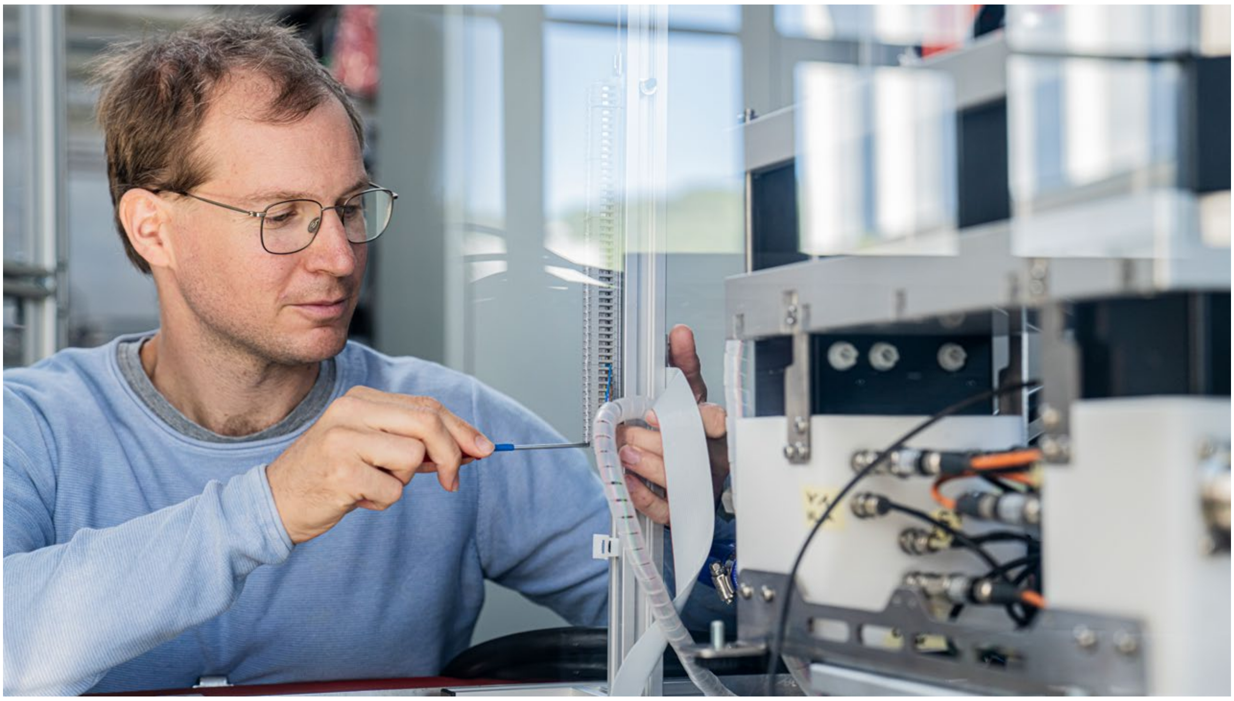

Energy and Environment

Research at the Paul Scherrer Institute

The Paul Scherrer Institute's experimental platform ESI – short for Energy System Integration – tests renewable energy alternatives in all their complex interplay.

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Cover image
Fuel cell research at PSI

Energy – the fuel of life

How to sustainably generate and store energy is a crucial question for the future of every society. Research at PSI helps to find answers to these questions of tomorrow today.

Every living being needs energy in the form of food. In addition to food, humans consume far greater amounts of energy: in private households, in the economy, and for mobility. If the global primary energy demand were to be met exclusively with crude oil, more than 135 trillion tonnes would be required. Switzerland's share of this would be more than 26 million tonnes, or just under 0.2 percent.

Energy comes in different forms, for example:

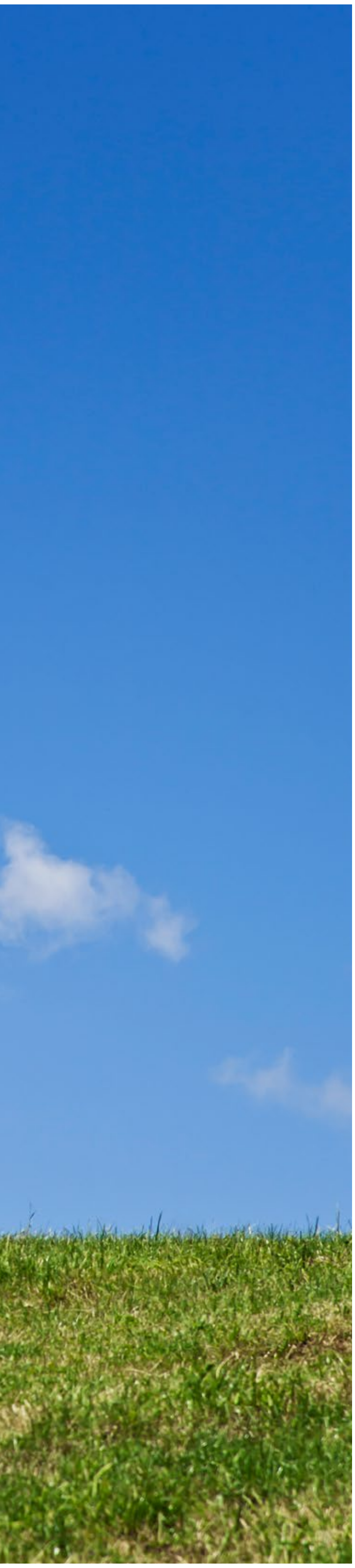
- as electrical energy in the form of electricity
- as thermal energy in the form of heat
- as kinetic energy in the form of movement.

The different forms of energy can be converted into one another. PSI researchers are working on developing the most efficient methods possible for generating, storing, and converting energy.
They focus on the following areas:

- Research into sustainable energy sources such as biomass
- Efficient conversion between energy sources for storage and recovery of energy for heat, electricity, and mobility
- Safe use of nuclear energy
- Safe disposal of radioactive waste
- Holistic assessment of energy systems
- Effects of energy use on the climate and atmosphere.

The aim of the PSI researchers is to achieve the highest possible efficiency in energy generation, energy use, energy storage, and their environmental impact while at the same time conserving resources. To do this, it is necessary to know the materials used in precise detail as well as their behaviour under various operating conditions.
The research infrastructure at PSI offers ideal conditions for this. Large research facilities such as the Swiss Light Source SLS, the X-ray free-electron laser SwissFEL, the Swiss spallation neutron source SINQ, the Swiss research infrastructure for particle physics CHRISP, and the Swiss muon source SμS allow deep insights into the smallest structures of materials. The Energy System Integration Platform, ESI for short, the Hotlab, and new high-performance computing systems also help PSI researchers achieve crucial advances towards securing a sustainable energy supply.
In addition to physical and chemical research on substances and processes, the modelling of new materials and the simulation of energy systems are of great importance.

Sustainably generating, converting, and storing energy – a research goal for today and tomorrow.



“We work both in the context of Switzerland’s Energy Strategy 2050”

In person

Andreas Pautz (born in 1969) has headed the Nuclear Energy and Safety Research Division at PSI since 2016 and he is Professor of Nuclear Technology at EPF Lausanne. He studied physics at the University of Hanover and the University of Manchester and received his doctorate in nuclear engineering from the Technical University of Munich.

Thomas Justus Schmidt (born in 1970) has been head of the Energy and Environment Research Division at PSI since January 2018. He studied chemistry at the University of Ulm, Germany, where he received his doctorate in the field of electrocatalysis of fuel cell reactions. He is also Professor of Electrochemistry at ETH Zurich.

Professor Schmidt, you head up the PSI Research Division Energy and Environment, and Professor Pautz, you oversee the Nuclear Energy and Safety Division. What are the differences between your two fields of research, and what do they have in common?

Schmidt: The Energy and Environment Division researches the production, conversion and storage of energy from renewable sources, as well as addressing the consequences our energy use has for the environment and atmosphere. Our research does not cover nuclear energy, however.

Pautz: That is our expertise. But we do have some common ground: we always work within the context of Switzerland’s Energy Strategy 2050. During this transition phase, we both have important tasks to perform: the Energy and Environment Division needs to push forward with renewables, while we have to solve the problem of how to ensure nuclear power stations continue to operate safely up to 2040 – possibly even well beyond – and lastly, how to safely dispose of radioactive waste. We play our part in maintaining high safety standards throughout and minimising the nuclear legacies for future generations to deal with.

So, you don’t see each other as rivals, championing different energy sources?

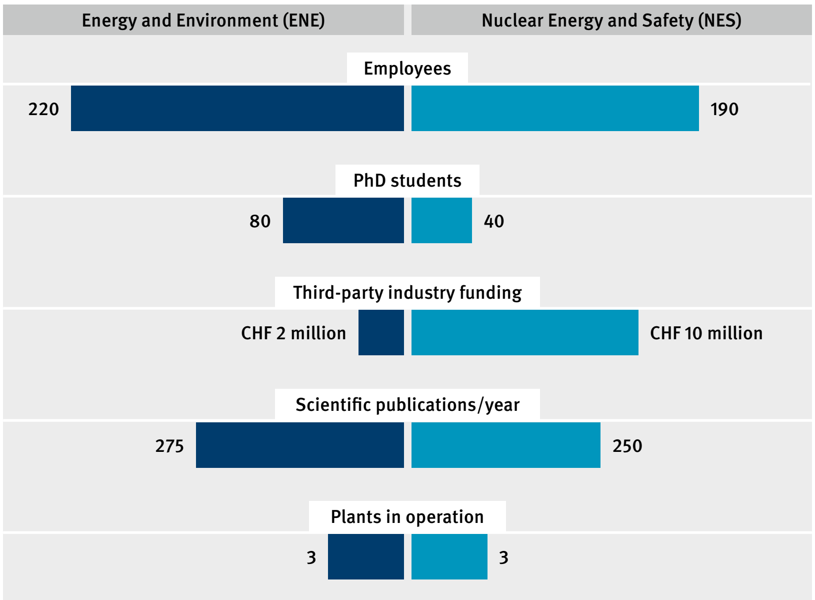
Schmidt: Not at all. We work closely together and in doing so have to keep an eye on time scales when it’s time to replace one technology with a different one.

Pautz: Exactly, our aim is to ensure optimal interplay with a view to avoiding potential environmental impacts as much as possible and minimising costs. We look at this purely from a scientific angle; we are not engaging in political discussions. The decision not to limit the lifetime of existing nuclear power stations effectively makes them an integral part of the country’s energy strategy. By the way, there is no other scientific institute in Switzerland where so much research is conducted into energy as at PSI, in other words where so many researchers are concentrated in such a small space.

Do you also work on joint projects?

Pautz: Certainly. For example, we work together on the SURE project,

Research divisions in comparison



whose aim is to determine how we can build a secure and resilient energy supply for the country over the coming years. This involves much more than just minimising CO_2 emissions, but other aspects such as reliability of supply, network stability, and defence against external and internal threats.

Schmidt: We carry out this research in a joint PSI lab, the Laboratory for Energy Systems Analysis. This specialises in holistic analyses of the entire energy system. Transport, industry, private households, electricity generation – everything comes together here.

Is more scientific objectivity necessary in the discussions about the energy transition and the various ways of achieving it?

Pautz: More objectivity in the energy debate would be extremely helpful. We simply need to carefully weigh up the facts currently available – such as those concerning climate change or security of supply – to reach a level-headed assessment.

Schmidt: This also underlines the importance of the holistic approach we adopt at PSI in order to understand energy systems as a whole. Only a few other places in the world follow this approach.

Is it difficult for you to attract young scientists in your area of research?

Schmidt: No. Our international outlook helps: people from around 45 different countries work in the Energy and Environment Division.

Pautz: The same applies for my division, even though the number of Swiss employees is shrinking. But we have an excellent international reputation and thus enjoy strong demand. Together with EPFL and ETH Zurich, we offer a Master's course in Nuclear Engineering, for example. Every year on average 15 students start this course, and more than 20 have enrolled this year. This shows nuclear energy still has a role to play internationally.

Do you often hear the criticism: "Switzerland wants to discontinue nuclear energy, so why is PSI still researching it?"

Pautz: Hardly ever. No one disputes that specialists are needed for the next 25 years at least, partly to solve the problem of radioactive waste disposal. The need for Switzerland to maintain its nuclear expertise is also widely recognised in political circles. When it comes to nuclear technology, Switzerland should also be able to defend its position as a global player and draw on a deep pool of know-how.

What has changed in your field of research over the past years and what do you expect for the future?

Schmidt: Amongst other activities, we have reduced our research into combustion technology. Although this used to be an important topic, it now has a limited future. On the other hand, we have taken on several new topics, such as hydrogen production. Another issue that has become more important is the impact of our energy use on the climate. For example, what effects do aerosols have on the atmosphere and the human health?

Pautz: The long-term operation of nuclear power stations tops our agenda, as well as the final disposal of nuclear waste and the dismantling of decommissioned plants. Since it became clear that Switzerland plans to phase out nuclear energy, we have suspended activities that are related to constructing new power stations, such as the development of new fuels. We are only marginally involved in investigating new safety systems. In future, I'd really like to see industry and research collaborations becoming much more international. We want to continue to capitalise on PSI's strong international reputation in nuclear energy research.

One platform – many energy systems

Energy systems around the world are under construction. More and more, this involves the so-called “new” renewable energy sources: sun, wind, and biomass. In Switzerland, too, their share of the energy supply is increasing and should continue to do so. In order to increase efficiency, research and development of new materials and processes will be necessary – both in the production of energy from renewable sources and in its distribution and use.

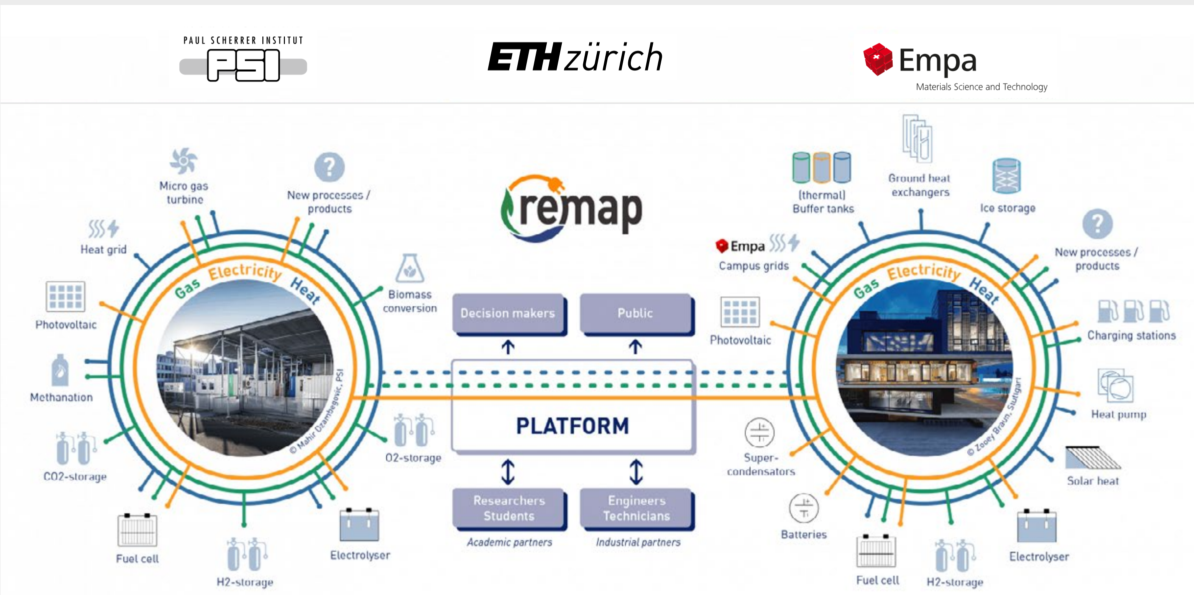
With its Energy System Integration Platform, PSI offers a unique combination of different energy systems in one place and thus excellent opportunities to investigate processes for efficiently generating, storing, and converting energy. PSI is working in close cooperation with partners from research and industry to investigate and further develop different variants of energy storage as well as the energy-efficient use of biomass, and to assess their technical and economic feasibility (see also “Storing energy in gas” on page 12f.). With the help of the ESI Platform, a process was developed that enables significantly more methane to be generated from biomass, for example from household biowaste. Methane is the main component of conventional natural gas and therefore a proven energy source. Methane is usually produced from biowaste through microbial processes known as fermentation. In this process, however, large amounts of carbon dioxide are also generated. The mixture of the two gases – that is, the raw biogas – consists of 60 percent

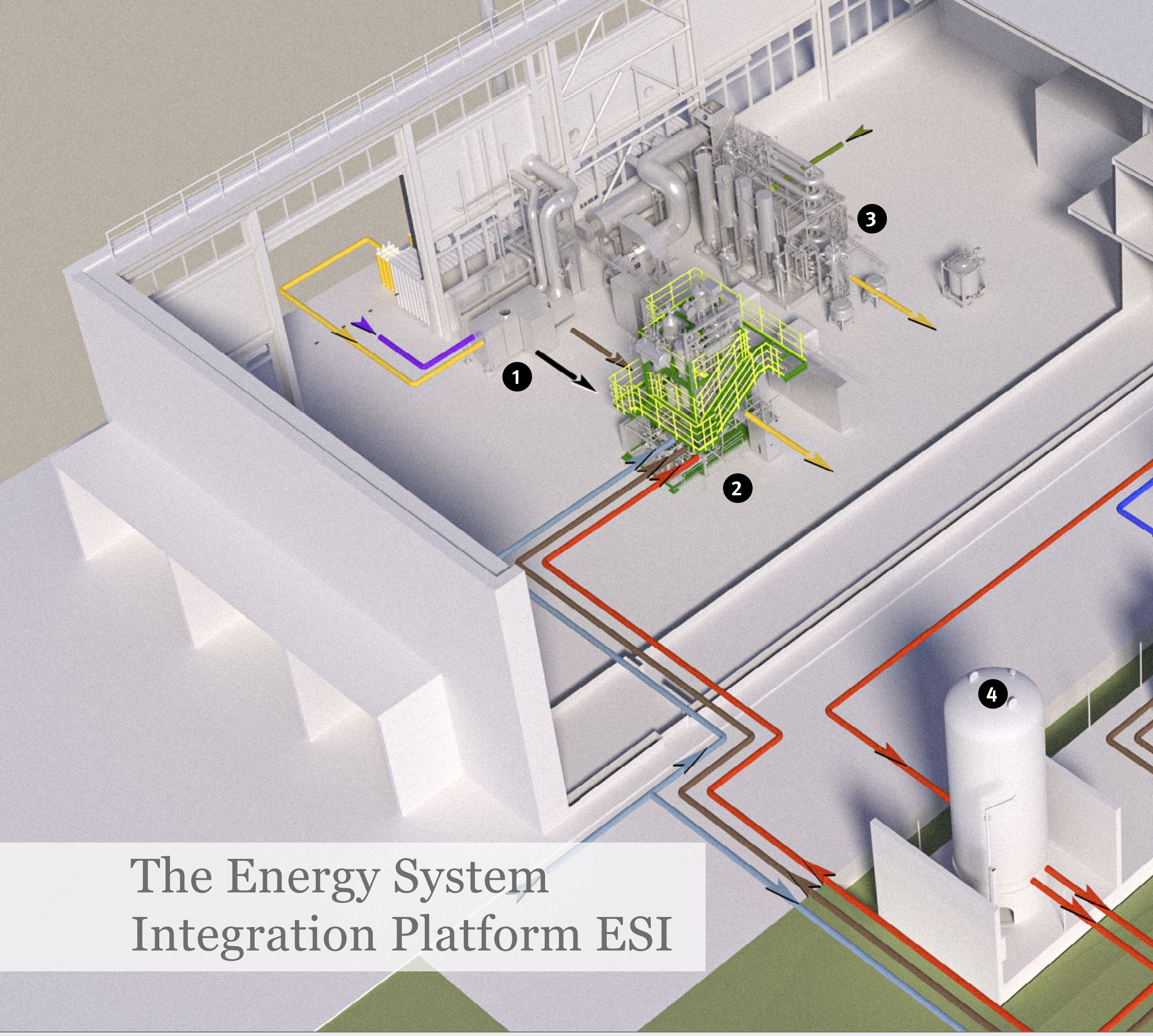
The ESI Platform enables research on how excess renewable energy from wind and sun can be stored and made available again when required. The individual elements of the ESI Platform are housed in containers so that they can be used flexibly on-site.

methane and 40 percent carbon dioxide. The latter is usually separated from the methane in a costly process and not exploited any further.
PSI researchers have succeeded in converting this carbon dioxide into methane by adding hydrogen directly to the raw biogas. For this they need, among other things, catalysts – substances that make the conversion of one chemical compound into another possible in the first place – so that hydrogen and carbon dioxide combine with each other to form methane (see: “The facilitators” on page 16f.). The carbon dioxide contained in the raw biogas is almost completely converted into methane. The resulting end product is of such high quality and so closely resembles commercial natural gas that it can be fed directly into the gas network. In a joint project with the Zurich-based energy provider Energie 360°, the PSI researchers tested the technology they had developed under real conditions. With the mobile Cosyma system, which converts hydrogen and carbon dioxide to methane, they were able to show that the new process is very well suited for use on an industrial scale. Even the experts at the Federal Office of Energy were impressed by the new process for efficient methane production from biomass. They awarded PSI and Energie 360° for this important contribution to a sustainable energy supply with the Swiss Energy Prize Watt d’Or; they were jointly named winners in the Renewable Energy category.

Synergy in service of energy research

In the ReMaP project, led by ETH Zurich, the ESI Platform is virtually interconnected with the demonstrators from the Federal Materials Testing and Research Institute (Empa). Together with the Empa platforms NEST (future buildings), move (future mobility) and ehub (energy networks at neighborhood level), the ESI Platform offers a unique experimental setup for research and industry to provide the knowledge and technical fundamentals needed to develop the energy systems of the future.





The Energy System Integration Platform ESI

❶ Mini gas turbine

The miniature gas turbine converts methane into electricity and heat. This makes it possible to generate electricity when the wind isn't blowing and the sun isn't shining. Using the mini gas turbine, the researchers are investigating how much hydrogen they can add to the methane while keeping the conversion safe and efficient. That's because hydrogen is easy to obtain, burns quickly, and could help to react to rapid changes in load.

❷ GanyMeth

In this reactor, methane is produced from hydrogen and carbon dioxide. The product is also called synthetic natural gas (SNG). The reaction takes place in a fluidised bed reactor with the help of catalysts (see “The Facilitators” on page 16f.). In the reactor, solid particles carrying a catalyst are constantly swirled around by an upward flow of gas, creating a good mixing where the reaction can take place.

❸ HydroPilot

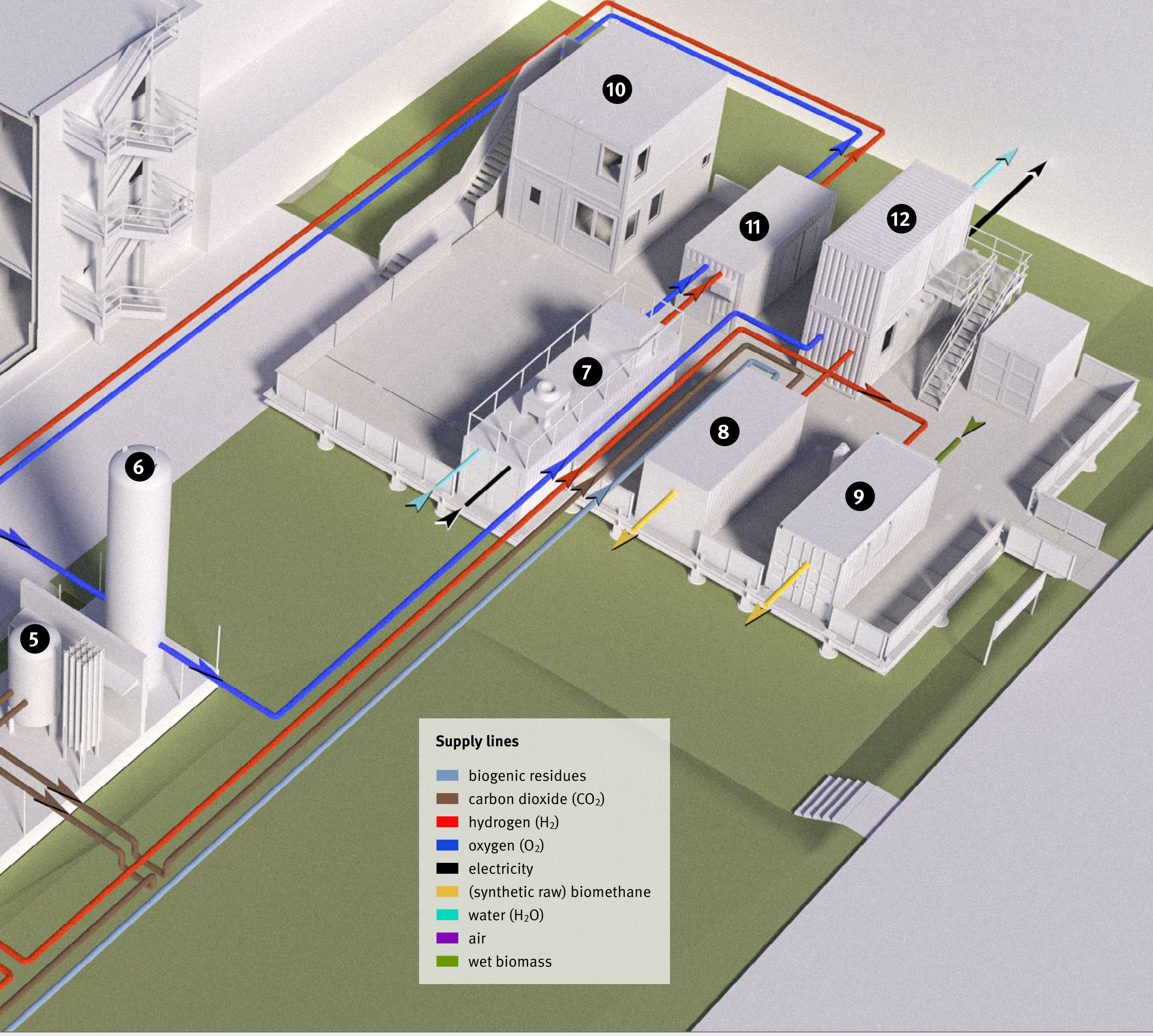
In a pilot plant, PSI is conducting research on the hydrothermal gasification of wet biomass with supercritical water. Waste with a high water content, such as sewage sludge, coffee grounds, and liquid manure, is exposed to high pressure and temperature. This creates a high-quality gas from the waste, similar to biogas. The project investigates processes similar to those being studied at Konti-C, but on a larger scale in order to simulate conditions closer to industrial practice.

❹ ❺ ❻ Gas tanks

hydrogen tank (4)
carbon dioxide tank (5)
oxygen tank (6)

❼ Electrolyser

Hydrogen and oxygen are produced from water with the help of electricity.



8 Cosyma

Raw biogas from a biogas plant contains only about 60 percent methane; the rest is carbon dioxide. The test facility Cosyma (Container-based System for Methanation) processes raw biogas by adding hydrogen, which reacts with the carbon dioxide. This increases the methane yield. This process is called direct methanation.

9 Konti-C

This test facility examines how energy can be obtained from wet biomass – liquid manure, sewage sludge, or algae. At high temperatures and pressures, the biomass is converted into synthetic biogas, i.e., methane. The advantage is that the biomass does not have to be dried beforehand, because that requires a lot of energy and often makes processing economically unprofitable.

10 Control room and visitors platform

11 Gas purification/drying

Here, hydrogen and oxygen from the electrolyser are dried and purified so that they can then be pumped into storage tanks.

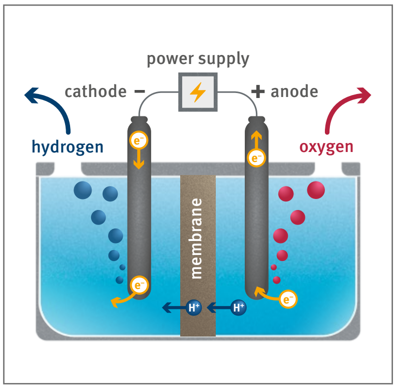
12 Fuel cell

The fuel cell generates electricity from hydrogen and oxygen. This creates water. Since a fuel cell system alone generates too little electricity, four systems, each consisting of 236 individual cells, are interconnected in this container. This is how an industrial environment is simulated.

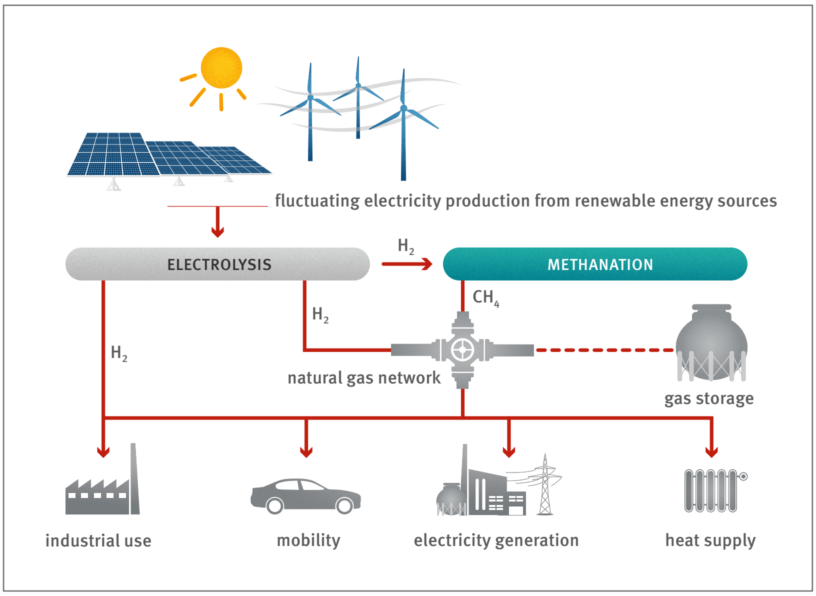
Storing energy in gas

Switzerland has set itself the goal of drastically reducing its direct emissions of greenhouse gases. According to the Energy Strategy 2050, Switzerland aims to reduce greenhouse gas emissions by 50 percent by 2030 compared to 1990 levels, and up to 85 percent by 2050. After 2050, the energy supply in Switzerland should be completely climate-neutral. In order to achieve this goal, the new renewable energy sources – biomass, wind, and solar power – are crucially important, as is the question of how the energy they produce can be stored.

One problem with wind and solar power is that their sources are not always or uniformly available. When there is enough wind, wind turbines produce plenty of electricity; when it's calm, this source dries up. Similarly, the irradiation of sunlight changes not only in a day-night rhythm, but also depending on the weather and the season.
A reliable energy supply therefore needs effective energy storage devices: They conserve the energy gained during high-production phases and release it when there is not enough wind or sunshine. One method that is used here is called power-to-gas. Electric power, for example from wind or solar energy, is used to generate gases such as hydrogen or methane. These gases serve as energy stores and feed their energy content back into the energy supply when required.



In proton exchange membrane electrolysis (PEMEL), electrical current causes water to break down into its components hydrogen and oxygen at the anode. First, oxygen and positively charged hydrogen ions (protons) are created. These migrate through the membrane, which is only permeable to them, and combine with electrons at the cathode to form gaseous hydrogen.



Vehicles with a fuel cell can be operated with hydrogen (see page 15). The gas can also be fed into the natural gas network. Industry, in turn, can use it to maintain its production processes: Hydrogen is an important raw material, for example in the manufacture of nitrogen fertilisers in the chemical industry, or in the "cracking" of hydrocarbons in oil refineries.

Producing hydrogen

Hydrogen is produced through the electrolysis of water, among other means. In principle, electricity is fed into water, which then breaks down into its components hydrogen and oxygen. There are different processes for electrolysis. PSI uses proton exchange membrane electrolysis (PEMEL, see page 12).

Methanation

Another option for temporarily storing energy in gas is called methanation. The gas methane, the main component of conventional natural gas, is generated from hydrogen and carbon dioxide. One special case of methanation is direct methanation. The hydrogen is not combined with pure carbon dioxide, but with biogas, which already consists largely of methane but still contains a comparatively high proportion of carbon dioxide. Additional methane can also be generated directly from carbon dioxide in this gas mixture with the addition of hydrogen, thus significantly increasing the methane content in the biogas, up to natural gas quality. PSI researchers have developed a new process for this and showed that up to 60 percent more bio-methane can be obtained from biogas from biowaste (see "One platform – many energy systems" on page 8f). The higher methane yield thus conserves resources and preserves the environment.

Both in the production of hydrogen and in methanation, auxiliary substances are used that make the reactions possible in the first place. These are catalysts, which are also the subject of intense research at PSI (see page 16f.).

White paper on Power-to-X

Scientists at PSI, together with colleagues from six Swiss universities and research institutions, have compiled extensive information on various aspects of Power-to-X technologies. This is the name given to technologies that allow electric power to be stored in other forms of energy, for example chemical energy carriers, in times when there is a surplus of electricity. In a white paper, the researchers have summarised the potential that Power-to-X processes have to help realise Energy Strategy 2050, the challenges the technology is facing, and the key factors favouring its widespread use. The white paper was commissioned by the Swiss Federal Energy Research Commission (CORE), drawn up by the partners of the Swiss Competence Centre for Energy Research (SCCER) Heat and Electricity Storage, Biosweet, Crest, Furies, and Mobility, and financed by the Swiss Agency for Innovation Promotion Innosuisse and the Federal Office of Energy (SFOE).

One conclusion: The contributions that Power-to-X can make in individual energy sectors such as transportation and heating or through reconversion are very different. Thus the re-conversion of electricity from energy sources such as hydrogen or methane generated using Power-to-X processes is currently still very expensive. However, the costs for such processes – also known as power-to-power – could fall by up to two-thirds by 2030 due to technological advances and increasing experience in dealing with these technologies. Fuels that are produced using electricity from renewable energy sources in Power-to-X processes can replace fossil fuels such as heating oil, natural gas, petrol, and diesel and thus help to reduce carbon dioxide emissions. However, this will only be economical if appropriate environmental incentive mechanisms come into play.

Download "Power-to-X: Prospects for Switzerland"
at https://bit.ly/3ASe4UC

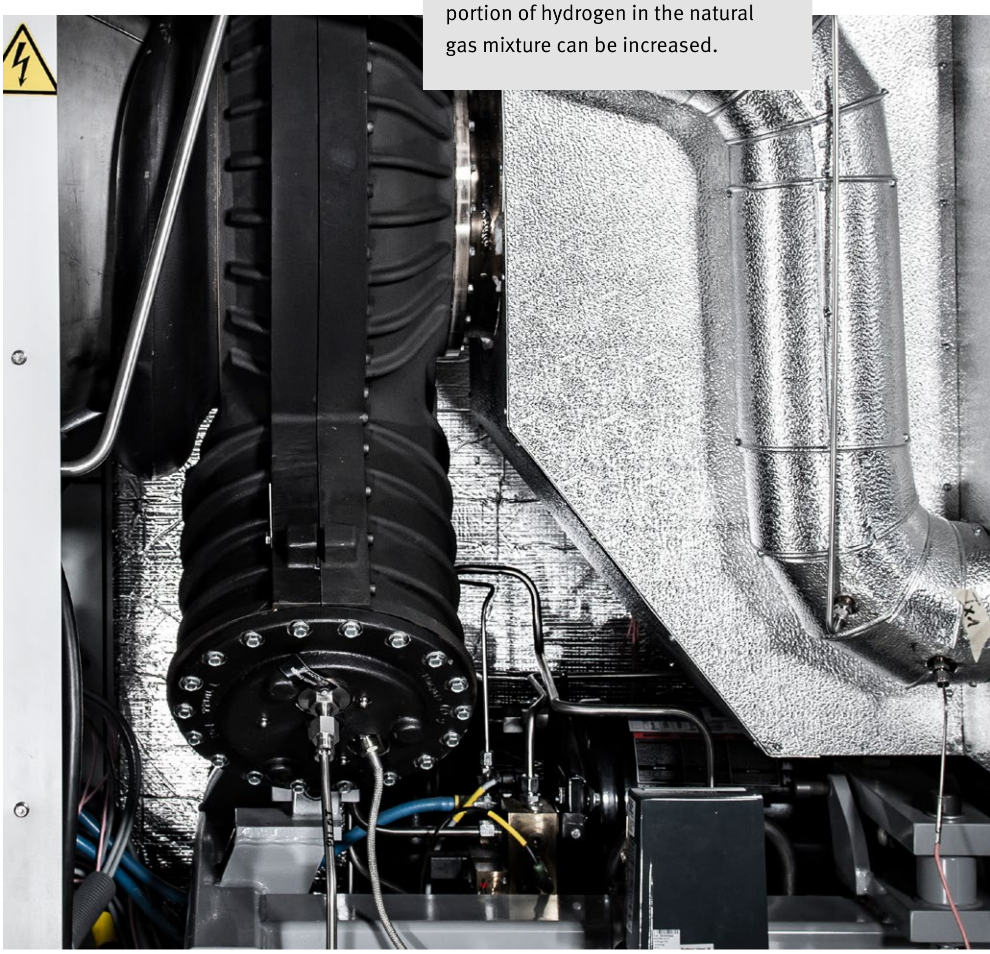
High-value hydrogen

Hydrogen is the most abundant element in the universe. On the earth it plays an important role in life and in the natural energy cycle. In the energy system of the future, it will be created using power-to-gas processes, drive fuel cells, or be fed into the existing natural gas network.

Hydrogen is already being fed into the natural gas network, albeit in a very small proportion. In a further step, hydrogen can also be converted into methane – the main component of natural gas.

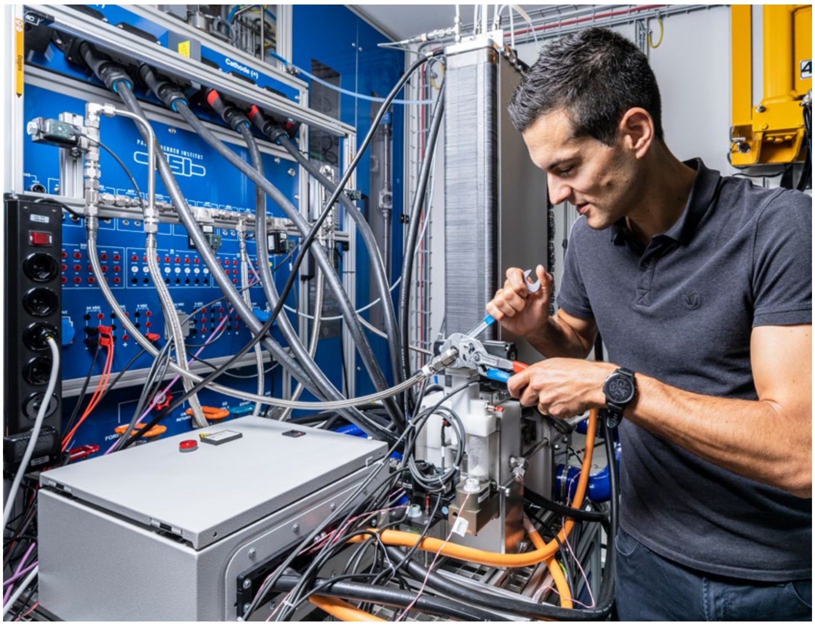
PSI researchers are now using a miniature gas turbine to test how the proportion of hydrogen in the natural gas mixture can be increased. In its housing, the system is no bigger than a wardrobe, and it delivers an electrical output of 100 kilowatts. This could cover the power requirements of a small neighbourhood with around five to seven single-family houses – in line with the trend towards decentralising the power supply. The mini gas turbine is a commercial product and a typical system for cogeneration of heat and power that can be used in hotel complexes, residential areas, and campsites to supply the local infrastructure with electricity and heat.

In the future, it will be possible to produce hydrogen in an environmentally friendly way with the help of electrolysis (see page 12) if enough electricity is available from new renewable energy sources. If more hydrogen can be used in natural gas, the conversion step from hydrogen to methane would no longer be necessary, increasing the efficiency of the entire conversion chain and opening up a wide range of storage options. Studies with gas burners have shown that up to 20 or even 30 percent hydrogen can be added to methane without the gas burners being damaged by local overheating. Therefore, the PSI researchers want to find out if small gas turbines could also handle that much hydrogen, and how they would react to short-term demand peaks with a higher hydrogen content. The scientists hope that since hydrogen is very reactive and burns very quickly, the turbine might even respond better to rapid load changes with more hydrogen in the fuel gas mixture. A look into the past shows that gas networks can be made fit for high hydrogen proportions: Up to around 50 years ago, municipal gas was widespread in Switzerland and contained up to 50 percent hydrogen.



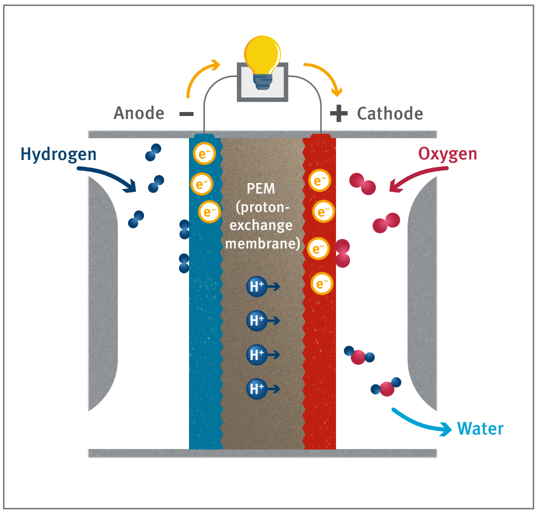
This mini gas turbine, part of the ESI Platform, converts methane into electricity and heat. PSI researchers are using it to test how the proportion of hydrogen in the natural gas mixture can be increased.

Clean energy, courtesy of fuel cells



When we breathe, we take in oxygen into our body. We need this vital gas to generate energy. One reaction involved in this is the combination of hydrogen and oxygen to form water. This is exactly what happens in a fuel cell.

A fuel cell generates electricity from a fuel and oxygen. The fuel is usually hydrogen, but it can also be methanol, butane, or natural gas. When hydrogen reacts with oxygen, energy is released and water is created. In this way, a fuel cell provides carbon dioxide-free, clean energy.
PSI has been involved in various stages of fuel cell research for many years: from the optimisation of individual components to the investigation of complete fuel cell systems. At PSI, researchers can carry out studies with the help of large research facilities – particle generators and accelerators – which provide unique insights into the interior of the fuel cells and the materials used. This gives the researchers a fundamental understanding of the processes in the fuel cell and enables them to improve this technology in a very targeted manner.
For example, water, the waste product from the reaction of hydrogen and oxygen, can pose a practical problem for fuel cell-powered motors. In colder climates, the water can freeze when the motor is switched off, thus impairing the function of the fuel cells. PSI researchers have directly mapped the distribution of ice and water in a fuel cell with the help of the spallation neutron source SINQ. They also checked how a specially developed material could better drain off the water produced. With the help of the Swiss Light Source SLS, PSI researchers also investigated how the polymer electrolyte membrane of a fuel cell wears out. A better understanding of these processes in fuel cells will help in the development of improved materials and methods for their use in the energy system.



Principle of the PEM fuel cell:
At the anode, under the release of electrons, hydrogen is oxidised to protons (H^+), which migrate through the membrane.
At the cathode, oxygen is reduced by electrons (e^-), and water is created. Anode and cathode are switched on to an electrical consumer; electricity flows.

The facilitators

At PSI researchers are developing more efficient catalysts as well as the necessary substrates.

Catalysts are substances that accelerate a chemical reaction, make it more efficient, or even make it possible in the first place. In biology, the role of catalysts is played by enzymes. These are natural protein molecules that enable humans, for example, to convert starch into sugar. Catalysts are also invaluable in industry.

As the end product of many combustion processes, carbon dioxide is a comparatively inert gas that does not like to react with other substances. To convert carbon dioxide to more energy-rich methane at moderate temperatures, you need catalysts. The element nickel is particularly suitable for the reaction of carbon dioxide with hydrogen to form methane. It is used in direct methanation, a technology developed at PSI to significantly increase the methane yield in the fermentation of biowaste (see pages 8, 9 and 13). The catalyst ensures that carbon dioxide and hydrogen combine to form methane and water.

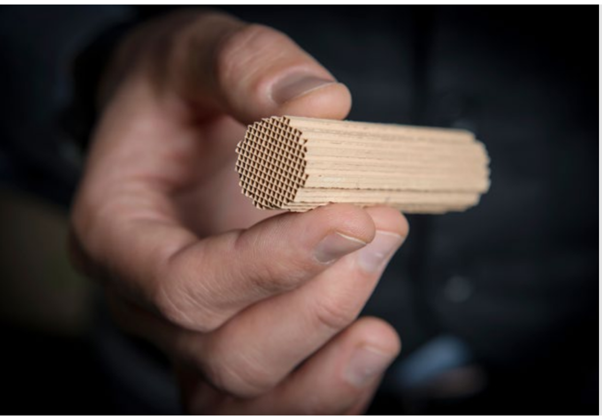
In the investigation and optimisation of catalysts, PSI researchers benefit from being able to use time-resolved X-ray spectroscopy at the Swiss Light Source SLS to observe the course of chemical reactions. This has a crucial advantage over conventional methods: Instead of just snapshots, the progress of the reactions can be captured and shown. It is important to understand exactly how the processes change over time, because temperatures and the quantities of precursor materials can vary during a chemical reaction.

Clean emissions thanks to a spong-like structure

Catalytic converters perform valuable services in filtering exhaust gases. Researchers at PSI are working to develop catalytic converters with higher performance for petrol-burning cars.
In a vehicular catalytic converter, the exhaust gas is routed through a large number of parallel ceramic ducts. Their surface is coated with the actual catalyst. It usually consists of finely distributed particles of precious metals, often palladium on a carrier substance. Depending on the type of engine, however, quite large amounts of the main component, methane, can be left over after burning natural gas or biogas. This is not easy to break down using conventional catalysts.
In tests conducted by the PSI researchers, zeolites proved to be the most suitable for this purpose. These are highly porous substances based on silicon dioxide. Under the microscope they look like a sponge: criss-crossed by many tiny holes that are connected to one another by channels. Such a structure offers an enormous amount of surface area. If the palladium is finely distributed in it, it can react even better with the exhaust gases – the pollutant emissions are significantly reduced.

Getting away from "dirty diesel"

In diesel engines, harmful nitrogen oxides are produced when the fuel is burned. To reduce this, gaseous ammonia is added to the exhaust gas, which, activated by a catalytic converter, reacts with the nitrogen oxides to form harmless nitrogen and water. The catalyst in this case is copper on a zeolite framework. However, the process does not yet work optimally at low temperatures.
The researchers investigated the structure and function of a copper-zeolite catalyst under realistic operating conditions at SLS. The most important finding: A stepwise addition of ammonia allows a faster reaction than a constant dose. From this, recommendations can be derived as to when and how much ammonia should be added to the catalytic converter in order to keep nitrogen oxides in the exhaust gas as low as possible at all times.



Due to their sponge-like structure, zeolites are excellent substrates for catalysts. Metals finely distributed within their scaffolding can react particularly effectively with exhaust gases.

Splitting water

One energy carrier of the future is hydrogen: It can be stored in tanks and later converted back into electrical energy, for example in fuel cells. Hydrogen is obtained from water in so-called electrolysers with electricity (see page 12). PSI researchers have developed a new material that acts as a catalyst and accelerates the splitting of the water molecules.
The PSI researchers' goal is to create a catalyst that is both efficient and inexpensive because it works without precious metals. To do this, they are going back to a well known material: perovskite, a complex compound of the elements barium, strontium, cobalt, iron, and oxygen.
They were the first to develop a process that produces perovskite in the form of tiny nanoparticles. This is the only way it can work efficiently, because a catalyst needs the largest possible surface area. If the particles of the catalyst are made as small as possible, their surfaces add up to a larger total surface. The new manufacturing process yields large quantities of the catalyst powder and should be easy to adapt to an industrial scale.

Green fuels for aviation

In the "SynFuels" initiative, scientists at PSI and its partner Empa are jointly developing a method of producing kerosene from renewable resources. They aim to produce top-quality liquid fuel mixtures that burn with as few residues as possible, making them suitable for aircraft propulsion.

Together, the two Swiss research institutes are looking for ways to combine carbon dioxide and hydrogen to form longer-chain molecules and thus produce synthetic fuels. Making such fuels suitable for an aircraft engine is an ambitious but very worthwhile goal: aviation fuels are the highest quality fuels around. If they can be manufactured from renewable resources, it will also be possible to synthesise all other types of fuel using the same method.

Kerosene is a mixture of hydrocarbons with very precisely specified chemical and physical properties, which must be strictly maintained in order to ensure economical and safe flight operations. A synthetic fuel must of course have the same properties.

The starting materials for the manufacturing process to be developed are carbon dioxide and hydrogen. The carbon dioxide comes from various sources, such as biomass, directly from the surrounding air or from industrial processes, such as cement production. The hydrogen required is produced from water with the help of renewable electricity. The liquid fuel is synthesised via one or more intermediate products, such as methane, carbon monoxide, methanol, ethene or dimethyl ether.

Molecular helpers

The key to success will be catalysts (see page 16, The facilitators). These are designed to enable the step-by-step conversion of carbon dioxide and hydrogen into liquid hydrocarbons at the molecular level.

The Swiss Light Source SLS is an indispensable tool in the "SynFuels" programme. This large research facility provides insights into the reaction mechanisms, or scientists can use it to study how the catalysts change during use and how these changes affect the range of products.

Another important part of the project is analysing the ecological footprint of the fuels produced, determining how much they can contribute to reducing greenhouse gas emissions in Switzerland and how economical they are to manufacture.

A good, long-lasting charge

Electricity provides light and warmth, powers most household appliances, and supplies our entertainment devices with energy. Electricity is also gaining in importance because of changes in mobility and new transportation concepts. Electricity can be stored in batteries, also known as accumulators, and thus can also be used on the move. This poses challenges for electricity storage systems, which PSI researchers are working to solve.

One problem that arises with all mobile energy storage systems – whether in smartphones, tablets, laptops, or electric vehicles – is their storage life. The question is not only how rapidly energy can be stored and accessed, but also how often, how reliably, and how much. Researchers in the PSI Laboratory for Electrochemistry are working to improve existing systems, for example those based on lithium, while also developing new storage systems based on other elements such as sodium.

With the help of the large-scale research facilities at PSI, scientists can look inside materials and track the processes that occur during charging and discharging, for example, down to the level of individual atoms. In doing so, they take into account all components of a battery, from the contacts through which electricity flows in or out to the storage material that holds the electrical energy.

Thus one research group at PSI, in cooperation with researchers from ETH Zurich, succeeded in developing a new process to significantly improve the performance of electrodes made from graphite, the material most commonly used for electrodes in commercially available batteries. By cleverly optimising the graphite anode – the negative electrode – in a conventional lithium-ion battery, the researchers tripled the storage capacity that can be used at high currents under laboratory conditions. Adding silicon further increased the usable storage capacity.

PSI researchers also achieved a substantial increase in performance with another type of lithium-based battery. Lithium-sulphur batteries can theoretically deliver significantly more energy than conventional lithium-ion batteries, but today's prototypes exhibit a noticeable loss in capacity after just a few charging cycles. The researchers found that optimisation of the electrode structure could increase the number of charging cycles considerably.

A deep look inside a completely different type of battery, so-called solid-state batteries, also revealed potential for improvement. This type of battery works completely without liquids, which in conventional batteries are responsible for transporting the charge. Since these liquids are flammable, solid-state batteries have the potential to make electromobility significantly safer. X-rays at PSI's Swiss Light Source SLS gave researchers unparalleled insights into the processes that take place in a solid-state battery during both charging and discharging. This led to better understanding of the damage that such batteries sustain, which in turn should help in the development of better energy storage systems for the future.

The Swiss Light Source SLS enables direct insights into the processes inside a battery.

Insights into the atmosphere

When we produce or use energy, we always influence our environment, especially the earth's atmosphere. That is why PSI is doing research on processes in the air – both close to the earth's surface and at an altitude of several thousand metres. Knowing about this helps to make the right decisions when it comes to controlling air pollution.

What do the Arctic and Antarctic, big cities like Beijing or New Delhi, and the Swiss Jungfraujoch have in common? PSI researchers work at all of these locations. They measure environmental factors and collect data to get a better picture of what is going on in the atmosphere.

In the Alps, PSI researchers extract ice cores from glaciers. These contain trace substances from the atmosphere of times long past. By analysing their composition, researchers can determine trends in climate history. This in turn enables them to make forecasts for the future development of our climate. In order to preserve this cold memory of the earth as a unique climate archive, PSI researchers are participating in the international Ice Memory project. Within the framework of this project, ice cores are being extracted worldwide and then stored in a warehouse in the Antarctic, protected against climate change and rising temperatures.

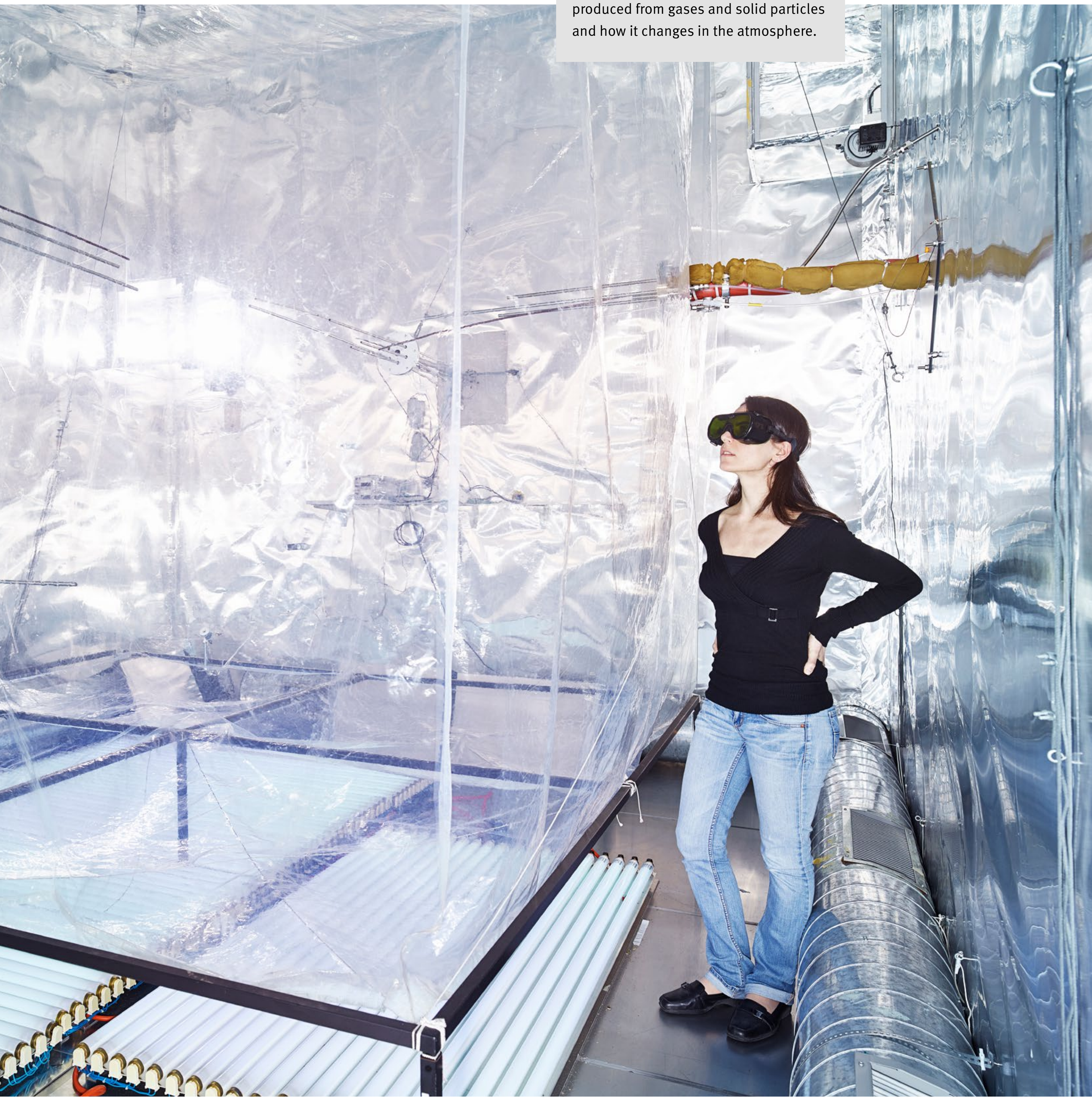
With the help of ice cores from the Alps, PSI researchers have shown for the first time that industrial soot can hardly be responsible for the melting of the Alpine glaciers, which mainly took place between 1850 and 1875. It was not until around 1875 that the soot content in the air exceeded its natural level and could therefore be traced back to human activities. Before that, the soot came mainly from natural sources, especially from forest fires.

High above

At around 3,500 metres above sea level, in the research station on the Jungfraujoch, PSI researchers examine, among other things, aerosols that are generally

PSI's smog chamber is a partner within the infrastructure programme EUROCHAMP-2020, an international programme for the integration of European simulation chambers in order to investigate atmospheric processes. This programme supports researchers in gaining access to state-of-the-art smog chamber facilities in Europe, including the PSI smog chamber. EUROCHAMP-2020 offers researchers the opportunity to bring their instruments and their specialist knowledge to various simulation chambers for measurement campaigns and instrument tests.

www.eurochamp.org



In the smog chamber at PSI researchers can study how particulate matter is produced from gases and solid particles and how it changes in the atmosphere.

Aerosol research on the Jungfraujoch helps, among other things, to better understand how soot particles turn into cloud droplets at different times of the year.

better known as particulate matter. These, too, influence the climate. Unlike the greenhouse gases carbon dioxide and methane, they do not always contribute to warming, but can also cool the climate. Some absorb sunlight, heating themselves up as a result, and thus contributing to the warming of the atmosphere. Others scatter light back into space, so they have a cooling effect. In addition, cloud droplets form on aerosol particles. Thanks to the high altitude of the Jungfraujoch, it is very easy to study how the short-lived particles change on the way from the earth's surface to the higher layers of the atmosphere and ultimately influence the formation of clouds there.

Bad air in Delhi

PSI researchers work at a location with much higher temperatures than at the poles of the earth or in the Alps when they study the air in gigantic metropolises like Delhi in India. There they measure 20 to 30 times higher concentrations of pollutants than in Switzerland – mainly from human sources. With their devices and analyses, the scientists uncover which sources and processes produce how much particulate matter and what steps could therefore improve the situation.

This has already been achieved in China: There PSI researchers have shown that the smog in Beijing consists to a large extent of secondary particulate matter, to which distant sources also contribute. In addition to on-site measurements, they also carried out experiments in the "smog chamber" at PSI and imported a Chinese stove and coal for this purpose. Their findings helped to improve air quality in Beijing through government measures.

The heart of PSI's smog chamber is a 27-cubic-metre cube made of thin Teflon film. Specific gases can be directed into this space. To simulate the natural environment as well as possible, the chamber can be irradiated with ultraviolet light, which corresponds to the UV component of sunlight. In this way, scientists can observe and analyse processes that normally take place in the atmosphere under controlled conditions.

From the big to the small

Energy production goes hand in hand with emissions in the form of particulate matter and gases. The climate and health effects that arise as a consequence result from an enormous number of complex processes in the atmosphere. To assign the effects of energy production to specific sources or processes or to project effects into the future, we need not only the diagnosis in the atmosphere but also experiments in the laboratory that make it possible to understand individual physical and chemical phenomena in detail. This involves not only smog chambers, but also reactors in the laboratory that are equipped with the latest analytical methods.

That's where the large research facilities at PSI come into play. PSI researchers have set up infrastructures at the Swiss Light Source SLS to investigate processes on the surfaces of particulate matter, ice, or water at the molecular level. In this way, they come to understand how water molecules organise themselves on the surface of an ice grain. Or they gain insight into the fate of nitrate, a breakdown product of nitrogen oxides, on the ice surface before it was archived in a glacier. Finally, they come to understand the interaction of dissolved substances on the surface of the water, for example when a cloud droplet forms. Another experiment makes it possible to take an X-ray view inside particulates to see how they are structured, or how they change their structure under the influence of a chemical reaction or changed environmental conditions. These experimental facilities are also available to external users to address questions at the interface between environmental research and physical chemistry.

Mobile monitor

To study the environment not only in individual locations, researchers can use the so-called smogmobile. This vehicle can be equipped with many different measuring instruments. During measurement runs, it can be used to examine the spatial as well as the temporal distribution of pollutants in the air.

PSI's smogmobile. Various devices, including an apparatus that draws air through the pores of a filter, can be installed in it. Researchers can then analyse the accumulated material.

The heart of the matter

Switzerland will phase out nuclear energy – this is what the Energy Strategy 2050 stipulates. The last nuclear power plant is expected to go offline in around 25 years. Beyond this point in time, knowledge about dealing with nuclear energy and all safety-relevant aspects is expected to be preserved and improved through research. Only in this way can valid facts be kept available in the future so that Switzerland can continue to make good decisions with regard to nuclear energy, nationally and internationally, and have a say as a competent discussion partner.

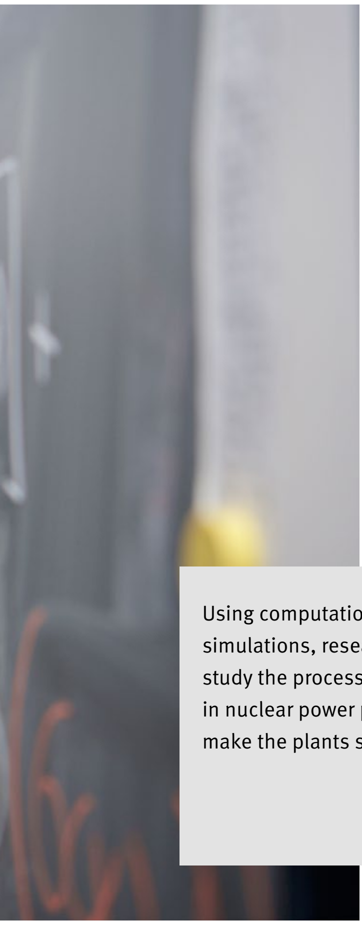
The researchers in PSI's Nuclear Energy and Safety Division are working on the following tasks:

- acquiring new scientific knowledge on nuclear safety
- further developing the most modern simulation methods for safety assessments
- assessing and/or updating nuclear safety criteria to reflect changes in power generation strategies, technological developments, modernisation, and long-term operation
- developing experimental facilities together with the most modern instrumentation technology for the design, execution, and interpretation of measurements on real physical phenomena of high relevance to safety, which are required for the verification, validation, and qualification of computational methods.

Specific questions are, for example: How does the material that is used in nuclear power plants age? How do the fuel rods, especially the cladding tubes that enclose the actual uranium oxide fuel, behave during operation and after their use? What would happen in the event of a serious reactor accident? How would the fuel material react in the event of a core meltdown, and how can it be ensured that radioactive substances do not get into the environment?

Like a sponge for hydrogen

For example, the Nuclear Fuels group found out how the integrity of the cladding tubes of nuclear fuel rods could be influenced. To do this, the researchers used neutron imaging, a process perfected at PSI that is regularly carried out by its own PSI working group at the local large research facility SINQ, the Swiss spallation neutron source. SINQ has one of the world's best neutron microscopes. It can be used to illuminate a wide variety of types of objects. In their investigations, the researchers



Using computational models and simulations, researchers closely study the processes that take place in nuclear power plants and thus make the plants safer.

concentrated on hydrogen that penetrates the metal of the cladding tubes and forms so-called hydrides with the metals, which can compromise the stability of the tubes. The group then looked into the effects of an additional protective layer on ducts, the so-called liners. These are used worldwide and especially in Switzerland. They protect the ducts against mechanical damage. The researchers found that liners do have a positive effect: Cladding tubes that have such a protective layer have fewer hydrides underneath. The hydrogen penetrates more and more into this coating, which stops it there. The liner acts like a sponge for the hydrogen. It's as if a person in a bathrobe walked into drizzling rain: The terrycloth would up the water, and the person's skin would stay dry. Evidently the coatings, which were originally introduced for mechanical protection, also make the cladding tubes more stable over the long term.

Simulations make nuclear plants safer

Computer simulations make a crucial contribution to the safe operation of nuclear power plants. Supervisory authorities also use them to check the safety of the systems. Almost everything, from the installation of new components to tests and measures to maintain security, has to be calculated and analysed on the computer beforehand. To this end, researchers at PSI develop computational models and computer programs that simulate components and subsystems in the nuclear reactor, as well as their interactions, with ever greater precision. In doing so, PSI acts as an independent research partner of the Swiss supervisory authority, the Federal Nuclear Safety Inspectorate ENSI, and thereby contributes to guaranteeing and continuously improving the safety of Swiss nuclear power plants.

For several years now, the trend has been towards realistic computational models called best-estimate models. The aim is to describe and quantify the processes in a reactor as precisely as possible on the basis of physical laws. hypothetical events, for example incidents in complex nuclear facilities, that are extremely unlikely but should still be studied for safety reasons. The researchers in the Laboratory for Scientific Computing and Modelling at PSI benefit from rapid advances in computer technology.

Safely sealed away

In Switzerland, the Nuclear Energy Act prescribes deep geological disposal of high-level, low-level, and medium-level waste from nuclear power plants and other sources. PSI researchers are contributing to this important social undertaking by investigating the natural processes that are important for the safety of a deep repository.

A question for the future

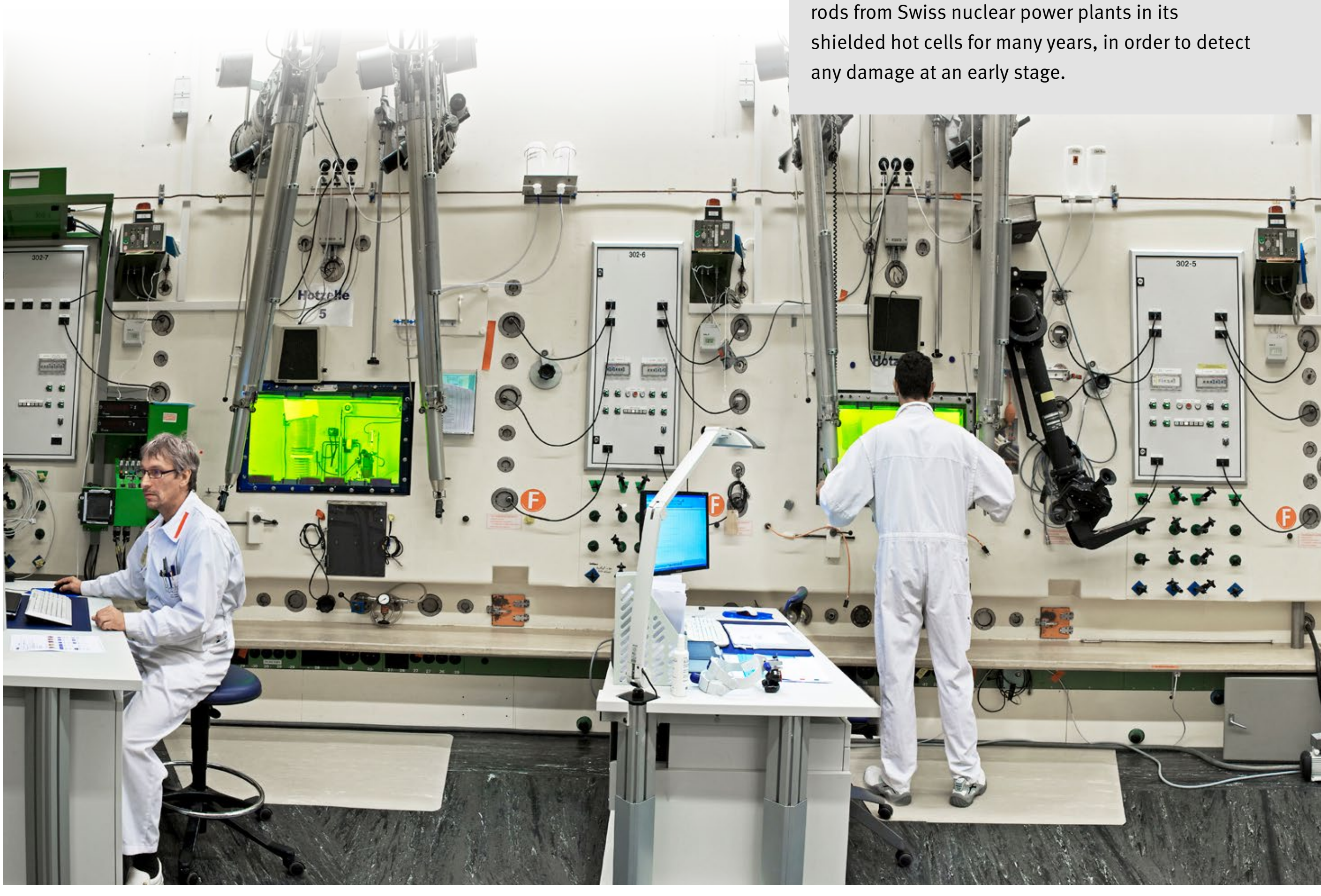
By supporting students, doctoral candidates, and young scientists, PSI and its partners ETH Zurich and EPF Lausanne are contributing to the long-term maintenance of specialist expertise in matters of nuclear energy in Switzerland: In the cross-location master's course in Nuclear Engineering, engineers learn how to operate nuclear power plants efficiently and safely, as well as how to decommission them and dispose of radioactive waste.

Hotlab: Knowledge from the hot cells

All of Switzerland's scientific expertise on the behaviour of materials and the ageing of nuclear power plants is concentrated at PSI. From the nuclear fuel itself to the cladding tubes of fuel rods and on to the reactor pressure vessels and coolant lines – researchers at PSI are investigating how materials change under the harsh conditions they are subjected to during the operation of a nuclear power plant.

Irradiated and therefore radioactive materials, whether from nuclear power plants or research facilities, may only be examined under strict safety precautions. Such tests are carried out in the PSI Hotlab, a facility that is unique in Switzerland. The radioactivity is hermetically enclosed and shielded in so-called hot cells, behind concrete walls up to one metre thick and leaded glass windows. This protects employees and avoids contamination of the environment. With externally controlled gripper arms, the researchers can safely carry out experiments with the radioactive material inside these chambers.

Around 35 staff members oversee the security and analytical infrastructure of the Hotlab – and also work on other research topics, for example in medicine. In the hot cells, PSI scientists produce some of their radiopharmaceuticals – radioactive drugs against cancer, which irradiate tumours directly inside the body. In the future, the radioactive isotope required for this, ter-

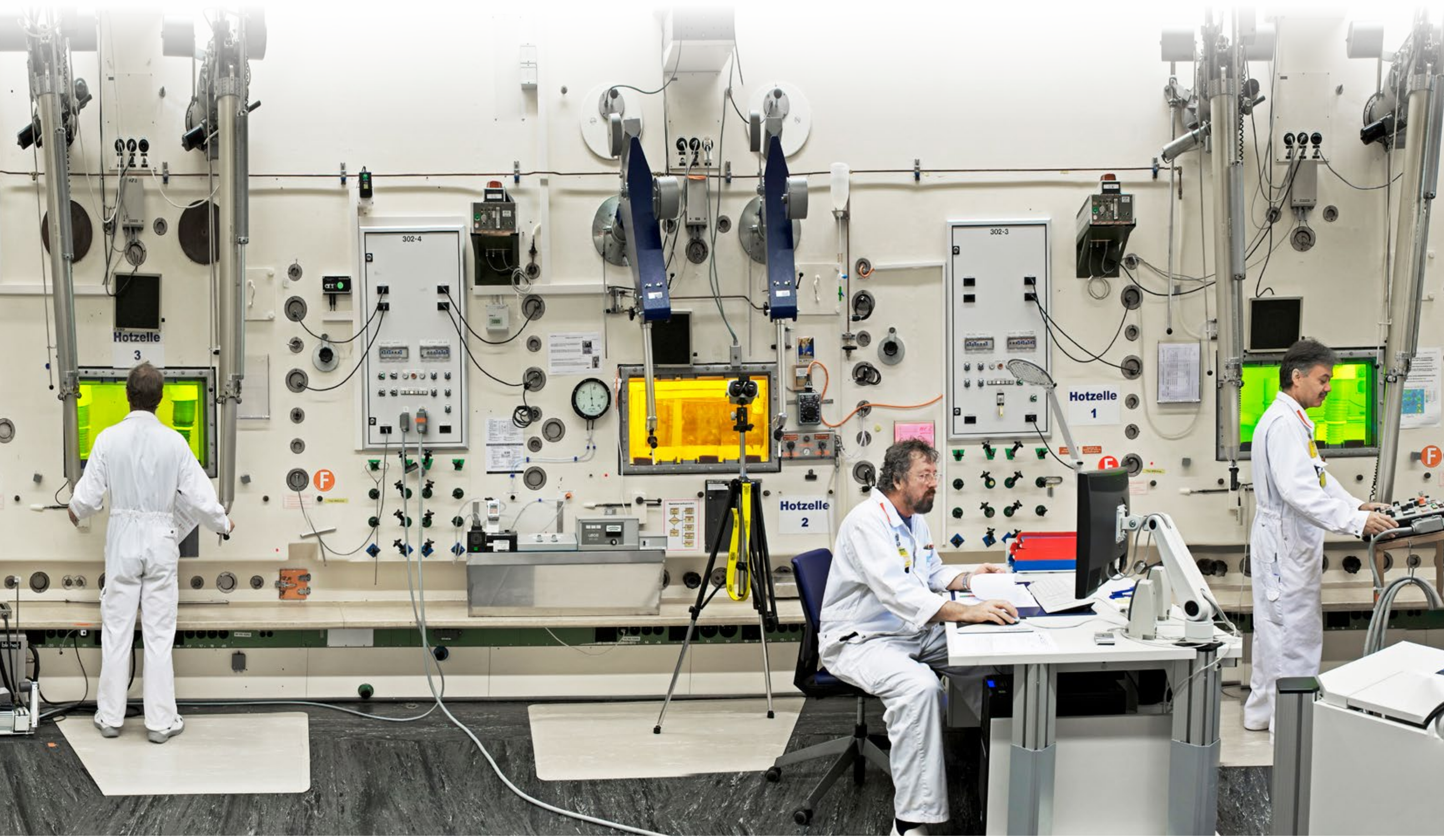


The PSI Hotlab has been examining spent fuel rods from Swiss nuclear power plants in its shielded hot cells for many years, in order to detect any damage at an early stage.

bium-161, is to be produced at PSI's spallation neutron source SINQ and then separated from the element from which it is created in the shielded cells of the Hotlab.

The main task of the PSI Hotlab is to carry out detailed examinations of irradiated fuel rods in order to understand how they change during operation or in the interim storage phase. Researchers in the Hotlab regularly examine the spent fuel rods from the Swiss nuclear power plants using modern analysis methods. They take a very close look at the possible embrittlement and oxidation of the fuel rod cladding. The focus is on continuously improving fuel rod design so that as much energy as possible can be obtained from the safely enclosed fuel. These findings help the nuclear power plant operators enhance the efficiency and safety of their power plants.

Special attention is paid to the cladding tube of the fuel rods. This first protective cover against the leakage of radioactivity from a nuclear reactor is exposed to very high stresses during operation, such as corrosion or the ingress of hydrogen. If too much hydrogen penetrates into the cladding tube, hydrides can be formed; compounds of hydrogen and the metals that make up the cladding tube material, hydrides can make the cladding more brittle and promote the growth of existing cracks. PSI scientists use the large research facilities in-house and the hot cells of the Hotlab to better understand how hydrogen is absorbed and then distributed in the cladding tube, thereby weakening it mechanically.



Energy systems: The holistic view

At PSI, scientists study energy systems in all their complexity, on both national and global levels. To do this, the researchers carefully examine the individual areas – electricity, heating, and transportation – as well as their interactions. They also look into the economic sustainability of these networked systems.

The researchers develop scenarios and make assumptions about which political guidelines, social trends, and technological developments could most strongly influence the overall framework conditions. Their results are not predictions set in stone, but rather well-founded answers to the question: "What if?"

Energy mix of the future

The proven economic expertise at PSI has led, among other things, to a partnership with the World Energy Council (WEC), whose framework is used to create scenario analyses of the global power supply. An updated version of the world energy scenarios is published every three years. In three different scenarios, researchers describe the global energy system and provide an idea of how it could develop further up to 2040 and beyond under specific framework conditions.
The scenarios have musical names that express a certain basic mood. Modern

Researchers at PSI perform detailed comparisons of the environmental impacts of passenger cars with different power systems and determine their ecological balance.

Jazz assumes that the markets will develop relatively freely and that consumer behaviour will change drastically by leaps and bounds – seen, for example, in a rapid switch to the purchase of large numbers of electric cars. In Unfinished Symphony, governments exert significantly more influence on how the energy system develops, for example through laws, framework conditions with long-term stability, and subsidies. In this scenario, climate policy decisions and other sustainability aspects carry much more weight. Hard Rock, on the other hand, assumes lower economic growth than the other two scenarios; there is less cooperation among individual states as well as less innovation.

Over the past few years, the Laboratory for Energy Systems Analysis at PSI has built up and continuously developed a computer-based model of the global energy system. It applies this to the world energy scenarios. This model – the Global MARKAL Model, GMM for short – maps out today's structures of the energy system as well as their interactions, and it integrates many possible future options for the energy supply. The researchers calculate how development goals and framework conditions will affect the energy mix, access to energy, carbon dioxide emissions, and economic and population growth. One finding that holds true for all three scenarios: Electricity is becoming increasingly important. Also, the average per capita energy consumption will reach a maximum in the next ten years and then decrease again. Total energy consumption will not decrease in any of the three scenarios; in two of them, it is projected to more than double.

Tomorrow's mobility

Petrol, diesel, or natural gas, electric cars, hybrids, or fuel cell vehicles – which fuels and technologies are the most environmentally friendly? In a life cycle assessment commissioned by the Federal Office of Energy, the Laboratory for Energy Systems Analysis at PSI analysed how the various types of passenger cars affect the environment. The researchers took into account the entire vehicle life cycle, from production through operation and disposal. Their results included, for example, greenhouse gas emissions, primary energy requirements, and the accumulation of ground-level ozone or particulate matter.

One finding: From a climate protection perspective, alternative vehicles and fuels – battery and fuel cell vehicles as well as those that can run on synthetic methane – only make sense if the electricity to operate the electric motor or to produce hydrogen and methane comes from low-carbon sources. This is true today and in the future. With electricity from nearly carbon dioxide-free production (hydroelectric, wind, and nuclear power plants), battery vehicles, fuel cell vehicles, and motors that burn synthetic methane make it possible to reduce greenhouse gas emissions by around half compared to conventional petrol and diesel cars. However, if the additional electricity demand due to electromobility is met by natural gas power plants, greenhouse gas emissions will not decrease. Therefore, renewable electricity production must always be expanded in parallel with the expansion of electromobility.

Bird's eye view of the Paul Scherrer Institute.

PSI in brief

The Paul Scherrer Institute PSI is a research institute for natural and engineering sciences, conducting cutting-edge research in the fields of future technologies, energy and climate, health innovation and fundamentals of nature. By performing fundamental and applied research, we work on sustainable solutions for major challenges facing society, science and economy. PSI develops, constructs and operates complex large research facilities. Every year more than 2500 guest scientists from Switzerland and around the world come to us. Just like PSI's own researchers, they use our unique facilities to carry out experiments that are not possible anywhere else. PSI is committed to the training of future generations. Therefore about one quarter of our staff are post-docs, post-graduates or apprentices. Altogether PSI employs 2200 people, thus being the largest research institute in Switzerland.

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