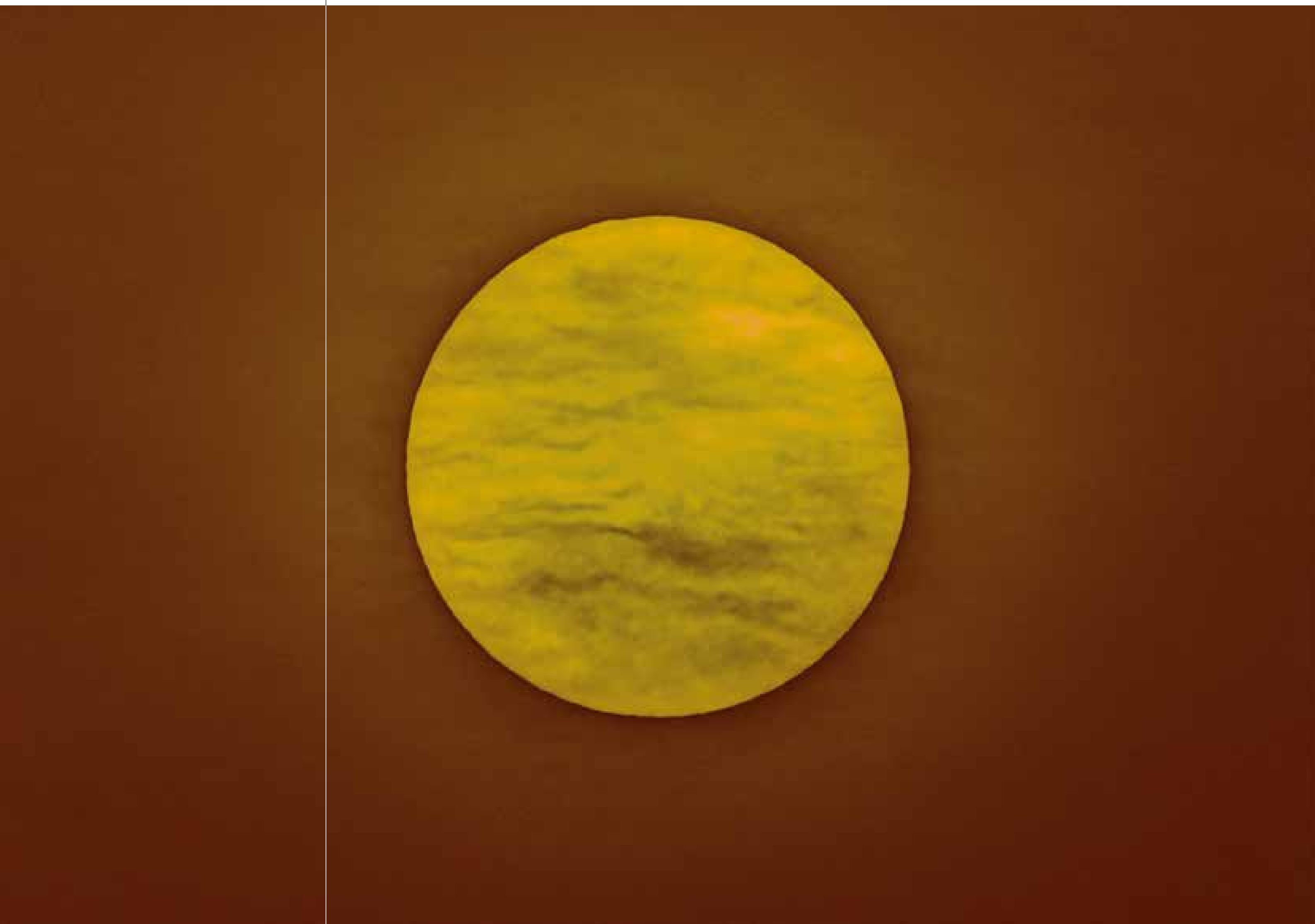
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

Energy research and innovation
Report 2021



Editorial

Energy supply security and the challenges of climate change are among the most important topics in Switzerland and worldwide. Alongside the implementation of efficiency measures and the application of renewable energy technologies, energy research plays an important role. Research helps to study the increasingly complex energy system with its various interactions between a wide range of actors and different energy sectors, and to develop technical and non-technical solutions which can be successfully implemented.

The Swiss Federal Office of Energy (SFOE) has been promoting and coordinating Swiss energy research in a programmatic approach for many years and supports application-oriented research, pilot and demonstration projects as well as larger interdisciplinary research consortia. Three different funding instruments are employed for this purpose, which complement each other. This brochure presents examples of projects that are supported and closely monitored by the SFOE, representing a large number of other research, pilot and demonstration projects. The QR codes provided will take you to detailed information.

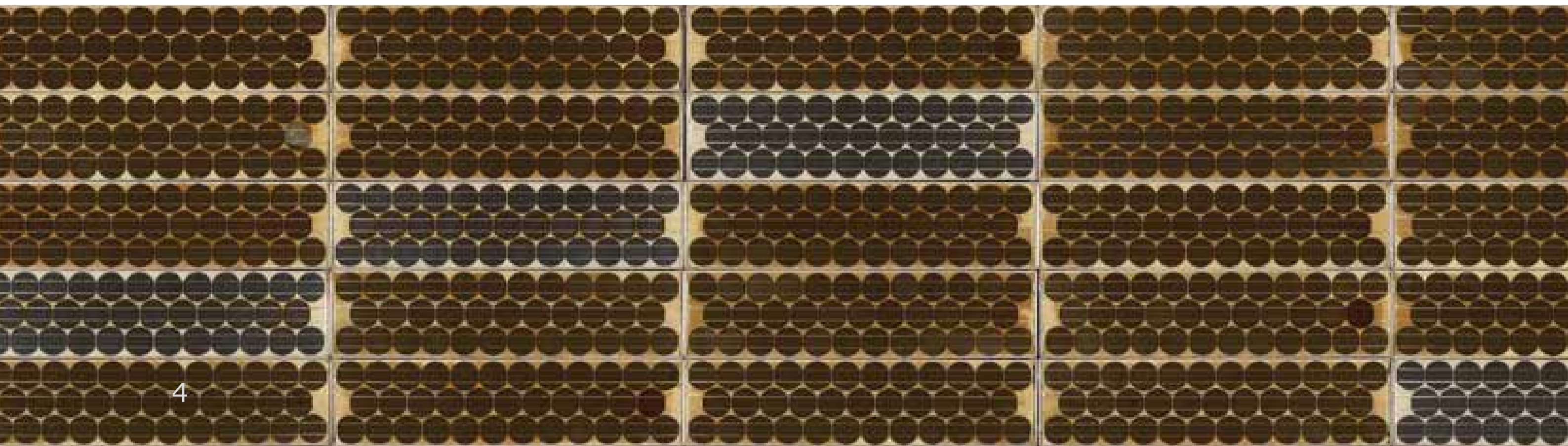
Swiss Federal Office of Energy SFOE
Section Energy research and Cleantech

(Cover picture) Weather has a great influence on photovoltaic systems' energy yield. Even a slight cloud cover can halve the solar energy yield compared to a cloudless summer day, and on a rainy day in November it drops to as little as one tenth. Exceptional weather events are also significant: several times a year, airstreams carry Saharan dust all the way to Switzerland. Such weather conditions with a high proportion of aerosols in the atmosphere reduce solar output by up to 10 % (source: Jan Remund, Meteotest AG).

(Left) A tandem solar cell with a certified efficiency of 29.2 % was recently presented at the Swiss Federal Institute of Technology Lausanne (EPFL) in Neuchâtel. This was made possible by combining a perovskite solar cell with a textured silicon solar cell. The challenge lies in particular in depositing the thin perovskite cell as a film uniformly on the intentionally textured silicon surface. The efficiency of this tandem cell is significantly higher than the maximum possible efficiency for a single silicon solar cell (source: Christian Wolff/EPFL).

Contents

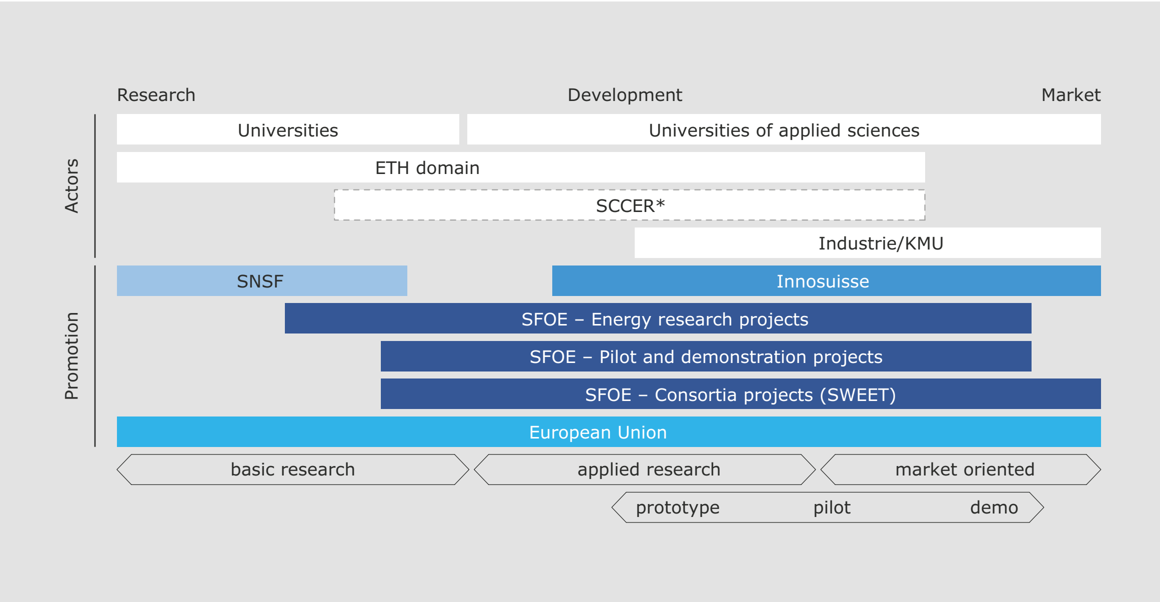
"Auguri di buon compleanno Ticino Solare": Near Lugano, the "TISO-10" was the first photovoltaic system in Europe to be connected to the electrical grid in May 1982. "TISO" stands for "Ticino Solare" and "10" for the installed capacity in kW. In 1982, the worldwide installed photovoltaic capacity totalled 9 MW and the cost of the TISO system was 28,500 Swiss francs per installed kW. For the 35th anniversary, all 288 modules were examined in detail. The analysis showed at that time that 56 % of the modules still achieved more than 80 % of the nominal output after 35 years and would therefore still fulfil a performance guarantee of a maximum loss of 20 % (image source: SUSPI).



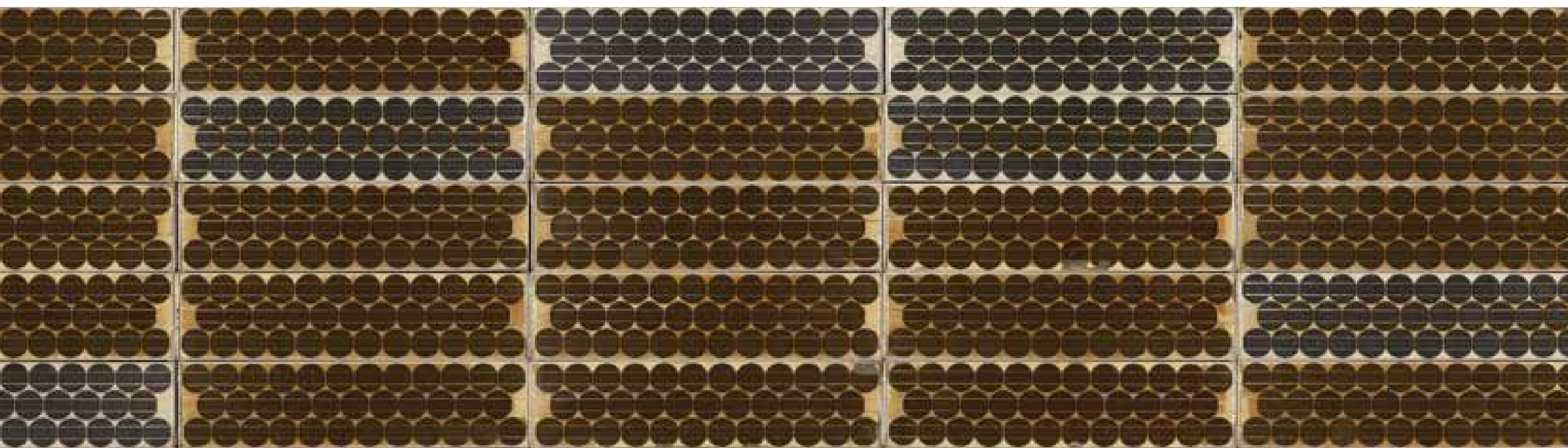
Promotion of technology and innovation

With three complementary funding instruments for research and innovation in the energy sector, the Swiss Federal Office of Energy (SFOE) covers almost the entire technology spectrum. The SFOE is guided by its own energy research concept 2021–2024, which in turn is based on the federal government's energy research strategy. For the current period 2021–2024, an even stronger focus is put on non-technical research (SSH: social sciences and humanities). Technical sciences and SSH are to work closely together as early as the conception stage of research projects in order to orient research results towards later application at an early stage.

Funds from SFOE for energy research are used in a subsidising manner to close gaps in the funding landscape and thus to coordinate Swiss energy research. Currently, around 50 million Swiss francs per year are available for this and around 300 ongoing projects are closely monitored each year.

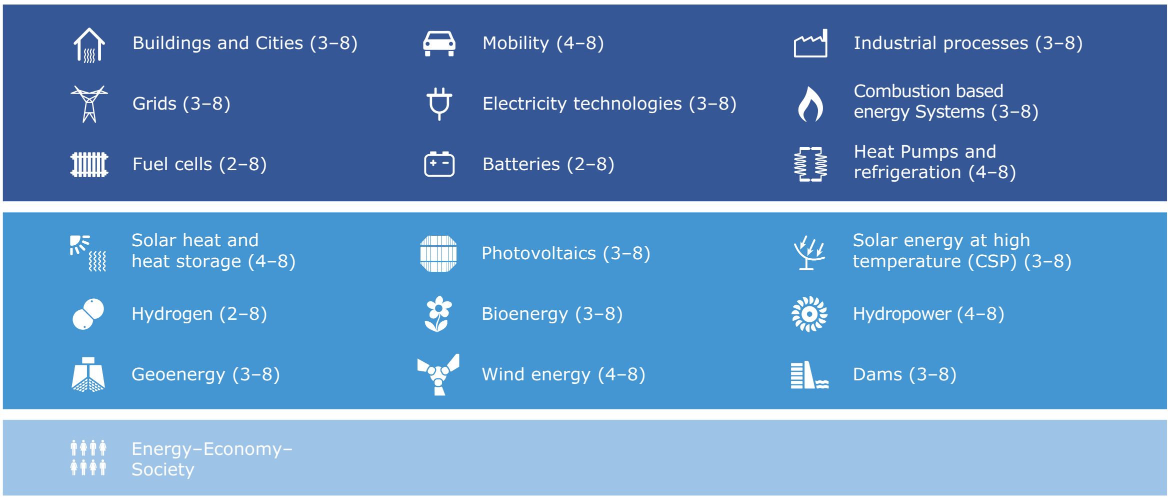


The Swiss Federal Office of Energy (SFOE) coordinates research and innovation in the energy sector across a large part of the value chain. (Innosuisse = Swiss Agency for Innovation Promotion; SNSF = Swiss National Science Foundation). * The Swiss Competence Centers in Energy Research (SCCER) were supported by the federal government from 2013 until the end of 2020.



Thematic energy research programmes

With its thematically oriented energy research programmes, the SFOE covers the entire spectrum of energy research in the fields of "Energy Efficiency" and "Renewable Energy". These programmes are closely linked to the SFOE's other funding instruments (Pilot and Demonstration Projects Programme and the SWEET Programme). The individual programmes are oriented along the axes of "Energy efficiency", "Renewable energy", "Humanities and social science topics", "Storage and grids". Central topics such as "digitalisation", "sector coupling" and "energy storage" are addressed across the programmes.



The SFOE's thematic energy research programmes. The numbers in brackets indicate the technology maturity level of projects funded by the corresponding programme.

Inter- and transdisciplinary energy research promotion with SWEET

End of 2020, the federal parliament approved the research funding programme SWEET – "SWiss Energy research for the Energy Transition", which smoothly follows the preceding SCCERs ("Swiss Competence Centers in Energy Research"). Funding of CHF 136.4 million is available for SWEET until 2028. In contrast to the SCCERs, SWEET as a programme is more competitive, i.e. calls for proposals are published regularly for consortia to apply. SWEET also does not impose any fixed requirements for "matching funds", i.e. the proportion of own or third-party funds that must be raised for a project. SWEET funds larger consortia via calls for proposals, which are made up of universities, higher education institutions and partners from industry and the public sector.

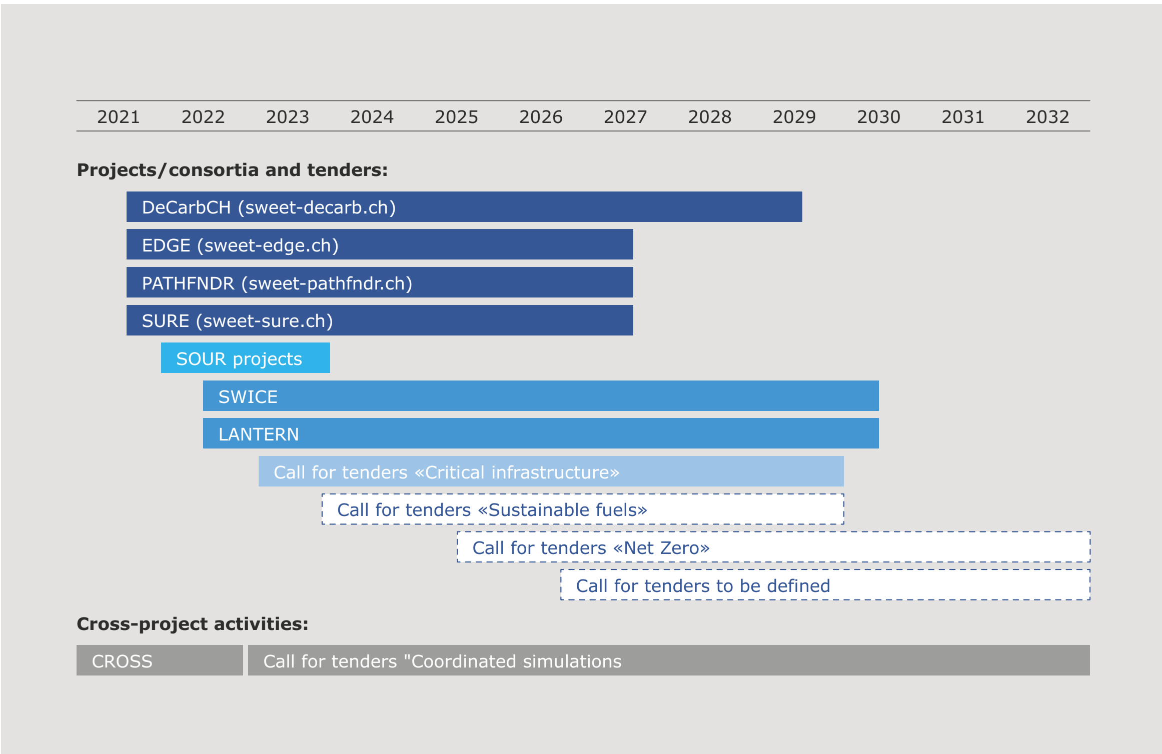
The first call for proposals on the topic of "Integrating renewable energies into a sustainable and resilient Swiss energy system" was concluded at the beginning of 2021. The four successful consortia DeCarbCH, EDGE, PATHFNDR and SURE started their research work in 2021. The DeCarbCH ("Decarbonization of Switzerland") consortium focuses on the decarbonisation of heating and cooling systems and aims to promote the use of renewable energies in the building sector as well as in the industrial and service sectors. For EDGE ("Integrating very high shares of decentralized renewable energy into the Swiss energy system"), the main objective is to show how a high proportion of decentralised renewable energy generation can be achieved within Switzerland, with a focus on the electricity sector. The PATHFNDR ("Pathways to an efficient future energy system through flexibility and sector coupling") consortium, on the other hand, is investigating how the Swiss energy system must be restructured so that it can accept a larger share of renewable energy. The fourth consortium from the first call, SURE ("SUstainable and REsilient Energy for Switzerland"), aims to demonstrate how energy supply security can be guaranteed in a future decarbonised energy system and is developing for this purpose new scenarios.

Alongside the SWEET consortia, the instrument SOUR ("SWEET OUtside-the-box Rethinking") deliberately promotes unconventional projects. In a first SOUR call – on the same guiding theme as the first SWEET call – four selected projects were granted funding.

The second SWEET call for proposals "Living & Working" was launched in spring 2021. In geographically clearly defined (sub)urban areas, research will focus on how energy supply and distribution can be ensured efficiently and cost-effectively and at the same time how energy consumption can be minimised. New energy-saving potentials will be identified and quantified by linking the buildings and mobility sectors and through technology adaptation and behavioural adaptations by consumers. The LANTERN ("Living Labs Interfaces for Energy Transition") and SWICE ("Sustainable Wellbeing for the individual and the Collectivity in the Energy transition") consortia will start their work in 2022.

In autumn 2021, the third SWEET call for proposals was announced with the central theme "Critical infrastructures, climate change and resilience of the Swiss energy system". The aim of this call is to analyse the impact of the transformation of the energy supply on critical infrastructures and to investigate the vulnerability of the energy system to technical, natural and societal hazards.

At present, another consortium is being sought to coordinate the various simulations of the individual SWEET consortia. In addition to technical and economic aspects, a central requirement will be to incorporate findings from the social sciences and humanities. The work of the consortium resulting from this call for proposals will follow on from the research activities of CROSS ("CooRdination Of Scenarios for SWEET"). CROSS is a joint activity of the first four consortia DeCarbCH, EDGE, PATHFNDR and SURE and will last until the end of 2022.



DeCarbCH

EDGE

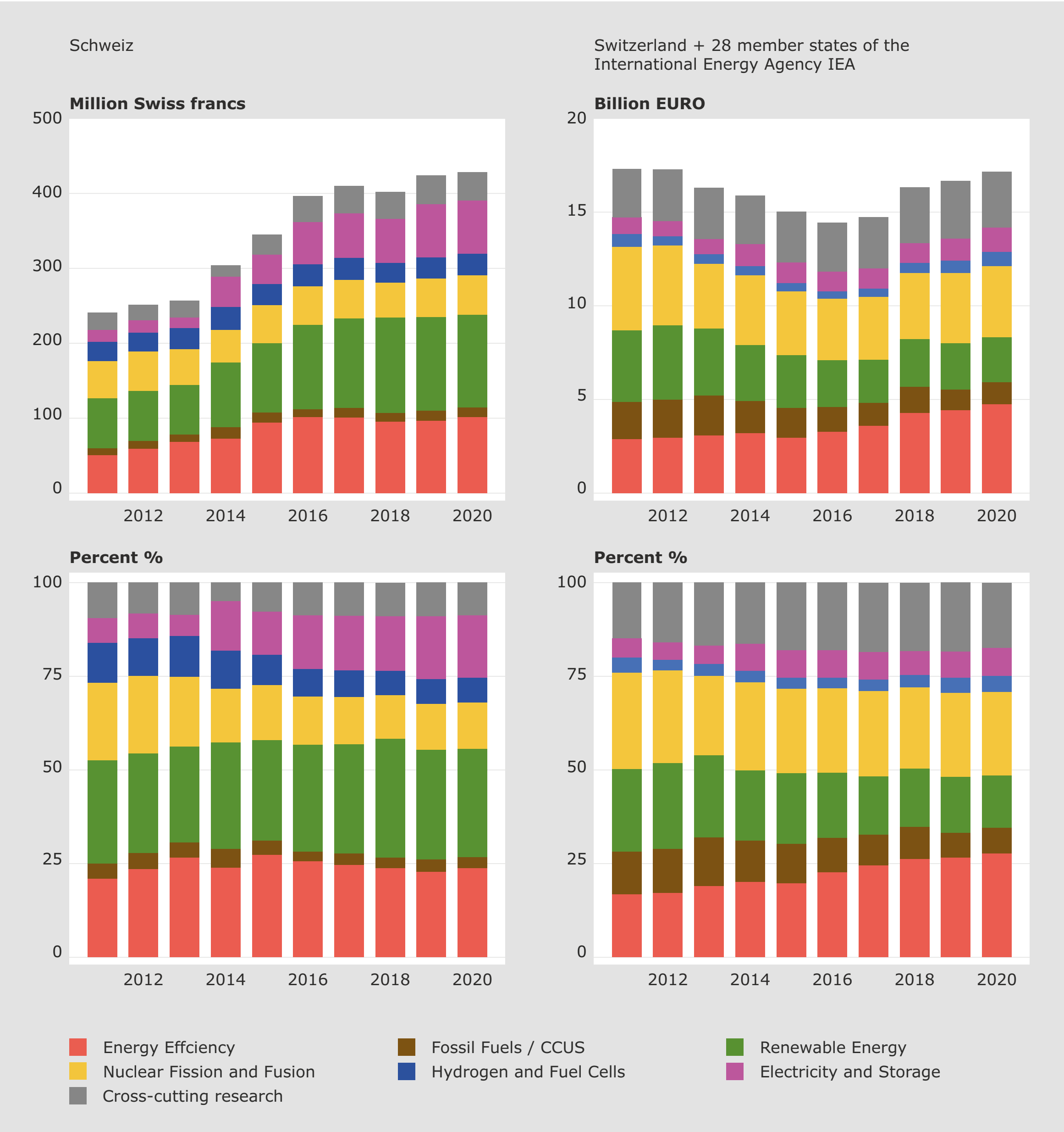
PATHFNDR

SURE

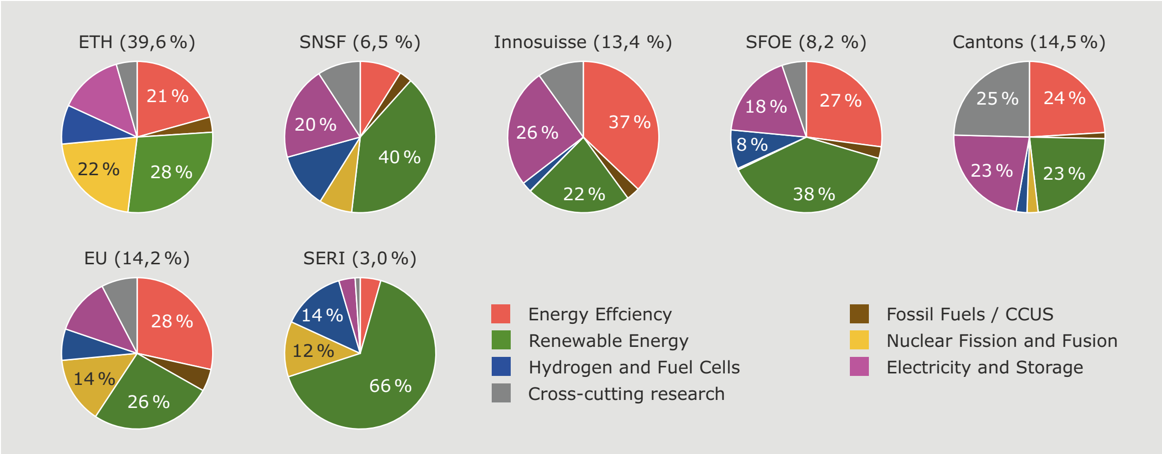
Overview of projects/consortia in the SWEET funding programme and of current and planned calls for proposals.

Swiss energy research statistics

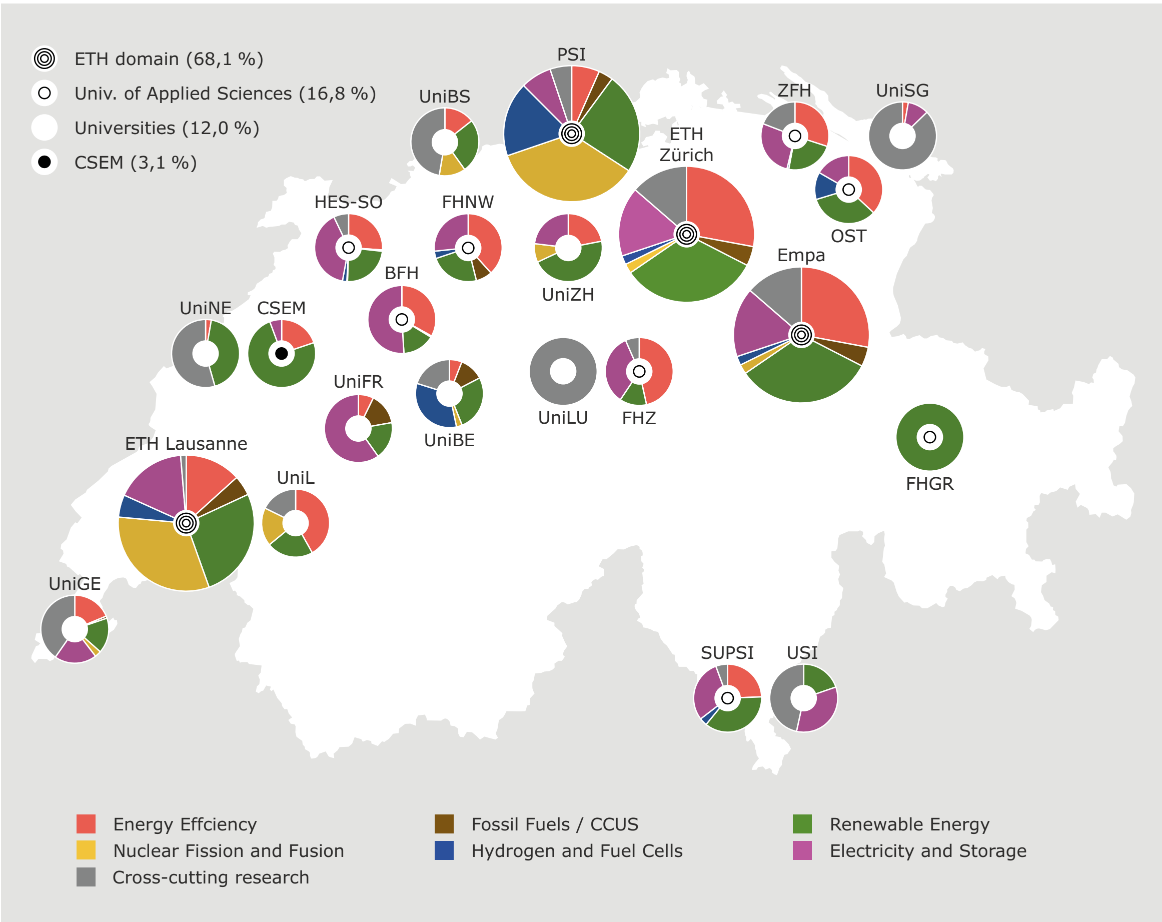
Since 1977, the Swiss Federal Office of Energy (SFOE) has been collecting data on projects that are funded in whole or in part by the public sector (Confederation and cantons), the Swiss National Science Foundation (SNSF), Innosuisse or the European Union (EU). Information on individual projects can be obtained from the publicly accessible information system of the Confederation (www.aramis.admin.ch), the SNSF (data.snf.ch), the EU (cordis.europa.eu) and the respective websites of individual institutes. In 2020, the public sector in Switzerland spent 432 million Swiss francs on energy research, which corresponds to 180 % of the expenditure in 2011. For comparison, the total expenditure of 29 member countries of the International Energy Agency (IEA) (including Switzerland) amounts to around 17 billion euros. Euros and remained more or less constant over the last 10 years.



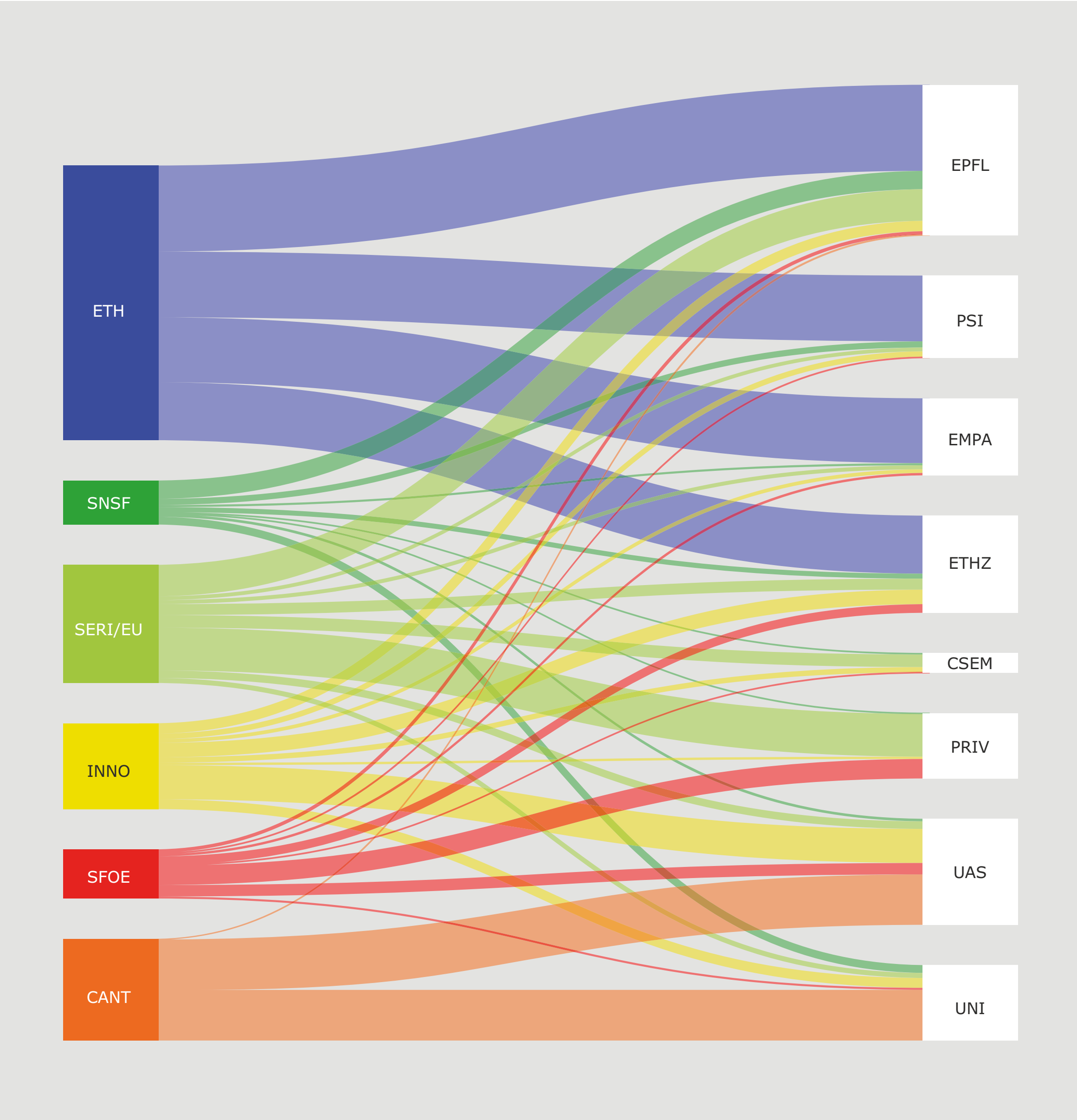
Public funds spent on energy research in Switzerland (left) and in 29 member countries of the International Energy Agency IEA (right). Swiss expenditure is in the range of 0.3 to 0.65 per mille of the gross domestic product. The funds are broken down according to the classification of the International Energy Agency (IEA) (source: SFOE energy research statistics).



Public funding for energy research (data 2019) by funding agency and thematic area. Around 40 % of the funding for energy research in Switzerland comes directly from the ETH Domain, and around 15 % from cantonal funding for universities of applied sciences and universities. The rest is competitive funding. ETH: Council of the Swiss Federal Institutes of Technology, SNSF: Swiss National Science Foundation, Innosuisse: Swiss Agency for Innovation Promotion, SFOE: Swiss Federal Office of Energy, EU: European Union, SERI: State Secretariat for Education, Research and Innovation (source: SFOE energy research statistics).



Various energy research topics at Swiss universities (data 2020). The topics are broken down according to the classification of the International Energy Agency. Most of the public energy research (68 % of the public funds used) takes place in the ETH Domain. BFH: Bern University of Applied Sciences, CSEM: Centre suisse d'éléctronique et de microtechnique, EMPA: Swiss Federal Laboratories for Materials Testing and Research, EPFL: Swiss Federal Institute of Technology Lausanne, ETHZ: Swiss Federal Institute of Technology Zurich, FHNW: University of Applied Sciences Northwestern Switzerland, FHO: University of Applied Sciences Eastern Switzerland, FHZ: University of Applied Sciences of Central Switzerland, HES-SO: University of Applied Sciences of Western Switzerland, PSI: Paul Scherrer Institute, SUPSI: University of Applied Sciences of Italian-speaking Switzerland, UniBE: University of Bern, UniBS: University of Basel, UniFR: University of Fribourg, UniGE: University of Geneva, UniLS: University of Lausanne, UniLU: University of Lucerne, UniNE: University of Neuchâtel, UniSG: University of St. Gallen, UniZH: University of Zurich, USI: University of the Italian-speaking part of Switzerland, ZFH: Zurich University of Applied Sciences (source: SFOE energy research statistics).



Where does the public funding for energy research in Switzerland come from and where does it go? A large part comes directly from the ETH Domain. Funds from private sources, such as own contributions to Innosuisse projects or pilot and demonstration projects of the SFOE, are not included. Cash flows of less than CHF 0.2 million are not shown.

Source of funds: ETH: ETH Board, SNSF: Swiss National Science Foundation, SERI/EU: funds from European projects or from SERI (State Secretariat for Education, Research & Innovation), INNO: Innosuisse, SFOE: Swiss Federal Office of Energy, CANT: cantons.

Use of funds: PSI: Paul Scherrer Institute, ETHZ: ETH Zurich, EPFL: ETH Lausanne, EMPA: Swiss Federal Laboratories for Materials Testing and Research, UNI: Universities, UAS: Universities of Applied Sciences, PRIV: Private Sector, CSEM: Centre Suisse d'Electronique et de Microtechnique (source: SFOE energy research statistics).

(Left) Secondary coil for an inductive power transfer to transmit energy contactless/wireless from a photovoltaic module ("Wireless Power Transfer" WPT). Thanks to this new concept, the mechanical assembly of such a WPT photovoltaic module is simultaneously accompanied by the electrical connection without classic connectors, thus increasing the reliability of the photovoltaic system technology. The coil consists of 280 windings, evenly distributed over 7 layers, and enables connection to a photovoltaic system string with a high string voltage of over 1400 V. Unlike today, the power electronics are laminated into the module. In a SFOE project, an efficiency of 97.9 % ± 0.83 % (coupling coefficient k=1) was demonstrated for the coil system. Including the modelled losses of the power electronics based on the resonant converter and rectifier, an overall efficiency of 95.7 % is possible (source: ZHAW).

Batteries for the energy turnaround

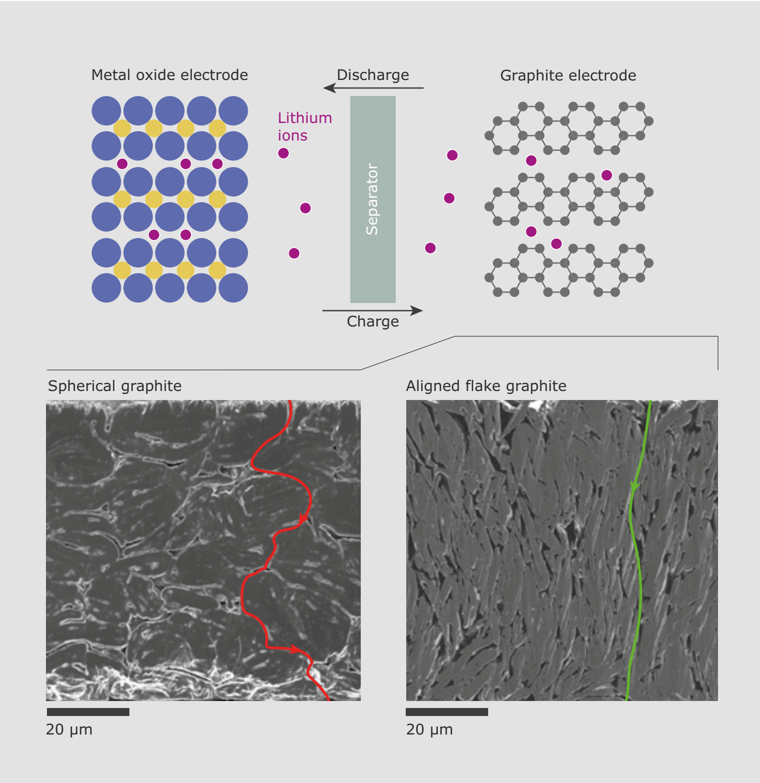
The spread of electromobility on Swiss roads relies on powerful batteries. Batteries also represent an important lever for shifting solar power from the sunny hours of the day to the high-consumption evening. These applications make it clear that batteries and other electrochemical storage systems are a key technology for the transformation of the energy system towards sustainability.

The "European Battery Alliance" launched by the European Union (EU) in 2017, which aims to establish an independent, competitive and sustainable value chain for battery technologies in Europe, underlines the central importance of this technology for the energy transition. To this end, the European Commission has approved a total of 20 billion euros in state aid in 2019 and 2021 for so-called "Important Projects of Common European Interest" (IPCEI), which have been notified by various EU member states. Furthermore, around 925 million euros will be provided directly from the EU budget for battery research projects until 2027. Indirect funding at European level is also being provided through the "Fit for 55" legislative package, which tightens CO_2 emission standards for vehicles and introduces regulations for the development of a nationwide charging infrastructure.

In Switzerland, battery research is also becoming increasingly important. In 2020, various research institutions and industrial companies joined forces to form the iBAT innovation platform. Switzerland's competitiveness in this core technology is to be further strengthened through this cooperation between science and industry. Although Switzerland is not a major battery manufacturer, it does hold a leading position in the research and supply of semi-finished products and machines.

Research activities in Switzerland, for example, are aimed at improving the lithium-ion rechargeable battery. This rechargeable battery technology started to be developed in the late 1970s and became increasingly widespread in the 1990s. Today, this battery technology is used in various forms in electric cars, mobile phones and many other electrical applications. Central to the functionality are the lithium ions that give the battery its name: these charge carriers move from the positive to the negative electrode when the battery is charged and in the opposite direction when it is discharged. The Swiss company Battrion, which emerged as a spin-off from the Swiss Federal Institute of Technology Zurich in 2015, is working on the negative electrode of lithium-ion batteries, which typically consists of graphite (carbon). In years of research and development, Battrion has improved the microstructure of such gaphite electrodes so that the intercalation of lithium ions into the electrodes

"Roll-to-roll" production line of the Swiss company Battrion for the industrial production of novel graphite (carbon) electrodes, which are intended to significantly reduce the charging times of lithium-ion batteries (source: Battrion AG).



(Top) In lithium-ion cells, lithium ions are exchanged between the electrodes during charging and discharging. (Bottom) Electron microscope images of graphite electrodes with (left) conventional spherical graphite and with (right) aligned graphite flakes produced in a process developed by the Swiss company Battrion. On the right, diffusion paths for lithium ions are significantly shorter (source: Battrion).

becomes faster. The technology thus offers the potential to significantly reduce the charging time of an electric vehicle.

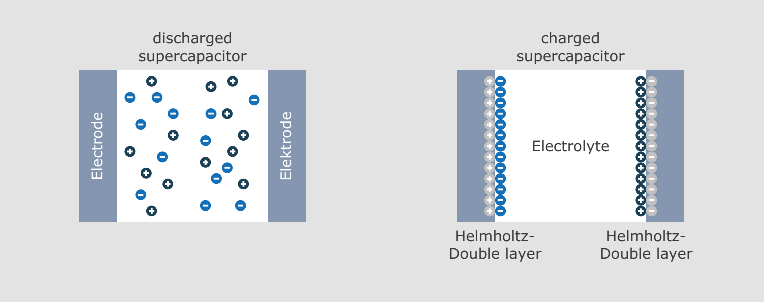
Batteries with sodium nickel chloride cells represent a technology that has been rather little widespread up to now. The fascination for this battery storage system stems from the fact that it works on the basis of common salt (sodium chloride). All the raw materials needed to build the battery cells are available in sufficient quantities and relatively cheaply. However, these battery cells operate at temperatures of around 300 °C and must therefore be thermally insulated. So far, this low-maintenance technology, which works reliably even at low outside temperatures, has been used mainly in niche applications such as the power supply of telecommunications and emergency power systems. In the future, it could also be used in stationary grid batteries, for example, to balance electricity production and demand.

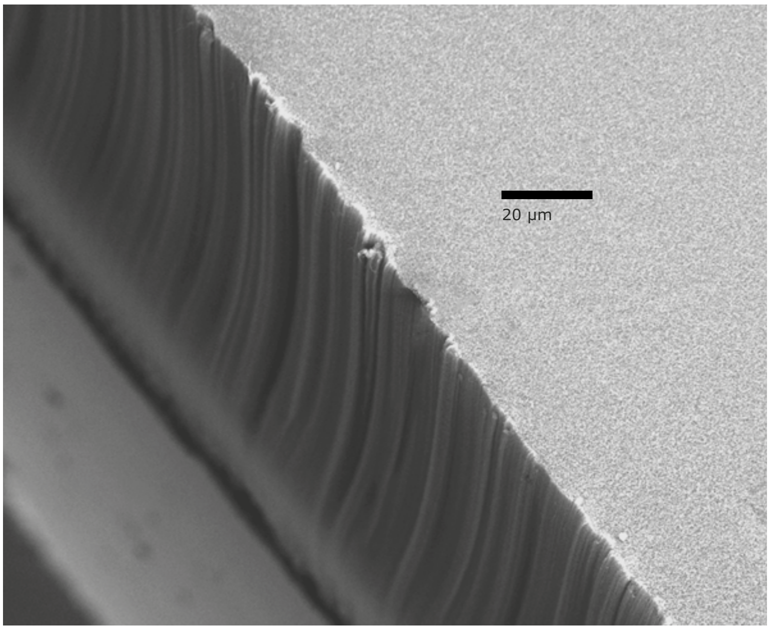
The Swiss Federal Laboratories for Materials Testing and Research Empa is working on optimising various components of sodium nickel chloride cells as part of a project supported by the Swiss Federal Office of Energy (SFOE). In particular, cells with a flat geometry have been developed in contrast to the classic tubular cells. The tubular shape of today's sodium nickel chloride cells is associated with great complexity in production, assembly and quality control, which is simplified by flat

The Swiss Federal Laboratories for Materials Testing and Research Empa is developing high-temperature battery cells based on sodium nickel chloride with a flat geometry that is easier to manufacture compared to conventional tube geometries. The passive cell components, the solid electrolyte as well as the negative electrode made of molten sodium metal tolerate high rates for charging and discharging currents (source: Empa).

Sodium nickel chloride battery cell:

Anode reaction:	2 Na	$\rightleftarrows$	2 NaCl + Ni
Cathode reaction:	$NiCl_2$ + 2 Na^+ + 2 e^-	$\rightleftarrows$	2 Na^+ + 2 e^-
Total reaction:	$NiCl_2$ + 2 Na	Discharge $\rightleftarrows$ Charge	2 NaCl + Ni





(Top) Simplified principle of a supercapacitor (double layer capacitor) with energy storage in Helmholtz double layers of negative and positive ions arranged in mirror images on the electrodes. (Bottom) Scanning electron microscope image of an electrode with a large number of vertically aligned carbon nanotubes (source: EPFL).

cells. The research results are being implemented by the Ticino-based company FZSoNick.

Another SFOE-funded project at the Swiss Federal Institute of Technology Lausanne (EPFL) aims to improve an available storage technology. The focus here is on so-called supercapacitors. The electrodes of such storage devices are connected to each other by an electrolyte that contains positively and negatively charged ions. When an external voltage is applied, the energy is stored in so-called Helmholtz double layers of negative and positive ions, which are arranged in mirror images on the electrodes. Unlike batteries, there is no chemical change in the material. Supercapacitors are characterised by high efficiency and high power densities and play an important role in electromobility to cover power peaks. However, conventional supercapacitors are less suitable as energy storage devices. In the EPFL project, the energy density of supercapacitors is to be increased in order to enable new areas of application. This includes, for example, the power supply of sensors, which are increasingly being used in networked smart devices. The electrodes of the supercapacitors studied at EPFL are tubular structures made out of carbon atoms, so-called “carbon nanotubes”, with a diameter of only a few nanometres. The electrodes are coated with electrochemically active materials, which greatly increases the energy density.

The Bern University of Applied Sciences in particular is looking into the question of how electrical storage systems can best be integrated into the electricity grid. In a recently completed project, investigations were carried out into how operators of solar systems with batteries can use their storage systems in a "grid-serving" manner, i.e. in a way that minimises the load on the electricity distribution grids. With the use of grid-serving algorithms for load balancing, overloads of power lines and transformers can be significantly reduced and in many cases completely prevented.

Sorption processes have long played an important role in industry. A more recent application example is the process for CO_2 capture from the atmosphere by the Swiss company Climeworks. In a first plant in Hinwil, that went into operation in 2017, 2.5 tonnes of CO_2 are captured per day. In the meantime, the industrialisation and scaling up is being pushed forward, for example with a larger plant in Iceland, where CO_2 is captured and finally stored underground (image source: Climeworks).

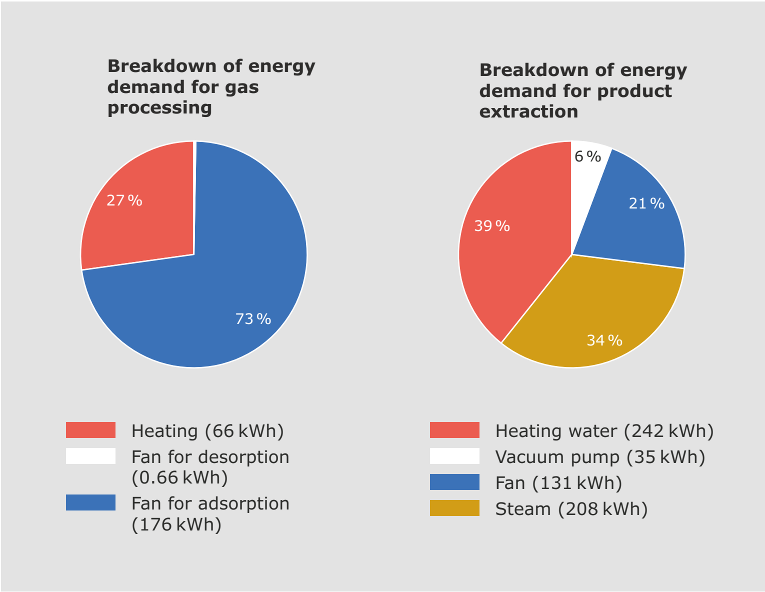
Energy-efficient sorption systems in process engineering

Adsorbers are used in many industrial processes, for example to remove unwanted colourants, odours or toxins from gases and liquids. Such technical systems are often oversized and therefore have excessive energy requirements. With correct dimensioning, energy and material can be saved.

In process engineering, the "absorption" of substances is the process of taking up atoms, molecules or ions in another phase, such as the absorption of gas molecules in a solid or in a liquid. In contrast, "adsorption" refers to the process of accumulation on the surface alone. "Desorption" stands for the inverse process, where gas molecules leave a solid or liquid and enter the gas phase. Sorption processes, i. e. sequences of absorption/adsorption and desorption, play an important role in industry, for example to purify the air of a lacquering plant from solvents. Food or chemical companies use these processes to separate gas mixtures. Sorption processes are also of great importance in environmental and energy technology.

From an energy perspective, there is huge potential for optimisation in adsorber systems in industry. Often, systems are oversized and have high safety margins. This drives up energy and material consumption and causes unnecessary costs. In several projects supported by the Swiss Federal Office of Energy (SFOE), the Lucerne University of Applied Sciences and Arts has looked into optimi-

sation possibilities in recent years. The energy saving potential of sorption processes was systematically analysed and suitable procedures were sought to exploit this potential. The work resulted in a guideline that can be used to better plan and dimension adsorption plants. A central step is the creation of a mathematical-physical model that quantitatively describes the respective adsorption process. After validation, such a model can be used for sensitivity analysis and optimisation of the adsorption process. With optimised and demand-oriented dimensioning, for example of gas purification plants, 25 to 30 percent of energy can be saved in this way.



Sorption processes play an important role in the purification of gases or in the extraction of a substance from a gas mixture. In the case of gas purification (left), around three quarters of the energy demand is accounted for by the power supply for the fan that conveys the gas mixture through the adsorber. One quarter of the energy demand goes to the heat requirement for the desorption air, which dissolves the substance molecules adhering to the adsorber. The energy requirement is distributed differently in a product recovery application (right). In this case, a lot of heat is required for the production of heating water and steam, and only about a quarter for the electrical drive of the fan. Detailed analysis by the Lucerne University of Applied Sciences and Arts has shown that there are different energy optimisation options depending on the application objective of sorption processes (source: Lucerne University of Applied Sciences and Arts, SFOE final report "Recommendations for the energy-efficient use of adsorption processes from the gas phase", 2021).

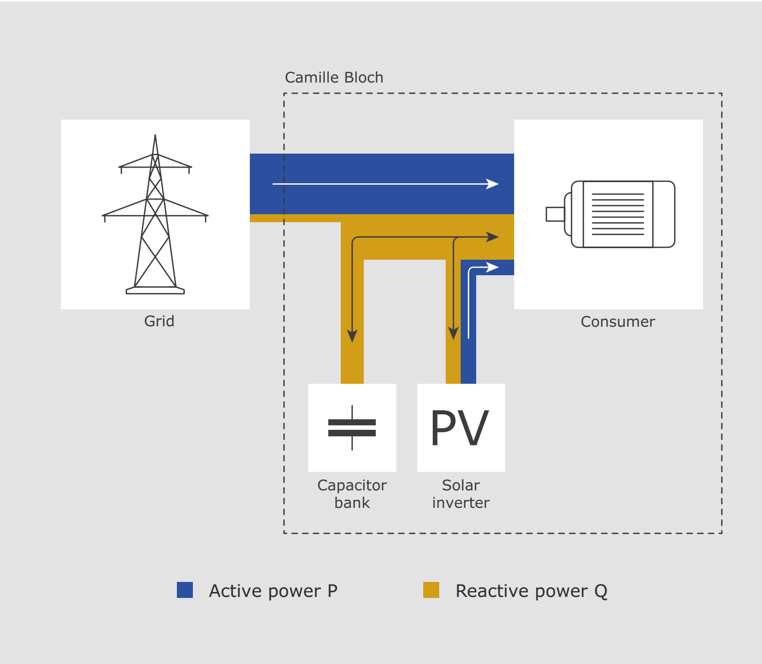
Additional benefits of photovoltaic inverters in industry

Photovoltaic systems in industrial environments are particularly interesting, as a large part of the solar electricity produced can be directly consumed. The inverters used in these systems can also be employed to compensate for reactive power, which is generated by the operation of electric motors, for example. If this compensation takes place before the grid connection point, costs can be reduced because charges for reactive power absorbed by the electricity grid are avoided. This innovative use of photovoltaic inverters was successfully tested at the Camille Bloch chocolate factory in the Bernese Jura.

Electricity consumers in industrial plants such as electric motors require both active and reactive power. Active power (P) corresponds to the part that is used for actual work, while reactive power (Q) cannot be used directly and is generated by inductive and capacitive loads. The purchase of reactive power from the grid is only tolerated by the electricity supplier up to a threshold value; for large amounts of reactive power, it is charged, as this places a greater load on the electrical grid. In industry, systems to avoid (compensate for) reactive power are therefore frequently installed.

Inductive reactive power is usually compensated in companies by means of capacitor banks. However, newer photovoltaic inverters can also be used for this which convert the direct current from the photovoltaic modules into alternating current for feeding into the grid. In a project supported by the Swiss Federal Office of Energy (SFOE), such reactive power compensation was tested at the Camille Bloch chocolate factory in Courtelary (BE). A photovoltaic system with an output of 260 % is installed on the roof of the factory, covering ten percent of the company's own electricity requirements. As part of the project, the solar inverters were used to compensate for reactive power. Depending on the demand, they compensated reactive power in the amount of up to 200 kvar (kilovolt amperes reactive). The pre-existing reactive power compensation system of capacitors has a capacity of 720 kvar.

Tests have shown that photovoltaic inverters are equally well suited for reactive power compensation as conventional capacitor banks. Photovoltaic inverters can also be activated during off hours of the photovoltaic system, as they can compensate for reactive power independently of the solar power production.



In the case of industrial power consumers such as motors, a phase shift of current and voltage occurs, which puts a strain on the electrical grid. In addition to capacitors, modern photovoltaic inverters can be used to compensate for this reactive power. In a project funded by the Swiss Federal Office of Energy (SFOE), this was successfully demonstrated at Camille Bloch's chocolate factory.

(Top) Photovoltaic installation on the roof of the Camille Bloch chocolate factory in Courtelary. (Below) View into the chocolate factory. Electrically driven machines cause reactive currents, which are conventionally compensated with capacitor banks (source: B. Vogel).

Reliable solar power thanks to reliable irradiation forecasts

Electricity output from photovoltaic systems is subject to fluctuations. In addition to the time of day, the weather is a key factor influencing the electricity yield. Already today, the yield can be predicted with good accuracy over several days. Accurate yield forecasts are becoming increasingly important in order to be able to guarantee a secure electricity supply with increasing expansion of photovoltaics.

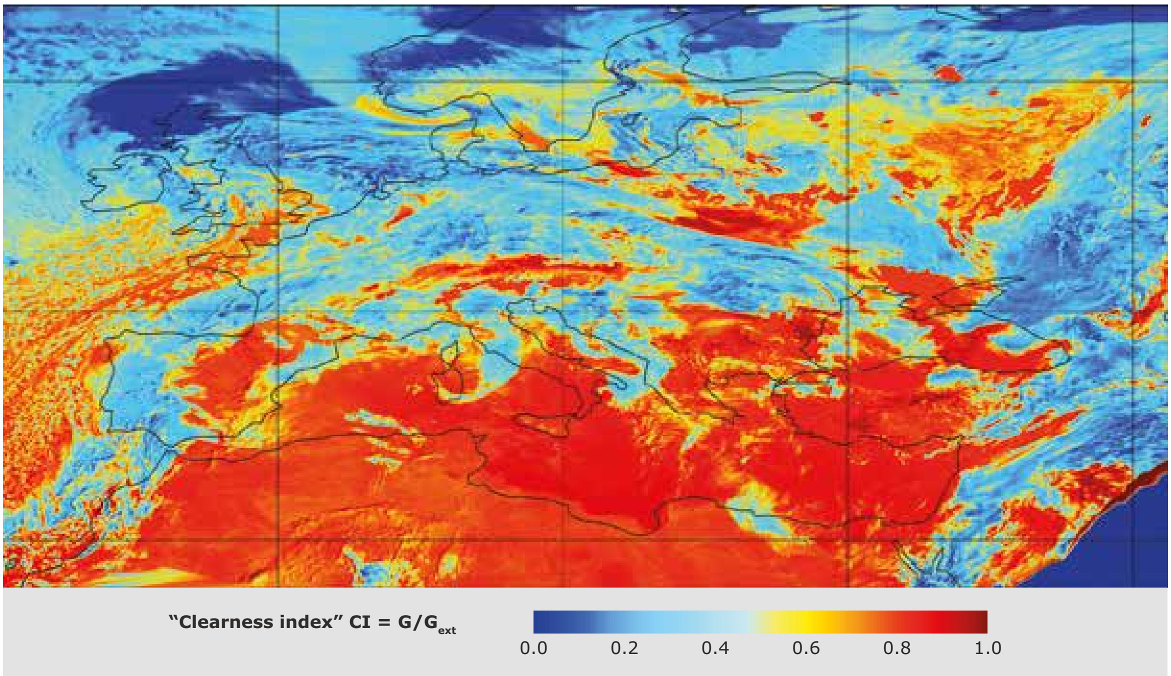
The ideal time to generate solar power is a bright day in spring: the sun is steep in the sky, the atmosphere is free of clouds or haze and the sun's rays hit the earth unhindered. A light breeze cools the photovoltaic modules and thus boosts their efficiency in converting energy. Under such favourable conditions, the sun in the Swiss midlands provides around 1000 watts per square metre. A solar system converts about one fifth of this into electricity.

However, the weather is not always so favourable to solar power generation. With light cloud cover, the yield drops to around half, on a dreary rainy day in November to a tenth. As capricious the weather, as surprisingly high can be the electricity yield, which is achieved for a short time under very special conditions. Very occasionally, situations can arise where the radiation falling on a photovoltaic system is greater than the radiation at the upper edge of the earth's atmosphere, namely when additional radiation is incident on a photovoltaic installation due to reflections – for example from a white thundercloud.

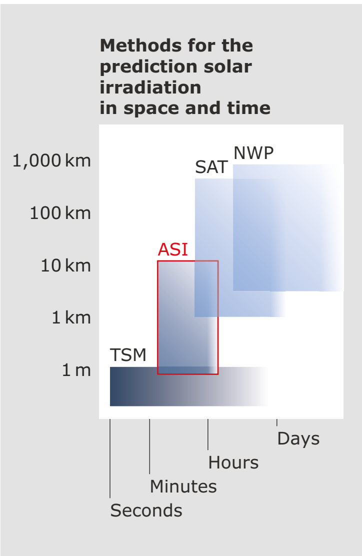
Anyone generating solar power has to be prepared for yields that vary greatly over time. Meteorology cannot influence these fluctuations, but it can predict how yields may develop in the coming hours and days. Yield forecasts provide predictability for the operation of solar plants and simultaneously create the basis for a secure electricity supply. If electrical grid operators know the amount of solar power to be expected thanks to the forecasts, or know how much will have to be purchased from other sources, they can prevent grid problems by taking proactive measures. These include the use of battery storage and the control of heat pumps and other electrical consumers. The national grid company Swissgrid uses forecast data today, as do the large Swiss utilities. Yield forecasts are also important in electricity trading, as they can be used to better estimate price developments on the electricity exchanges.

Solar power yields can already be forecast quite reliably today. For example, the total amount of solar electricity produced in Germany for the following day can be predicted

High air streams can transport dust from the Sahara to Switzerland several times a year. In such weather conditions, the yield of photovoltaic systems can be reduced by up to 10 %. (Image source: Jan Remund)



"Clearness Index" CI over Europe: CI is defined as the ratio between the global solar irradiance G measured on the ground and the solar irradiance G_{ext} estimated at the top of the atmosphere. The index is used for the prediction of solar irradiance. The image shows a three-hour forecast from the satellite-based nowcast system Cloudmove on 5 February 2021 (source: Meteotest AG).



Different methods for predicting solar radiation, both locally and temporally, are based on statistical models with different input variables. ASI = All sky imagers: Cloud cameras for modelling cloud movements. SAT: Satellite images for modelling cloud movements. NWP = Numerical Weather Prediction: detailed modelling of atmospheric development based on ground, air and satellite data. TSM = time-series models: the prediction is based solely on local measurement data (radiation or electrical power) without physical models (source: according to IEA PVPS Task 16, Solar Resources Handbook, 2021).

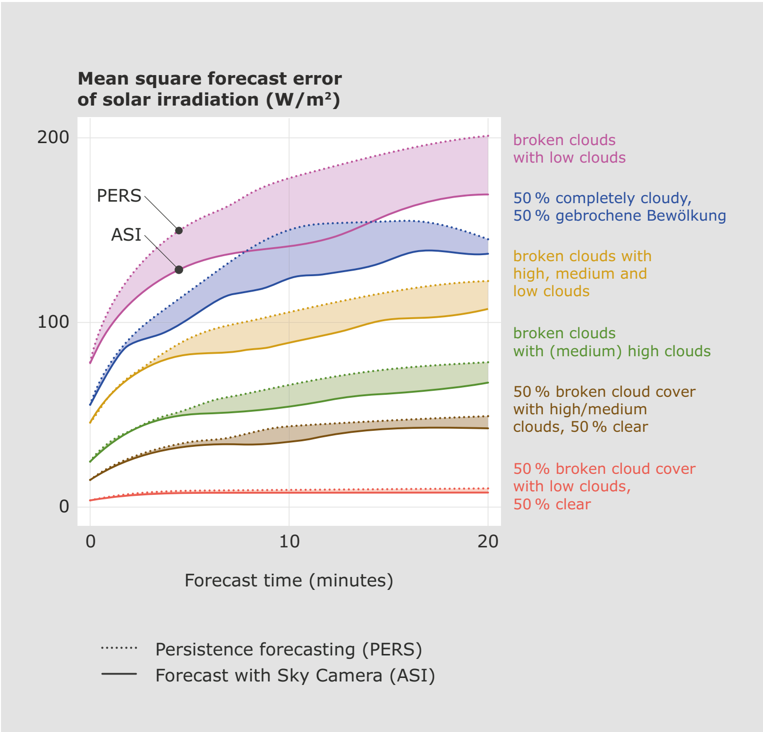
with an accuracy of around 5 % on an hourly average: if, for example, a nationwide solar yield of 20 GWh is predicted for the following day in the period from 11 a.m. to 12 p.m., the actual yield is in the range between 19 and 21 GWh. Such a forecast refers to the whole country, for a single solar plant the forecast accuracy is much less accurate. Compared to its northern neighbour, the forecast errors in Switzerland tend to be more significant, due to the smaller area of the country and the diverse topography.

In 2017, an expert group called "Solar Resource for High Penetration and Large Scale Applications" was formed under the umbrella of the International Energy Agency (IEA) with experts from 21 countries, with the aim of improving the reliability of weather forecasts for applications of photovoltaics and concentrating solar power plants. A recently completed project of this expert group examined the quality of irradiation forecasts based on cloud cameras ("All Sky Imager" ASI) in a cross-comparison of different systems. This method involves photographing the sky at short intervals and using software to analyse the cloud images in order to derive a solar irradiance forecast from their changes. Such short-term forecasts can be used, for example, in hybrid systems with photovoltaics and diesel generators to automatically throttle the latter if a high solar power production is expected in the near future.

When comparing six different ASI systems – all prototypes – on a test site in Almería, southern Spain, it was shown that meaningful predictions of solar radiation are possible for a period of a few minutes. In all systems, the error in the prediction turned out to be always smaller compared to the persistence prediction ("solar radiation remains the same"). Two of the systems involved in this test were developed in Switzerland, one by the weather service provider Meteotest in collaboration with the Centre Suisse d'Electronique et de

Microtechnique CSEM, the other by the École polytechnique fédérale de Lausanne.

The IEA expert group also deals with forecasts for periods of several days. For this purpose, more detailed numerical weather prediction (NWP) models are used. They model the temporal change of radiation in the Earth's atmosphere on the basis of measurement data from numerous ground-based weather stations, weather balloons and satellites. Recently, different NWP models for estimating regional solar power yields were investigated with applications to a large region in Italy and another region in the Netherlands, each the size of the canton of Zurich. Models using machine learning were compared with so-called analogue forecasts, which derive forecasts from a comparison of the current weather situation with similar situations in the past. Models based on machine learning tend to deliver more accurate forecasts. However, the best forecasts are obtained with a combination of different models.



(Top) SkyCam installation at CSEM Neuchâtel (source: CSEM). (Bottom) Solar radiation prediction models based on cloud images (All Sky Imager ASI) provide temporally and spatially highly resolved short-term forecasts for the next 15-20 minutes. Such forecasts are useful, for example, for detecting steep power ramps in photovoltaic production and the possibility of gently operating battery storage systems, for regulating power grids and for the operational control of hybrid power plants (photovoltaics plus diesel generators, photovoltaics plus pumped storage). The mean square error of the solar irradiance forecast is smaller for ASI models compared to the persistence forecast (PERS: "solar irradiance remains the same") (source: according to IEA PVPS Task 16, Solar Resources Handbook, 2021).

In the Bedretto rock laboratory of ETH Zurich, a drilling rig drives a 22 cm diameter borehole several hundred metres long into the granite of the Gotthard massif. Such boreholes are used to test a new, gentle stimulation method for extracting deep geothermal energy, designed to minimise the risk of unwanted earthquakes during deep drilling. Part of the research project involved very sensitive sound measurements, an area in which ETH Zurich has a great deal of experience. ETH measuring equipment can register vibrations ten million times smaller than a perceptible earthquake (source: Swiss Seismological Service of ETH Zurich, 2019).

Heat from the earth's depths

An almost inexhaustible supply of energy lies dormant beneath our feet: geothermal energy is practically everywhere and is available at all times. It is already being used intensively today with heat pumps from near-surface layers of the earth. Research efforts are needed to safely utilise geothermal energy in deep layers of the earth. The rock laboratory of the Swiss Federal Institute of Technology Zurich (ETH Zurich) in the Bedretto Valley in Ticino is contributing to this research.

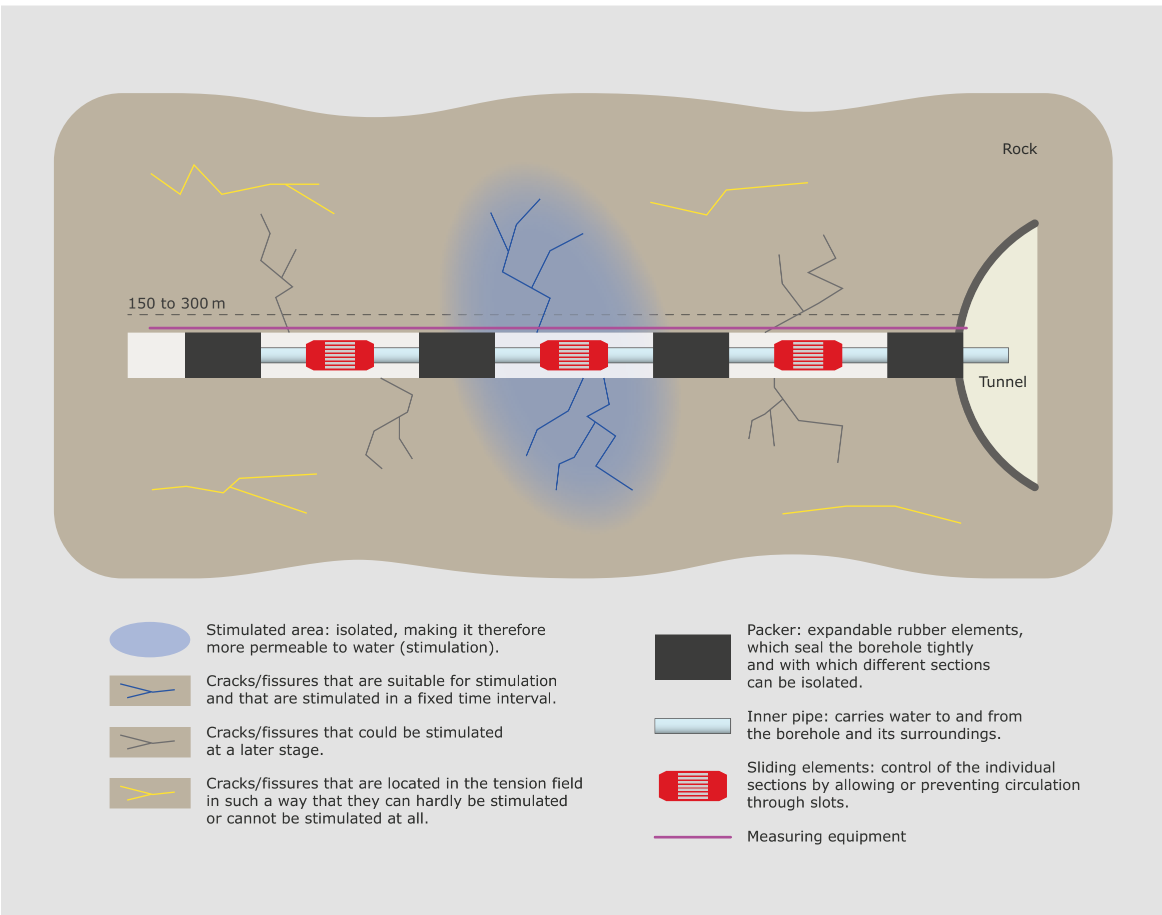
At a depth of five kilometres, the earth's rock is up to 160 °C hot. If this heat can be brought to the surface, it can significantly support the supply of renewable and CO_2-free energy in the form of heating and electricity. In Switzerland, petrothermal geothermal technology is the method of choice. With this method, water is injected into the rock at high pressure through a borehole. The water penetrates existing cracks in the rock and expands them. This so-called stimulation creates cavities in the rock in which the circulating water can absorb the heat from the surrounding rock. The geothermal heat returns to the earth's surface as hot steam through a second borehole and can be used as heat or, if applicable, to generate electricity.

In 2005, several noticeable earthquakes occurred during such a geothermal drilling in Basel and the project had to be abandoned afterwards. To avoid such earthquakes, a gentler stimulation method has since been developed for Switzerland and patented in 2012. With this new method, the entire lower part of the borehole is no longer pressurised with the water injection, as it was the case in Basel at the time. Instead, the borehole is divided into several sections with rubber sleeves. This allows the water to be injected in a spatially and temporally staggered manner. Uncontrolled strong earthquakes should thus be avoided.

In a project supported by the Swiss Federal Office of Energy (SFOE), this was demonstrated in the Bedretto rock laboratory at ETH Zurich with numerous tests. The results show that the process can be used to increase the water permeability of the rock to the extent required for economic heat extraction. At the same time, the risk of earthquakes during deep geothermal drilling can be reduced to a minimum. Although the stimulations in the Bedretto laboratory also led to vibration of the rock, these were about a hundred thousand times weaker than in the strongest quake in the Basel geothermal project.

The research results from the Bedretto rock laboratory form an important basis for a planned geothermal pilot project in Haute-Sorne in the Jura. Over the next few years, a power plant is to be built there in several stages that will extract geothermal energy from a depth of up to 5,000 metres and make use of it directly or, if possible, for electricity generation. A successful implementation of this pilot project would provide a technology that could be used in many areas of Switzerland to develop deep geothermal energy.

“Packer” system in the Bedretto rock laboratory at ETH Zurich, which is being used to test a new method of gentle stimulation for the use of geothermal energy with deep geothermal methods (graphic: SFOE, based on information from ETH Zurich).



Photovoltaic pilot plant at the Agroscope research site in Conthey (VS), where modules with modulable transparency are installed above a raspberry crop, so that the plants growing underneath are shaded to a greater or lesser extent. The solar modules were specially designed for such applications by the Swiss company Insolight (source: Agroscope).

Double harvest with photovoltaics in agriculture

Switzerland is aiming for ambitious targets for the expansion of photovoltaics. In addition to photovoltaic electricity from systems on building roofs and façades, photovoltaic electricity could also be harvested from agricultural areas in the future. Currently, the potential is assessed and the advantages and disadvantages are being investigated. This information will serve as a basis for regulatory adjustments to allow agricultural land to be used for the generation of solar electricity.

By 2050, at least 40 % of Switzerland's electricity demand should be covered by photovoltaics. There is no shortage of space for solar installations. There is still plenty of space on the roofs and facades of buildings, as only a small proportion is covered with photovoltaic modules. In addition, infrastructure areas such as car parks or wastewater treatment plants can also increasingly be used.

If agricultural land is used for solar power production, this is referred to as "agri-photovoltaics" (agri-PV). While berries, vegetables or fruit grow on the ground, photovoltaic modules installed above or next to them generate electricity. Agri-PV exists in various forms. For example, the modules can be installed with sufficient distance above the agricultural land, or they can be placed between the agricultural fields. In the latter case, the modules may also be installed vertically and the solar radiation is captured on both sides in so-called bifacial modules.

Worldwide, solar power generation from agricultural land has become established over the last decade. According to the German Fraunhofer Institute for Solar Energy Systems, agri-PV systems with a total capacity of more than 14 gigawatts are in operation worldwide, which is about five times the installed photovoltaic capacity in Switzerland. Most such plants are located in Asia, including a Chinese agri-PV plant over a berry crop on the edge of the Gobi Desert with a total capacity of 700 megawatts.

Interest in agriculture that harvests solar power alongside fruit and vegetables is also growing in Switzerland. At the test site of the Swiss Competence Centre for Agricultural Research Agroscope in Conthey (VS), a 165 square metre Agri-PV system was built and commissioned as a pilot by the energy company Romande Energie in mid-2021. Photovoltaic modules from the Swiss company Insolight are integrated into this plant, which is installed above a raspberry plantation. These modules were specially developed for such an application and their tansparency can be dynamically adjusted between 30 and 80 %. This allows the plants growing underneath to be shaded to a greater or lesser extent and the sunlight can be used either more for crop growth or more for electricity generation. These Agri-PV system replaces conventional foil tunnels that are commonly used to protect berry crops.

Agri-PV is also the subject of a project by the Zurich University of Applied Sciences. It examines agronomic, area planning, legal and technological aspects. According to a provisional estimate, there is an Agri-PV potential of 10 to 18 GWh per year in Switzerland. In addition to electricity generation, environmental reasons are also cited in favour of Agri-PV. The more the consequences of climate change become apparent in the form of extreme heat or heavy rainfall, the more Agri-PV systems could play out their advantages, for example by reducing the need for irrigation through shading by solar modules. Biodiversity and resource conservation in agriculture can also be improved through agri-PV, because fewer agrochemicals are used and nutrient losses through nitrate leaching are reduced.

Photovoltaic systems may exploit agricultural land for electricity generation in various forms, (1) vertically mounted with bifacial modules that harness sunlight from both the front and the back, (2) protective element for vulnerable crops, or (3) integrated into greenhouses.

International cooperation

Switzerland attaches a great deal of importance to international cooperation in the field of energy research. At the institutional level, the SFOE coordinates its research programmes with international activities in order to utilise synergies and avoid redundancies. Cooperation and exchanges of experience within the framework of the International Energy Agency (IEA) are of particular importance to Switzerland. Here, for example, the SFOE participates in various IEA "Technology Collaboration Programmes" (formerly called "Implementing Agreements, cf. https:// www.iea.org/tcp), see list on following page.

At the European level, wherever possible Switzerland actively participates in EU research programmes. Here, at the institutional level the SFOE coordinates its energy research in alignment with the European Strategic Energy Technology (SET) Plan, the European Research Area Networks (ERANET), the European technology platforms, joint technology initiatives, etc. Beyond that, intensive multilateral cooperation with selected countries also exists in certain fields (smart grids, geothermal energy, hydrogen etc.).

The next two pages present two examples of projects where Swiss actors have worked closely with European partners within the framework of ERA-NET projects, one in the field of CO_2 capture, utilisation and storage (CCUS) and one in the field of photovoltaics

Green roofs with simultaneous use for photovoltaics lead to a conflicting objectives. An interdisciplinary pilot project in Winterthur, funded by the Swiss Federal Office of Energy, is addressing this issue by using vertically mounted photovoltaic modules and special substrate layers to study biodiversity and water retention potential in detail (image source: ZHAW).

Participation in technology cooperation programmes of the IEA

Energy Conservation through Energy Storage (iea-eces.org)

Energy Efficient End-Use Equipment (iea-4e.org)

User-Centred Energy Systems (userstcp.org)

High-Temperature Super Conductivity

Clean and Efficient Combustion (ieacombustion.com)

Hybrid & Electric Vehicles Technologies (ieahev.org)

Geothermal (iea-gia.org)

Hydropower (ieahydro.org)

Solar Heating and Cooling (iea-shc.org)

Wind (community.ieawind.org)

Gas and Oil Technologies (gotcp.net)

Energy in Buildings and Communities (iea-ebc.org)

Heat Pumping Technologies (heatpumpingtechnologies.org)

International Smart Grid Action Network (iea-isgan.org)

Advanced Fuel Cells (ieafuelcell.com)

Advanced Motor Fuels (iea-amf.org)

Bioenergy (ieabioenergy.com)

Hydrogen (ieahydrogen.org)

Photovoltaic Power Systems Programme (iea-pvps.org)

Solar Power and Chemical Energy Systems (solarpaces.org)

Greenhouse Gas (ieaghg.org)

Energy Technology Systems Analysis Program (iea-etsap.org)

Participation in ERA-NETs – European Research Area Networks

Bioenergy (eranetbioenergy.net)

Smart Cities and Communities (jpi-urbaneurope.eu/calls/enscc)

Concentrated Solar Power (csp-eranet.eu)

Smart Energy Systems (eranet-smartenergysystems.eu)

Solar (Cofund1 & Cofund2) (solar-era.net)

Accelerating CCS Technologies (act-ccs.eu)

Geothermica (geothermica.eu)

Materials (https://m-era.net/)

Further international cooperation

International Partnership for Hydrogen and Fuel Cells in the Economy

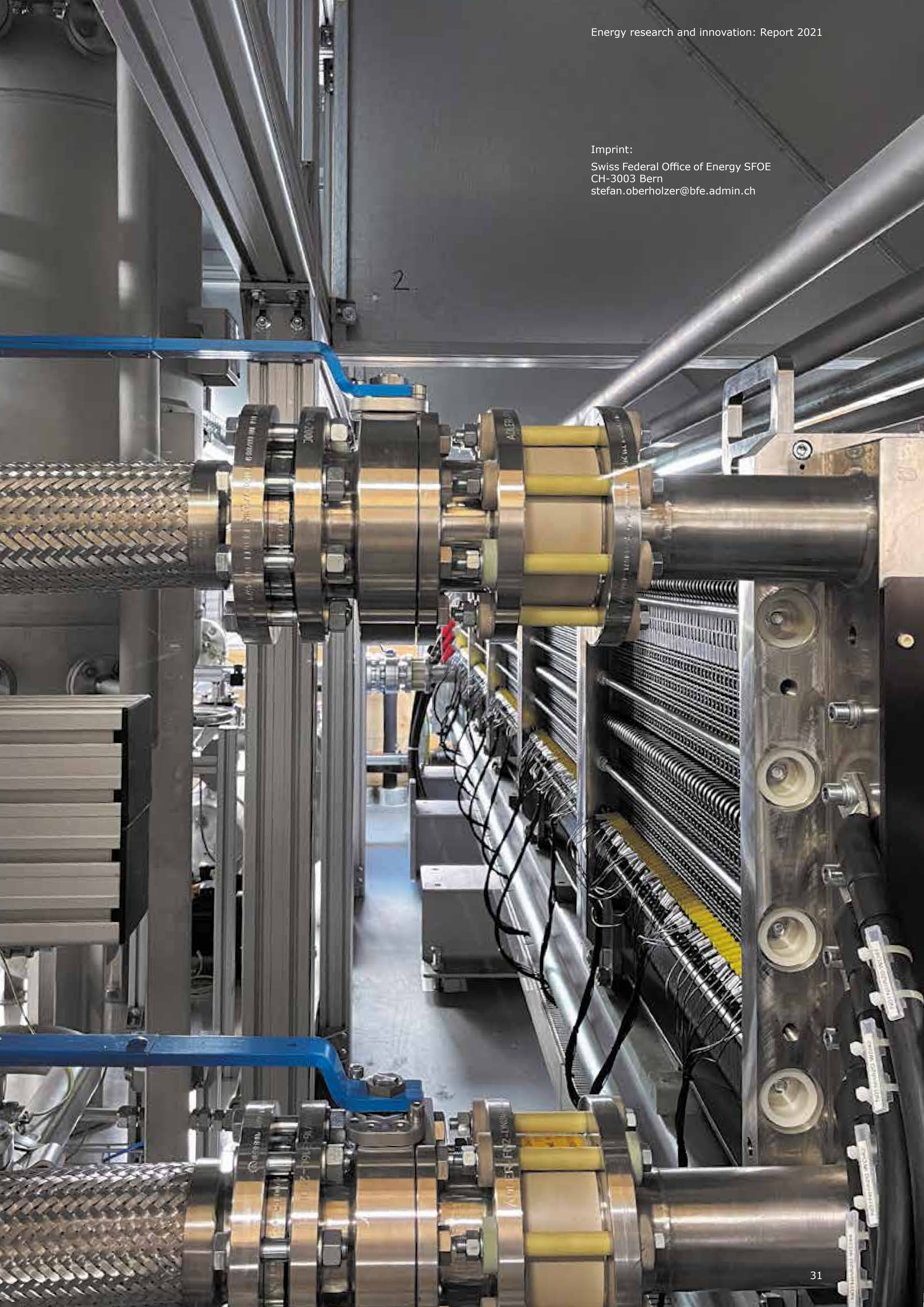
DACH-Kooperation Smart cities and communities

International Partnership for Geothermal Technology

Fuel Cells and Hydrogen Joint Undertaking

DACH-Kooperation Smart grids

(right) The company Limeco, which is active in the field of waste recycling and wastewater treatment, operates a power-to-gas plant with continuous methanation (powertogas.ch) at its site in Dietikon, which is unique on this scale in Switzerland. The plant was co-initiated by Swisspower AG and is supported by various Swiss municipal utilities. Electricity from the waste recycling plant is used to produce hydrogen, which is methanised with CO_2 from the sewage gas of a wastewater treatment plant in a biological reactor and fed into the natural gas grid. Shown is one of the two electrolysis units, a Proton Exchange Membrane (PEM) electrolyser from Siemens (SILYZER 200) with a nominal power of 1.25 MW and a hydrogen output pressure of 35 bar (photo source: S. Oberholzer).



Imprint:
Swiss Federal Office of Energy SFOE
CH-3003 Bern
stefan.oberholzer@bfe.admin.ch

Swiss Federal Office of Energy SFOE
CH-3003 Bern

www.energy-research.ch