electricity demand would double in the second half of this century. Even if less synthetic SAF is needed due to blending with bioSAF, the sheer scale poses a huge challenge.

In addition, technologies like direct air carbon capture and storage (DACCS) are needed to sequester atmospheric CO_2 to eliminate persisting warming impacts from the use of SAF. DACCS is an energy-intensive process, which will require not only additional low-carbon energy, but also substantial geological CO_2 storage infrastructure that is not yet available.

Necessary but not sufficient

Synthetic SAF is without a doubt an important piece of the aviation decarbonisation puzzle. It offers compatibility, lower fossil CO_2 emissions, and modest reductions in non-CO_2 impacts. But it is not a panacea. Our research makes clear that fuel substitution will not be enough to make flying truly climate neutral.

Other options for mitigating the climate impact of aviation include new aircraft designs, engine improvements (particularly relevant for reducing nitrogen oxides), and market measures to restrain demand. Ultimately, climate-neutral flying will mean higher costs for passengers – and fewer trips by plane.

4.78 billion

Global air passengers in 2024

12.4 billion

Global air passengers expected in 2050

(Sources: IATA and ICAO)

"Decarbonisation poses considerable challenges for aviation." Ramon Hess

A conversation with Ramon Hess and Gabriel Müller of Swiss International Airlines

Air traffic is picking up again after the peak of the coronavirus pandemic. At the same time, the aviation industry seems committed to reducing the climate damage it causes. How does that fit together?

Gabriel Müller: Yes, air traffic is increasing again, which shows how important mobility is for our society. At the same time, we are aware that we have a responsibility as an industry to significantly reduce our environmental impact. The transformation towards more sustainable air transport is associated with major challenges. At SWISS, we have set ourselves ambitious CO_2 targets and are focusing on a variety of measures to reduce CO_2 emissions during flight operations. We have embarked on this journey, but we are still at the beginning of the path towards sustainable air transport.

SWISS has set itself the goal of achieving net-zero CO_2 emissions by 2050. How will this work in practice?

Ramon Hess: Exactly, as Gabriel just indicated, we at SWISS are pursuing various approaches to reduce our CO_2 emissions. One key lever is our fleet: modern aircraft such as the A320neo and the A350 use significantly less fuel than their predecessors. We are also focusing on measures to increase efficiency in daily flight operations. This includes, for example, optimised procedures, digital decision-making aids and optimisations to save fuel.

The key to decarbonising air travel lies in promoting and using Sustainable Aviation Fuels (SAF), for example through targeted partnerships with technology pioneers such as Synhelion. As many key technologies for decarbonising aviation are still in the development or early scaling phase, it is essential that they be specifically promoted today.

In addition to reducing emissions through SAF, removing the remaining CO_2 from the air is an indispensable part of our strategy to achieve net-zero CO_2 emissions, but also of the strategy of the entire sector.

> "Currently, global SAF production capacity is only sufficient to meet around 0.7 per cent of global demand."
>
> Gabriel Müller

Hydrogen is also being discussed as a potential aircraft fuel – do you foresee any realistic applications for an airline like SWISS, or will the focus remain on synthetic hydrocarbons?

RH: Hydrogen is rightly being discussed as a promising fuel for aviation – but this applies in particular to smaller aircraft and short-haul flights in the future. Long-haul aircraft, which account for the majority of CO_2 emissions, will – as things stand today – still be powered by liquid fuel in 2050. We do not consider the direct use of hydrogen to be realistic in the medium term. Our focus is therefore clearly on synthetic hydrocarbons, in other words SAF, which are produced using green hydrogen and CO_2. These are compatible with the existing fleet and infrastructure, offering a scalable solution for decarbonising aviation.

What challenges do you foresee in the transition to sustainable aviation fuels?

GM: One of the biggest challenges in switching to sustainable aviation fuels is their availability. Currently, global SAF production capacity is only sufficient to meet around 0.7 per cent of global demand, and synthetic fuels are not yet commercially available.

RH: Added to this are the high costs. Biogenic SAF is currently three to five times more expensive than fossil kerosene, and synthetic SAF is up to ten times more expensive. Fuel already accounts for around 30 per cent of the operating costs of an airline. Broad use of SAF is not economically viable for airlines, which is why international support schemes are urgently needed. The transition can only succeed if production, technological developments, and demand are advanced simultaneously.

> "The key to decarbonising air travel lies in promoting and using Sustainable Aviation Fuels."
>
> Ramon Hess

Are customers willing to pay for more sustainable flying?

GM: We see growing interest in sustainable flying among our customer base, which is central for transforming the aviation sector. Currently, around 5 per cent of our passengers choose one of our options to make their flight more sustainable. In the premium classes, the willingness to pay is significantly higher.

In addition to greenhouse gases, non-CO_2 effects such as contrails also contribute to the climate impact of aviation. How is SWISS addressing this issue?

RH: SWISS recognises that the overall impact of air traffic on the climate is not limited to the effects of CO_2 emissions. The extent of non-CO_2 effects is still the subject of ongoing research, which is why we specifically support research projects investigating these effects and possible mitigation measures. And as previously mentioned, we promote the use of SAF, which contains fewer aromatic hydrocarbons and has a lower sulphur content. This results in fewer soot particles and aerosols being produced during combustion, which can reduce contrail formation. SAF can therefore play a significant role in reducing non-CO_2 effects.

Political measures such as quotas for SAF or a kerosene tax are the subject of heated debate. What kind of regulation would you consider appropriate for promoting more sustainable aviation? Are the ambitious European targets for SAF realistic?

RH: Political measures must be coordinated internationally – ideally globally – and designed to be competition-neutral. Only then can climate policy instruments be effective and avoid carbon leakage,

Ramon Hess

is Corporate Responsibility Manager at Swiss International Air Lines. His responsibilities include monitoring and managing the CO_2 roadmap, ensuring compliance with environmental regulations and establishing strategic partnerships for CO_2 removal.

Gabriel Müller

has been with Swiss International Air Lines for 10 years in various roles. Since 2022, he has been working in the sustainability team, where he is particularly involved in driving forward the development and market launch of sustainable fuels, customer offers for more sustainable flying, and various strategic partnerships.

when traffic and CO_2 emissions are shifted abroad. While national instruments are by no means effective, the SAF mandate under ReFuelEU Aviation, for example, also creates distortions of competition. The blending quota makes connections via European hubs more expensive and leads to competitive disadvantages and emission displacement. This highlights the importance of coordinating climate policy legislation internationally and the challenges involved in developing effective instruments for aviation.

GM: Whether companies and politicians achieve their sustainability goals also depends on fair conditions for global competition. This requires regulations to be adjusted so as to have a neutral impact on competition – for example, through a final destination-based passenger levy in the EU, the revenue from which could be used for SAF. At the same time, a support strategy for SAF is needed. The production of sustainable fuels must be scaled up rapidly to ensure the necessary quantities are available at competitive prices.

Cooperation is key when it comes to a complex issue such as CO_2-neutral aviation. Which partnerships is SWISS pursuing in order to achieve its net-zero goal?

RH: We are collaborating with airports, fuel producers, research institutions and technology partners to develop and scale concrete solutions. These include projects to optimise flight procedures, introduce SAF and remove CO_2. We are proud of our partnerships with two pioneering Swiss companies, Synhelion and Climeworks, with whom we are working towards the development and implementation of key technologies to decarbonise.

Cooperation is also important in increasing the efficiency of daily flight operations. For example, SWISS has developed a platform based on Google Cloud technology together with Google to improve the planning and control of its daily flight operations. This has led to significant fuel savings.

We are continuously reviewing potential partnerships with a view to expanding our portfolio in a targeted manner. In 2025, for instance, we formed a partnership with neustark, a Swiss company that stores CO_2 permanently in recycled concrete.

> “The production of sustainable fuels must be scaled up rapidly to ensure the necessary quantities are available at competitive prices.”
>
> Gabriel Müller

Aviation is frequently criticised, particularly when compared with other modes of transport. What is your response to the suggestion that the most effective solution would be to “fly less”?

GM: Mobility is indispensable for many people and companies; it enables global exchange and trade. Today, a world without air travel is no longer conceivable. Our goal is therefore to make flying more sustainable. We are committed to transparency and offer our customers clear ways of reducing their flight-related CO_2 emissions.

RH: Decarbonisation poses considerable challenges for aviation. One thing is certain: CO_2 reduction measures require cooperation – with start-ups, scientists and customers.


CAUTION 9'6" HIGH

Sector focus: shipping

Decarbonising shipping

Shipping is a challenging sector to decarbonise, with its massive vessels, immense fuel needs, and global infrastructure. As the industry searches for sustainable alternatives to heavy fuel oil, a new generation of electricity-based fuels like e-ammonia and e-methanol is emerging. But each comes with its own technical and environmental trade-offs.

Achieving net-zero greenhouse gas emissions in the growing shipping sector is an essential part of a sustainable transportation industry, but the route is anything but clear. Large amounts of energy are required to power these giant ships over long distances without frequent opportunities to refuel. Most ships worldwide operate primarily on very low-sulphur fuel oil (VLSFO), which is derived from the refining of crude oil. As in aviation, direct electrification is not an option for shipping. The long voyage lengths would make recharging difficult, and the much lower energy density of batteries compared to marine fuels mean that the huge and heavy batteries would significantly reduce cargo capacity.

Meanwhile, the availability of low-carbon marine fuels is very limited, and there is a lack of global infrastructure to support alternative propulsion systems. Most low-carbon shipping fuels in use today are biofuels, such as hydrotreated vegetable oil (HVO) and fatty acid methyl esters (FAME), which can be produced from feedstocks such as used cooking oil, animal fats, and certain vegetable oils.

However, a growing mix of emerging 'green fuels' is expected to begin to enter the market this decade (see Figure 7). Among the front-runners of these future fuels are e-ammonia, e-methanol, e-diesel, and e-LNG (the 'e-' prefix stands for electricity-based). Hydrogen is one of the core building blocks of all of these fuels. That means that, much like in aviation, a net-zero shipping sector may depend on building up a reliable supply of hydrogen-based fuels. However, unlike in the aviation sector, which is highly sensitive to fuel weight and

Cargo ships, which can measure over 400 metres in length, move over 80 per cent of traded goods by volume. They can carry thousands of containers at once, as well as bulk commodities like coal, iron ore, or grain.

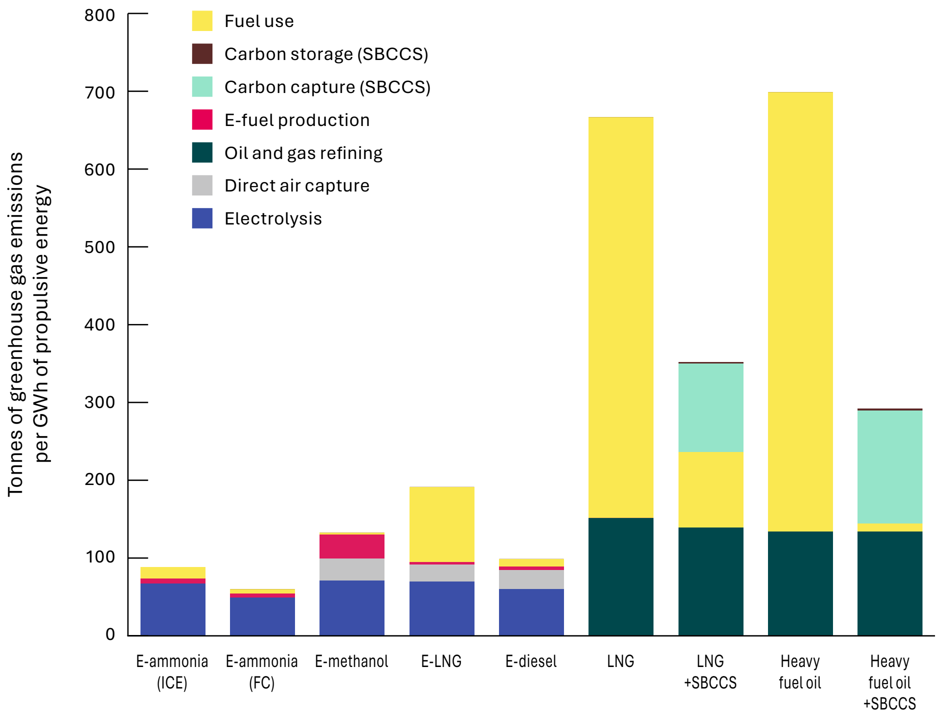


Figure 7: **Life-cycle greenhouse gas emissions (CO_2 equivalents) of various shipping fuel types**

This figure compares life-cycle greenhouse gas emissions of different shipping fuels. A gigawatt hour of marine propulsion energy reflects both the fuel's energy densities and the respective engine efficiency. ICE stands for internal combustion engine; FC for fuel cell; LNG for liquified natural gas; and SBCCS for ship-based carbon capture and storage. The SBCCS sub-process includes the combustion emissions resulting from additional fuel combustion for the operation of the capture unit. Results in this plot represent e-fuel production using green hydrogen in Spain.

(Source: PSI Laboratory for Energy Systems Analysis)

volume, ships can carry heavier fuels and engines can be adapted more easily.

Our research shows that synthetic fuels made using renewable electricity and captured carbon or nitrogen could meet or exceed the 80 per cent reduction in greenhouse gas emissions stipulated in the FuelEU maritime regulation. However, there are still open questions around the feasibility of scaling up these technologies and what they would cost. Furthermore, there are specific concerns regarding each fuel type.

E-ammonia, for example, is toxic and corrosive and is not compatible with current engines. Likewise, the bunkering infrastructure needed to supply such fuel to ships is still being developed. The major environmental concern with ammonia as a marine fuel is the potential for nitrous oxide (N_2O) emissions during combustion in internal combustion engines, as N_2O is an extremely potent greenhouse gas. Beyond its combustion, the production of ammonia – particularly the heat source used in its synthesis – can cause emissions of nitrogen oxides (NO_x). Both N_2O and NO_x are harmful to human health and ecosystems, requiring strict emissions controls. To achieve the maximum reduction in GHG emissions and other environmental impacts, e-ammonia could be used in solid oxide fuel cells (SOFCs), avoiding combustion on ships altogether.

E-diesel and e-methanol stand out for their compatibility with current engines. However, they are both expected to be 35 to 90 per cent more expensive options than e-ammonia in the long term. Additionally, the combustion of e-methanol can produce formaldehyde and other toxic byproducts, especially under incomplete combustion conditions. Formaldehyde is a harmful pollutant associated with respiratory issues and environmental concerns, making emissions control important when using methanol as a fuel.

Another candidate, e-Liquid Natural Gas, or e-LNG, has a more complicated profile. Although it benefits from an established global infrastructure and engines that naturally meet strict NO_x emission standards, unburned methane leaking from ship engines (known as 'methane slip') threatens its climate credentials. Methane slip could potentially push emissions well above the 80 per cent reduction target, making e-LNG less favourable than its competitors.

Ultimately, our research shows that decarbonising shipping will require a hybrid strategy. Low-carbon fuels, including both biofuels and e-fuels, should be adopted, and carbon capture systems should be installed on large vessels. Rigorous oversight of emissions across the fuel lifecycle, and monitoring and managing hydrogen leaks, methane slip, and NO_x emissions from ammonia combustion will become regulatory priorities. Wind-assist technologies and efficiency improvements on small ships should also play a role. Making progress will require targeted investment, coordinated international standards, and a willingness across the sector to act before the fuels of the future are fully ready for widespread use. It's a classic chicken-and-egg challenge and overcoming it will require early commitments from fuel producers and shipping and harbour operators.

"Ships can already run on these new fuels today."

A conversation with Accelleron CEO Daniel Bischofberger

On the one hand, we have global economic growth and an increase in freight transport by ships, which are traditionally powered by dirty heavy fuel oil. On the other hand, we have net-zero CO_2 emission targets. How do you think these two things can be reconciled?

Daniel Bischofberger: The shipping industry transports around 80 to 90 per cent of all goods. By 2050, the volume is likely to double, with fuel consumption set to increase by 70 per cent. So there is still potential for efficiency gains here.

In the past, the shipping industry was something of a dumping ground for the oil industry. It scraped together the dregs from oil barrels and burned them on ships. However, we are now seeing a radical change thanks to the International Maritime Organisation (IMO). The IMO is a UN organisation responsible for the entire shipping industry. It has committed to achieving climate neutrality by 2050. The first priority is to move towards lower-carbon fuels, and the second is to improve efficiency. As the only globally regulated industry, shipping has a unique opportunity to take a leading role in decarbonisation.

Which solutions for reducing greenhouse gas emissions do you believe hold the greatest potential?

DB: Shipping is what is known as a "hard-to-abate industry", meaning that it cannot be decarbonised through electrification alone. For instance, a large container ship travelling from China to Europe requires 40 gigawatt hours of energy. That is roughly equivalent to one and a half times the daily output of Leibstadt, Switzerland's largest nuclear power plant. The battery required would weigh around 200,000 tonnes. A ship of this size does not have the cargo capacity for this.

The main long-term solutions are clearly synthetic fuels. In shipping, the trend is towards ammonia and methanol. In general, synthetic fuels are expensive and require a lot of equipment for production. Ammonia and methanol also have a low energy density. Compared to diesel, twice as much fuel is needed, which means it takes up more space on board.

Another challenge is that ships today are built to last 30 years. This means that, halfway through a ship's life cycle, it will probably need to be modernised to accommodate new fuels. This is ideal for us, because it means we can modernise or overhaul our products two or three times.

> "What we need to do now is link the sectors with each other because we all need the same thing: green hydrogen."

What technological challenges are involved in adapting ships to new, low-carbon fuels?

DB: It is important for everyone to understand that ships can already run on these new fuels. They have been using biodiesel and similar fuels for some time now. The first container ships to run on methanol entered service in 2023, and the first ammonia-powered ones are due to be launched this year.

The ships are ready. The technology is there. All that is missing is new standards. Since ammonia is toxic, new safety and handling standards must now be defined and the ships' crews trained. The first pilot projects are already underway.

What changes are needed in ports?

DB: This is a major challenge. It is not enough to know that there is a port and that it has fuel; you also need to check whether it is ammonia, methanol, natural gas or heavy fuel oil.

Then there is the "chicken and egg" problem: the ships are ready, but the fuel isn't available. There are many so-called "hard-to-abate industries" and they are all looking for green hydrogen. Who will ultimately produce it? The shipping industry is big, but not big enough to set up such a hydrogen ecosystem on its own. So what we need to do now is link the sectors with each other because we all need the same thing: green hydrogen. If we pool our demand, we will require huge quantities. Aviation, shipping, steel production, the chemical and cement industries, the fertiliser industry and even power stations will require around 600 million tonnes of hydrogen per year.

So synergies between these industries should be exploited?

DB: Yes. Competition would only mean that nothing happens because everyone wants the cheapest fuel. Someone has to provide the initial funding because these synthetic fuels are probably five to ten times more expensive than fossil fuels at the moment. However, it is estimated that they will only cost two or three times as much once large quantities are produced and the technologies have been industrialised. So who wants to invest in a production plant now when cheaper solutions will be available in five years' time? When it comes to fuels, the challenge is not technological, but commercial.

> "When it comes to fuels, the challenge is not technological, but commercial."

What is the current situation in the shipping industry regarding the obligation to purchase these new fuels?

DB: Regulations are a must here. Either everyone is obliged to invest, or we start with those players in the shipping industry who can most easily afford it. The freight costs for goods that are actually of high value are negligible. If a pair of trainers costs an extra 5 or 10 cents, people will still buy them.

Does that mean the costs of synthetic fuels should first be passed on to globally transported consumer goods that are the least price-sensitive?

DB: Yes. The shipping industry doesn't care if transport costs increase by 10 or 20 per cent. Just because ships become more expensive, transport will not be carried out by aircraft. Rail is not an alternative either. Ships are the only efficient means of transporting goods over long distances between continents.

Daniel Bischofberger

has been the CEO of Accelleron, a company specialising in turbocharger technology and energy system solutions, since 2022. Focusing on decarbonisation, he has expanded the portfolio to include injection systems for the energy transition as well as digital and AI-based solutions, in addition to the company's 100-year core competence in turbochargers. He previously held various management positions in industry.

Accelleron operates internationally. What differences do you see between the European, Asian and other regional markets with regard to the energy transition in the transport sector?

DB: There are differences. The EU is leading the way. For example, the EU requires every ship entering an EU port to purchase certificates for 50 per cent of its CO_2 emissions from the last port of call to Europe. We are also seeing China and Australia investing in hydrogen production. Western Australia already has an ammonia hub, for example. Canada is also investing in ammonia production based on green hydrogen. And we are seeing ports such as Singapore and Rotterdam investing in infrastructure.

What about the regulations of individual ports regarding the use of clean fuels? Do air quality regulations play a role?

DB: Yes, firstly, ships are no longer permitted to use heavy fuel oil in certain areas. Many ships now have so-called dual-fuel engines that run on a combination of diesel and methanol or heavy fuel oil and natural gas. There are all kinds of combinations to meet the various requirements.

Secondly, ships require electricity in ports, but the necessary infrastructure for supplying it from land has yet to be built. It's all feasible, and things are moving, but more legal certainty is needed to recover the investments. The shipping industry is clearly on the move. Decarbonisation is the project of the century, but we only have 25 years left to achieve it. So, we should speed things up. At the current pace, it will be more like a 200-year project.

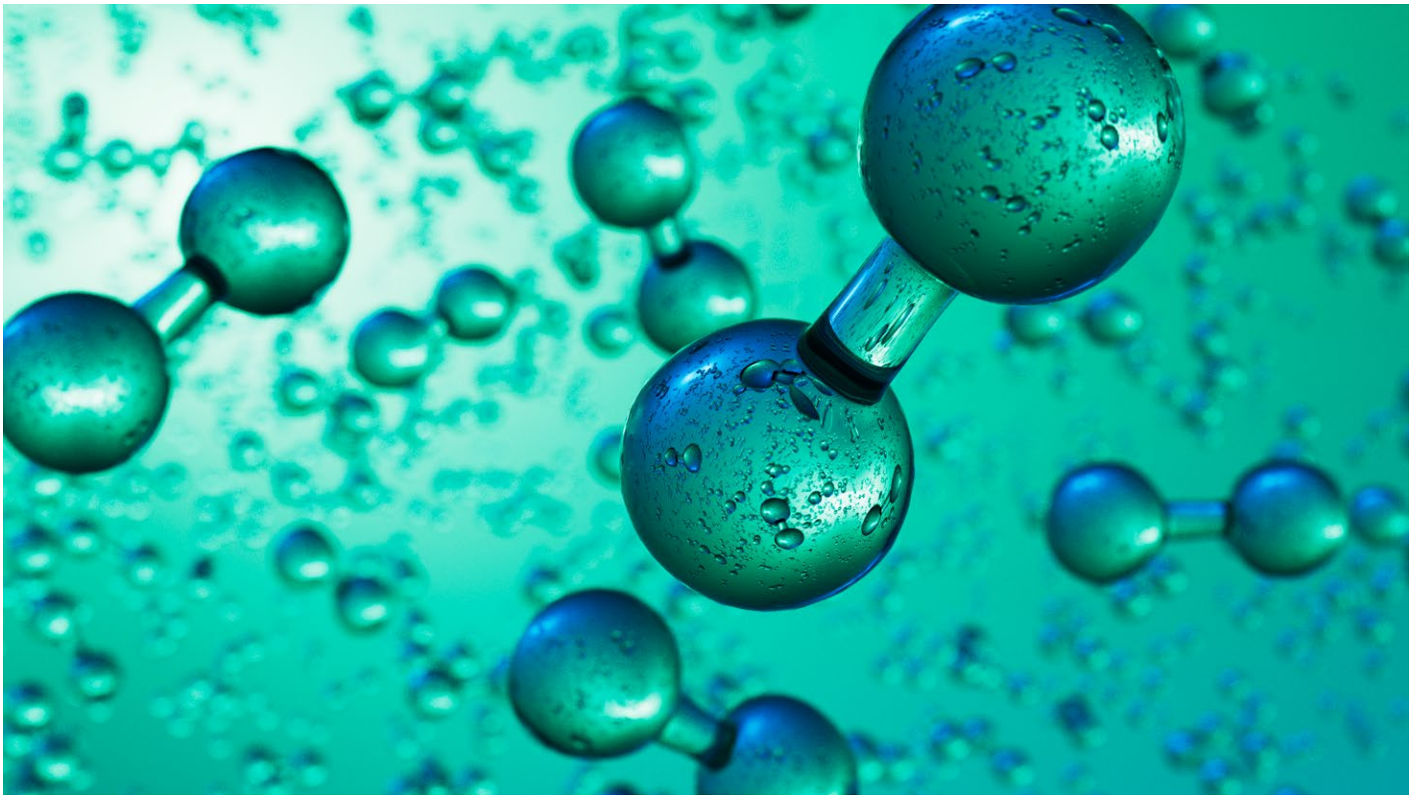
What political or regulatory framework conditions do you think are crucial in order to accelerate the market ramp-up of sustainable propulsion systems?

DB: Currently, biofuels and natural gas are still preferable to heavy fuel oil. However, we must ensure that today's transitional solutions do not become permanent solutions.

The other thing is: One must not destroy the entire shipping industry by imposing heavy penalties. But we also have to be careful that people don't just pay the penalty as the easiest solution and nothing ends up happening.

Decarbonisation does not come for free. Low-carbon fuels are more expensive. But I believe we cannot compare apples and oranges. Fossil fuels are the cheapest option, but their price does not reflect the true costs of these fuels. In the future, we will have to pay huge sums to compensate for the damage caused by the increase in CO_2 in the atmosphere. Personally, I find this deeply unfair to future generations, including my own children. We are leaving the next generation with a huge burden, essentially saying, "We had cheap fuels, and now you have to pay for the consequences." I believe that ultimately the question is: Is society prepared to invest in the future and not just in its current consumption?

> "Decarbonisation is the project of the century, but we only have 25 years left to achieve it."



Outlook

The future of hydrogen depends as much on governance as technology.

Hydrogen and e-fuels might not be the Swiss Army Knife of the energy transition, but they are needed in several sectors, where they face high costs, resource constraints, and infrastructure hurdles. In this issue of the PSI Energy Compass, we have made the following arguments:

- **Prioritization is essential.** Green hydrogen consumes scarce water, land and critical minerals, while blue hydrogen relies on CO_2 storage that Switzerland lacks. The highest value lies in cement, steel, and chemicals, long-haul transport and seasonal balancing — not in heating or cars.
- **Global supply implies trade-offs.** Most low-cost production potential lies in Australia, Africa and the Americas, often in water-stressed regions and reliant on fragile critical-material supply chains. Hydrogen is as much about geopolitics and environmental limits as technology. Key issues include impacts from mining and processing materials, and land and certification challenges.
- **Hydrogen has key roles in Switzerland,** but they must be understood in a system context. Hydrogen supports industrial decarbonisation and seasonal storage, shifting summer solar into winter supply. Domestic production will remain limited, leaving Switzerland dependent on imports. Cross-border pipelines, certification, standards, and long-term contracts are unavoidable.
- **Markets also matter.** Without hubs or grids, seasonal storage works only with wider winter-summer price spreads and rules favouring low-carbon supply. Under market power or risk aversion, assets may sit idle. European alignment on markets, standards and infrastructure is more resilient than isolated approaches.
- **Aviation and shipping show the limits to substitution.** Synthetic fuels are indispensable but insufficient: aviation still requires demand restraint and new aircraft; shipping needs hybrid strategies combining e-fuels, efficiency, and carbon capture.

Further research into how hydrogen fits in the puzzle of the energy transition is crucial. Ongoing projects at our lab explore the social acceptance of hydrogen technologies, the global prioritization and distribution of hydrogen applications, and the environmental impact and feasibility of planned global hydrogen projects. The question is not whether hydrogen has a role to play, but how to align policies, infrastructure, and international cooperation so that hydrogen and its derivatives are deployed where they deliver the greatest value for the climate and society.

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Imprint

PSI Energy Compass — Navigating the energy transition

Issue # 1/2026
ISSN 3042-7215

Publisher
Paul Scherrer Institute PSI
Forschungsstrasse 111
5232 Villigen PSI

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Cover picture/page 27: Monika Blétry,
page 12: Scanderbeg Sauer Photography,
page 19: Ramon Hess, Gabriel Müller,
page 25: Accelleron
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Research supported by: the Swiss Federal Office of Energy; InnoSuisse; the Center for Sustainable Future Mobility; the Swiss National Academy of Science; the European Commission; the European Health and Digital Executive Agency; the Swiss State Secretariat for Education, Research and Innovation; UK Research and Innovation; Gaznat; PSI's Energy System Integration platform; the German Federal Ministry of Education and Research; the Swiss Federal Office of Civil Aviation; and the ETH Board.

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