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Swiss Federal Office of Energy SFOE

Energy research and innovation
Report 2019

Editorial

Switzerland's future energy supply and the challenges of climate change are among the most important topics in Swiss day-to-day politics. Energy research has an important role to play in analysing the increasingly complex energy system with its various interactions between a wide range of actors and different energy sectors (keyword sector coupling) and to find and develop technological solutions.

In recent years, a substantial amount of structural effort has been invested in this area, particularly with the various Swiss Competence Centres for Energy Research (SCCERs), which will end after eight years in 2020. The "SWEET" support programme initiated by the Swiss Federal Office of Energy SFOE is expected to make a decisive contribution to ensure the built-up research capacities are now specifically aligned with the energy strategy. In general, the SFOE has played a central role throughout Switzerland for several decades with its programmatic research and technology promotion.

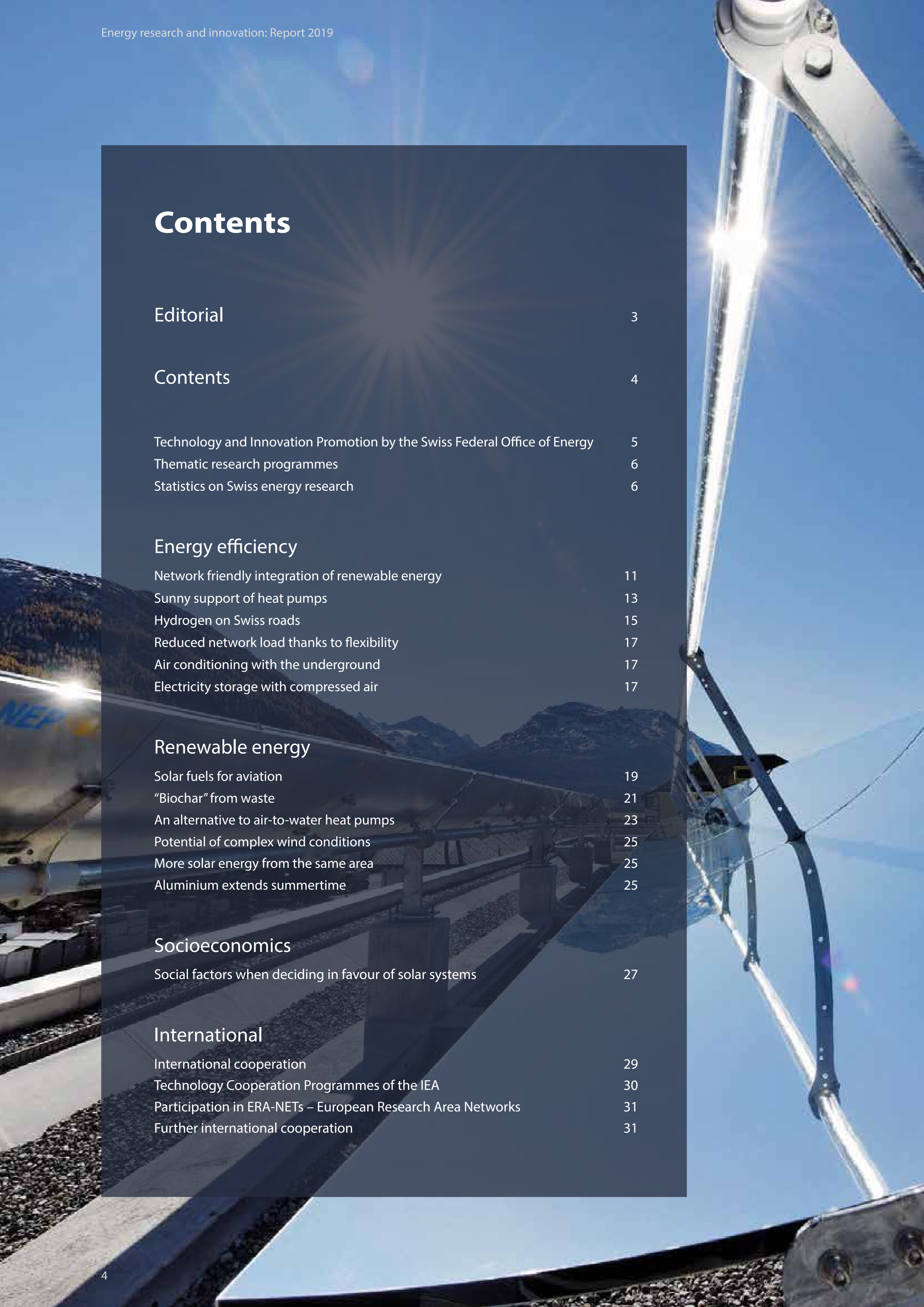
This brochure contains a number of examples of projects supported and in many cases closely monitored by the SFOE, representing a large number of research, pilot and demonstration projects. The given QR codes lead to detailed information (e.g. final reports). In this issue, special attention has been paid to the topic of "heat", by highlighting several innovative projects on the use of heat pumps.

Swiss Federal Office of Energy SFOE
Section Energy research and Cleantech

(Cover picture) Floating photovoltaic system on the water reservoir "Lac des Toules" at 1810 m above sea level, installed in 2019. Thanks to the use of bifacial modules with a high albedo in winter and due to higher irradiation in the alpine environment, energy production is expected to be up to 50 % higher compared to a similar system in the Central Plateau. The challenges lie in the extreme climatic conditions (snow, ice, strong winds, temperature fluctuations) and the seasonal fluctuations in water levels (0 to 50 m) (source: Romande Energie, www.solaireflottant-lestoules.ch).

(Left) Run-of-river power plant of the energy utility Alpiq in Gösgen. The company Hydrospider is commissioning a 2-MW electrolysis plant on this site, which produces up to 300 tonnes of renewable hydrogen per year and is capable of supplying 40 to 50 fuel cell trucks. Significant experience has been gained in a pilot project in Aarau over several years (see article: "Hydrogen on Swiss roads", page 15) (picture source: Alpiq/Patrick Lüthy, Imagopress).

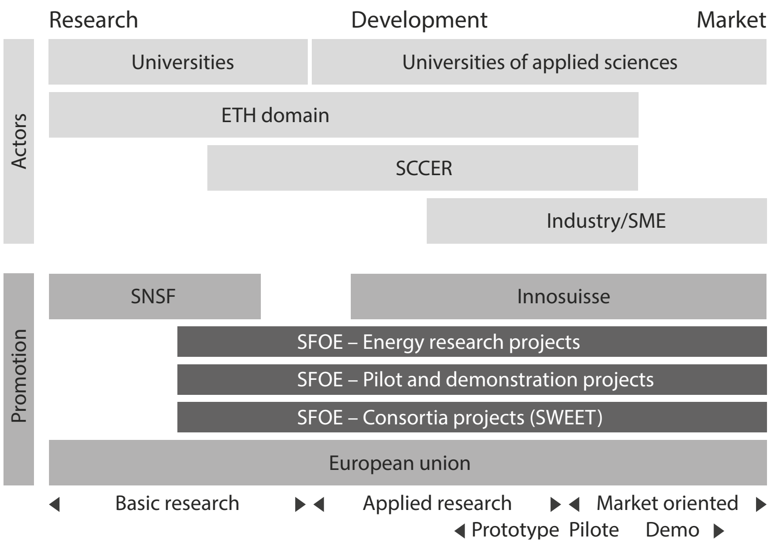
(Next page) Close-up of a concentrating solar collector from NEP Solar in the solar process heat plant at Lataria Engiadinaisa SA in Bever operated by ewz. The 115 m² installation has been in operation since 2011 and is being monitored by the Institute for Solar Technology SPF at the University of Applied Sciences Rapperswil (source: ewz).



Contents

Technology and Innovation Promotion by the Swiss Federal Office of Energy

With the landmark decision in favour of a gradual transformation of the Swiss energy system up to 2050, taken by the Federal Council and Parliament in 2011 and supported by the Swiss people, energy research by the Confederation is gaining in importance. The Swiss Federal Office of Energy (SFOE) covers the entire spectrum of energy research in the fields of energy efficiency and renewable energy with its own programmes, based on the "Concept of federal energy research" worked out by the Swiss Federal Energy Research Commission CORE. Thanks to a programmatic funding approach and its coordinating role, the SFOE acts as a central hub in the Swiss energy research landscape.



The Swiss Federal Office of Energy (SFOE) coordinates research and innovation in the energy sector along a large part of the value chain. (Innosuisse = Swiss Innovation Agency; SNSF = Swiss National Science Foundation).

Switzerland's energy and climate policy faces major challenges. In order to achieve the goals set out in the Federal Council's Energy Strategy 2050, the growth of renewable energy must be pushed forward and energy efficiency in buildings, industry, transport and electrical installations significantly increased. Progress in research and technology development for achieving these goals by 2050 will also be necessary. Therefore, completely new ways of thinking, new approaches and new technologies are asked for. However, leaving the well-trodden paths in particular calls for a strategy of promotion that does not primarily equate the franc invested in research with the kilowatt hour that is directly saved. Research needs a free space that allows fundamentally new ideas to be taken up and tried out.

The SFOE's funding, with its various instruments, makes this possible by supporting implementation-oriented research as well as application-oriented basic research and pilot and demonstration projects. The SFOE is the only funding agency in the public sector that supports research topics in the energy sector via national programmes, even over longer periods of ten or more years. With its new funding programme SWEET ("Swiss energy research for the energy transition"), the SFOE also enables long-term consortia projects on selected topics and provides funding for research on disruptive technologies.

National and international and cooperation strengthens the effectivity of the resources used and enables an optimal exchange of knowledge between researchers. The national and international networking of Swiss researchers constitutes therefore one of the main tasks of the SFOE's promotion, along with the active support of economically risky research projects and the closing of gaps in the innovation chain.

Thematic research programmes

With its thematically oriented research programmes, which are closely linked to the SFOE's other funding instruments (programme for pilot and demonstration projects and the new SWEET programme), the SFOE spans the entire spectrum of energy research in the fields of energy efficiency and renewable energy. The individual programmes are oriented along the axes of energy efficiency, renewable energy, humanities and social sciences, storage and grids. Central themes such as "digitisation", "sector coupling" and "energy storage" are dealt with in cross-programme cooperation.

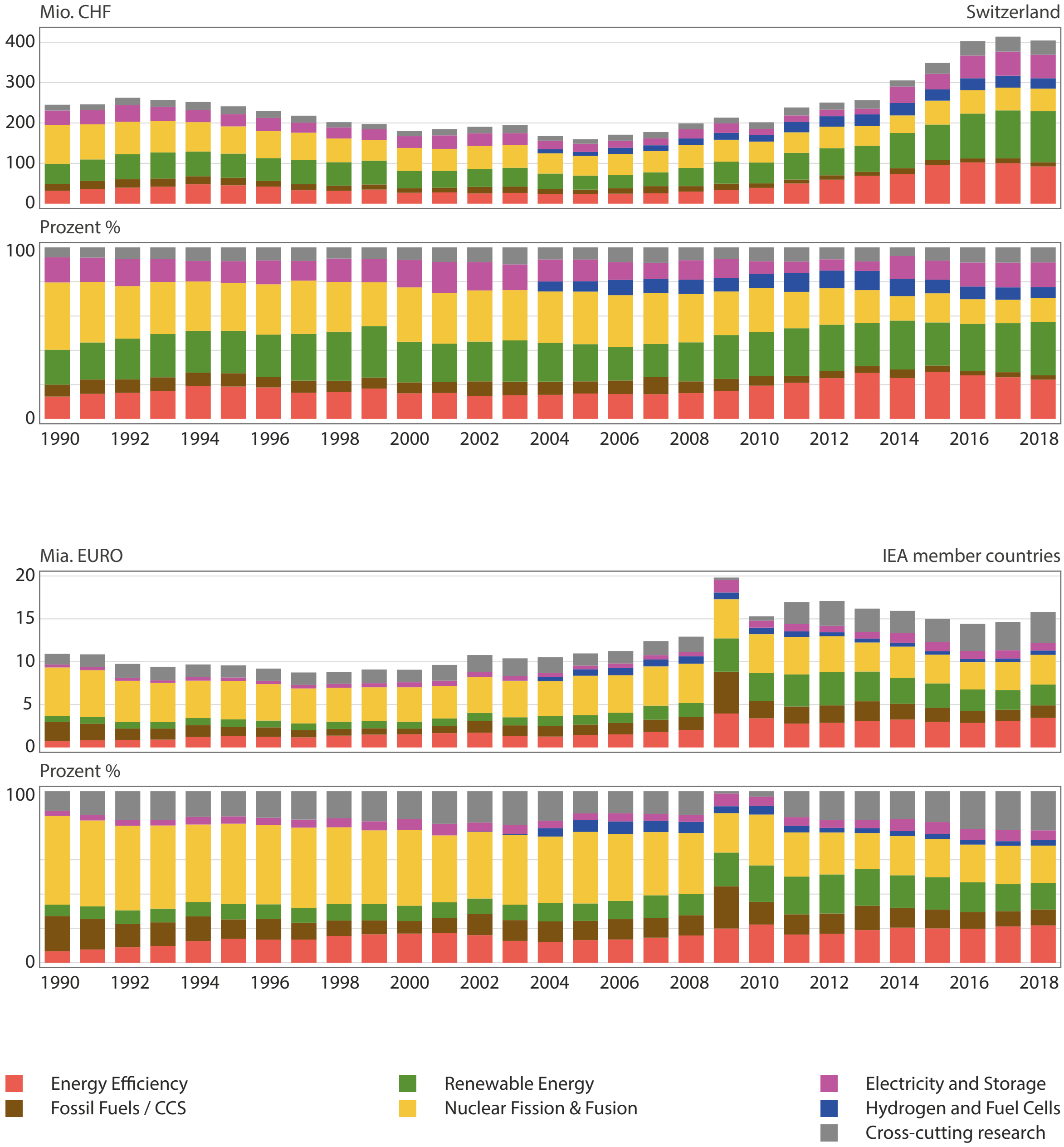
Research programmes in the field of energy efficiency:		
Buildings and Cities (3–8)	Mobility (4–8)	Industrial Processes (3–8)
Grids (3–8)	Electricity Technologies (3–8)	Combustion based Energy Systems (3–8)
Fuel cells (2–8)	Batteries (2–8)	Heat Pumps and Refrigeration (4–8)
Research programmes in the field of renewable energy:		
Solar Heat and Heat Storage (4–8)	Photovoltaics (3–8)	Solar energy at high temperature (CSP) (3–8)
Hydrogen (2–8)	Bioenergy (3–8)	Hydropower (4–8)
Geoenergy (3–8)	Wind Energy (4–8)	Dams (3–8)
Research programmes in the humanities and social sciences / cross-cutting issues:		
Energy–Economy–Society	Radioactive Waste	

Overview of the SFOE's thematic research programmes. The area of technological maturity covered by the programme is indicated in brackets. Further information: "Federal government energy research concept 2017–2020", CORE (2016) and "Energy research concept of the Swiss Federal Office of Energy 2017–2020", SFOE (2016).

Statistics on Swiss energy research

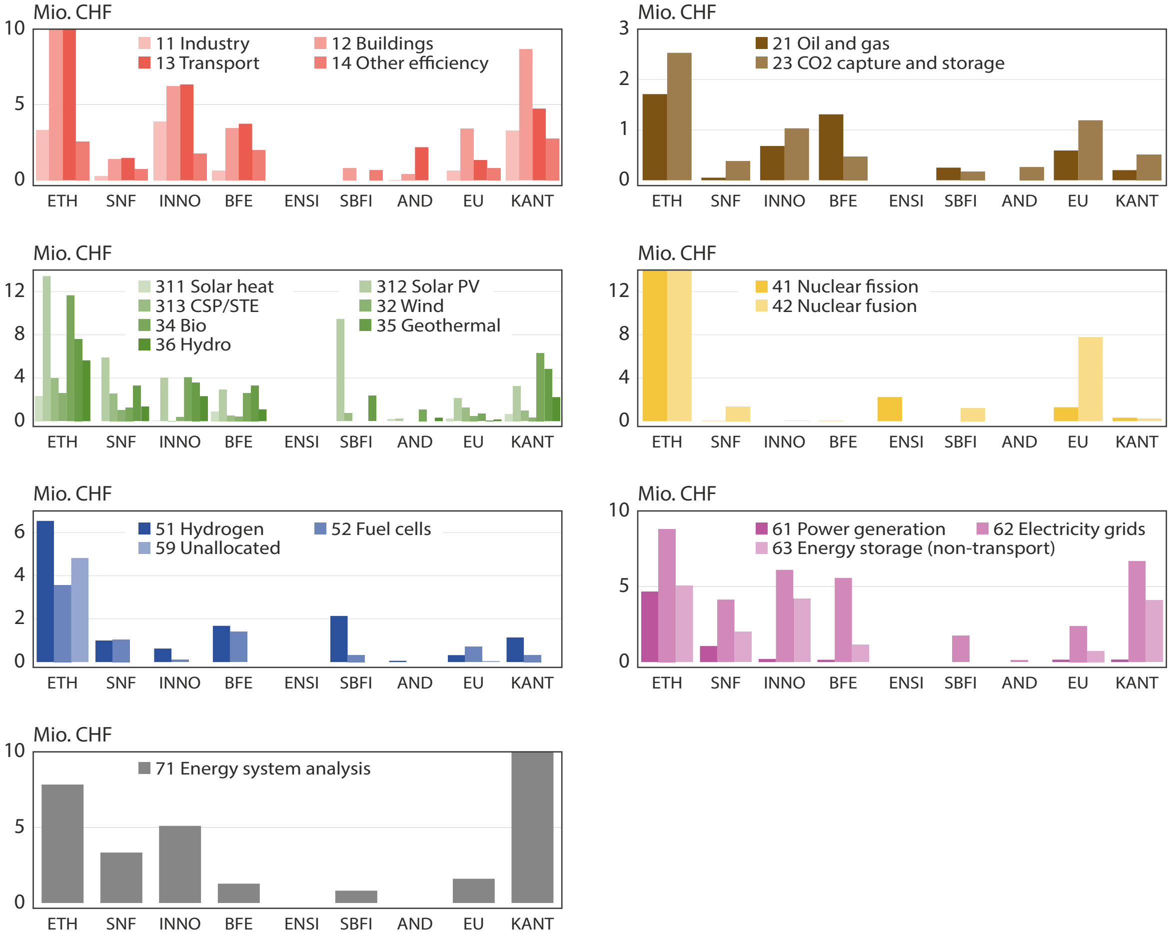
Since 1977, the SFOE has been collecting data for projects funded in whole or in part by the public sector (Confederation and cantons), the Swiss National Science Foundation (SNSF), Innosuisse or the European Union (EU). The survey is carried out by querying databases of the Confederation, the Swiss National Science Foundation (SNSF) and the EU, analysing annual and business reports, and by means of a self-declaration by those responsible for research at the research institutions. Information on individual research projects can be obtained from the publicly accessible information system of the federal government (www.aramis.admin.ch), the SNSF (p3.snf.ch), the EU (cordis.europa.eu) and the respective websites of the institutions.

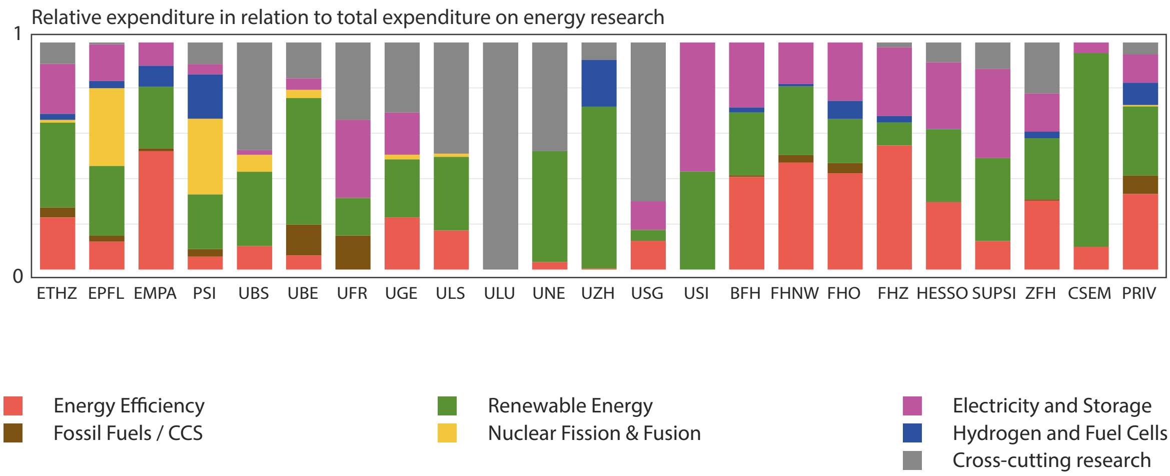
The chart on the right shows the public sector expenditure on energy research in Switzerland and in the member countries of the International Energy Agency (IEA) since 1990 (in million Swiss francs, corrected for inflation or in billion Euros), broken down according to the classification o fthe International Energy Agency (IEA).



Long-term overview of the public funds spent on energy research in Switzerland and in the member countries of the International Energy Agency IEA. Real values (corrected for inflation) are shown, which for Switzerland range between 0.3 and 0.65 per thousand of gross domestic product. Funds are broken down according to the classification of the IEA.

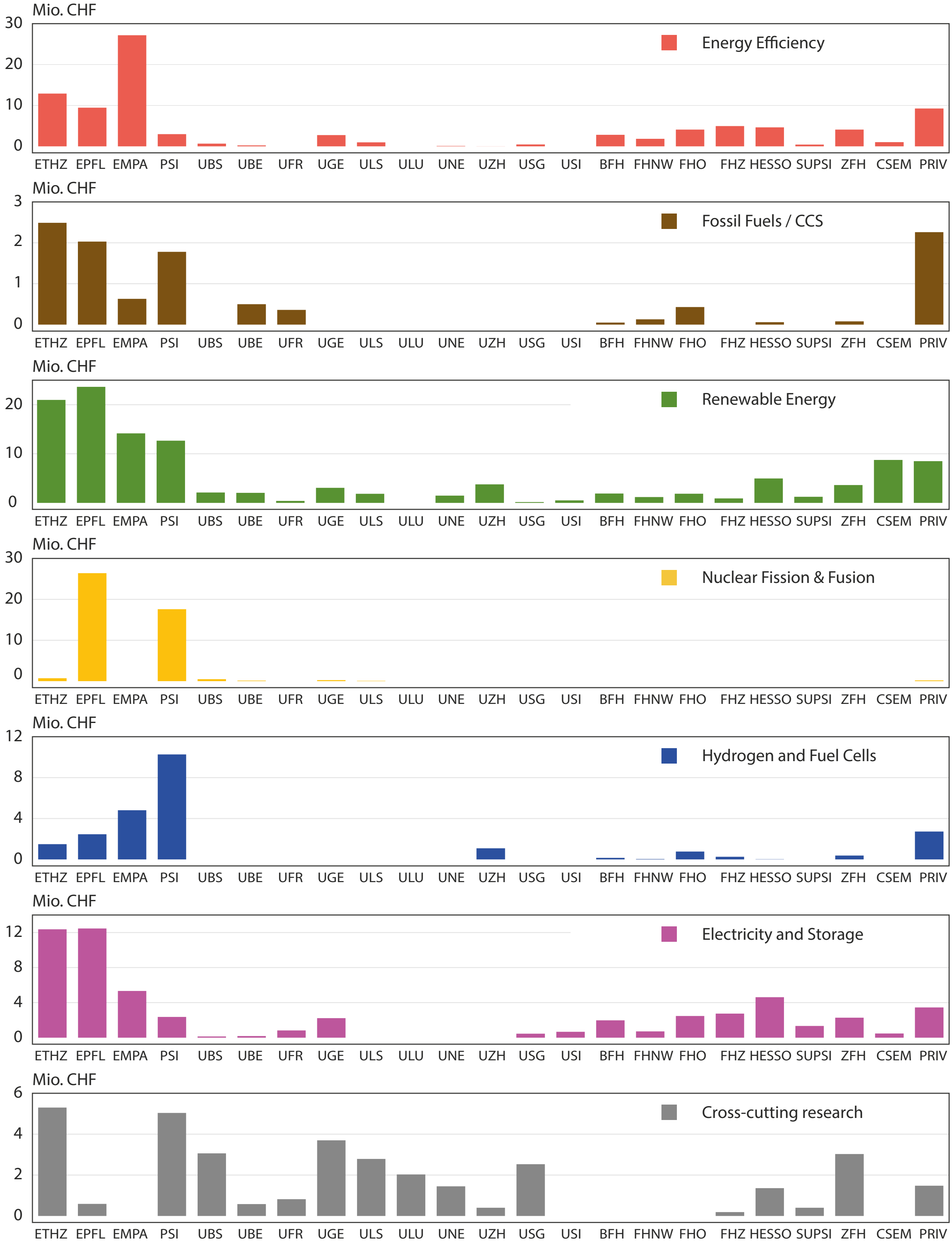
In 2018, the public sector has spent CHF 404 million on energy research. The ETH Domain contributed the largest share of this, 39 % (see chart on next page). Together with the Swiss National Science Foundation, the SFOE was the third largest research sponsor after Innosuisse (13 %) with a share of 9 and 8 % respectively. Of the CHF 35.3 million spent by the SFOE in 2018, around CHF 18.5 million went into energy efficiency projects, around CHF 16.9 million into renewable energy projects and around CHF 2 million into projects in the area of social sciences.





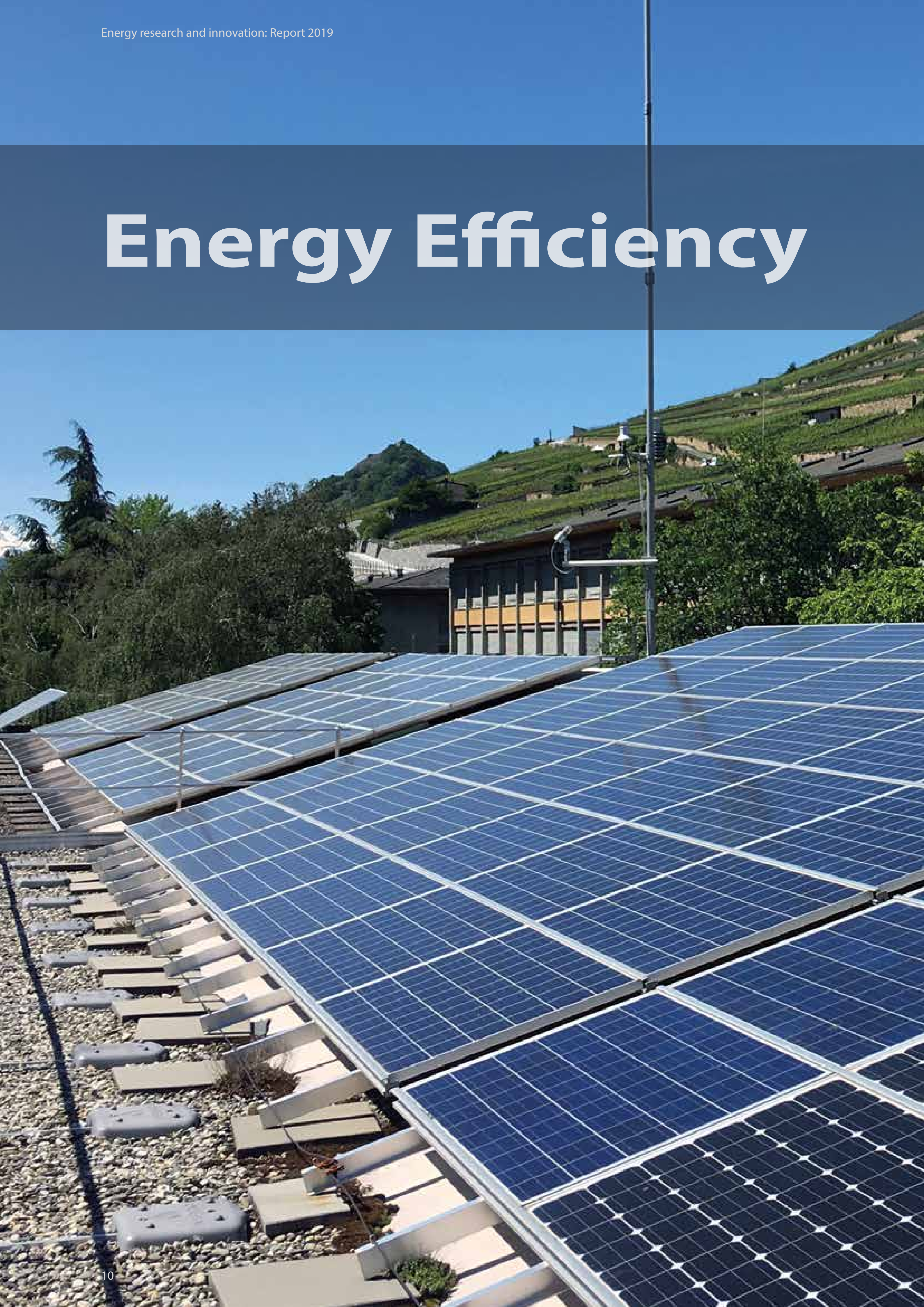
(Top) Origin of public funding in 2018, broken down by research areas according to the classification of the International Energy Agency IEA (in million Swiss francs, not corrected for inflation). ETH = ETH Domain, SNF = Swiss National Science Foundation, INNO = Innosuisse, BFE = Swiss Federal Office of Energy, ENSI = Swiss Federal Nuclear Safety Inspectorate, SBFI = State Secretariat for Education, Research and Innovation, AND = Other, EU = European Union, KANT = Cantons.

(Bottom) Relative expenditure in 2018 for energy research activities at Swiss universities (see legend in the figure on the next page) according to the IEA classification.



Expenditure in 2018 for energy research activities at various Swiss universities: ETHZ = ETH Zurich, EPFL = EPF Lausanne, EMPA = Swiss Federal Laboratories for Materials Testing and Research, PSI = Paul Scherrer Institute, UBS = University of Basel, UBE = University of Bern, UFR = University of Fribourg, UGE = University of Geneva, ULS = University of Lausanne, ULU = University of Lucerne, UNE = University of Neuchâtel, UZH = University of Zurich, USG = University of St. Gallen, USI = University of Italian Switzerland, BFH = Berne University of Applied Sciences, FHNW = University of Applied Sciences Northwestern Switzerland, FHO = University of Applied Sciences Eastern Switzerland, FHZ = University of Applied Sciences Central Switzerland, HESSO = University of Applied Sciences Western Switzerland, SUPSI = University of Applied Sciences Italian-speaking Switzerland, ZFH = Zurich University of Applied Sciences, CSEM: Centre Suisse d'Electronique et de Microtechnique, PRIV = Private Sector.

Energy Efficiency



Network friendly integration of renewable energy

As local power networks, microgrids can serve to support the distribution grid by balancing fluctuating renewable energy generation. The efficiency within a microgrid could be increased if conversions between direct current (DC) and alternating current (AC) can be waived. In Switzerland, various projects on this topic are underway, partly also in European cooperation, where the necessary technologies are being developed and tested.

Microgrids are self-contained electricity networks with energy generators, storage modules and consumers (see chart on the next page). They can be structured as local island networks or as autonomous networks. With the increasing production of electricity from renewable energy, microgrids are gaining in importance: Instead of feeding locally produced solar electricity into the public grid it is directly consumed or stored locally. In this way transmission and distribution networks are less affected by fluctuations in generation and renewable energy up to a share of 50 % of total annual energy consumption could be integrated without expanding the power grid.

Photovoltaic modules generate direct current, usually converted into alternating current and locally consumed or fed into the public power grid. Especially in the industrial sector, many DC loads such as motors or LED lighting are installed. So why convert solar energy first into alternating current before re-rectifying again? Every conversion results in losses and pure DC micro grids are therefore attracting growing interest.

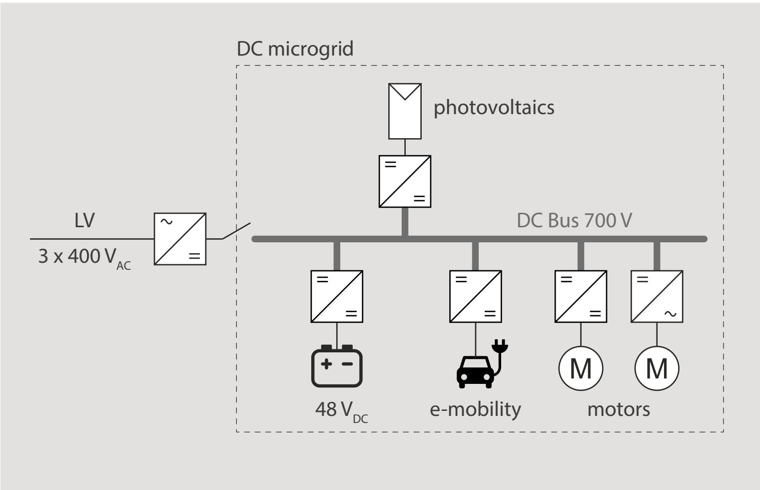
So far, the technology of direct current transmission has been little used in Switzerland and there are hardly any standard systems available on the market. This is what researchers from the University of Applied Sciences of Western Switzerland (HES-SO Valais Valais) intend to change: as early as 2015, a semi-autonomous DC microgrid was set up as a demonstrator. Since that time, the system has been continuously expanded and newly developed components, control algorithms and communication interfaces have been implemented. Today, this demonstrator offers all necessary functions for a wide range of applications in an industrial environment and allows further new developments and components to be tested.

In the European project "DCSMART" direct current technologies are developed for use in so-called intelligent networks (smart grids). Swiss

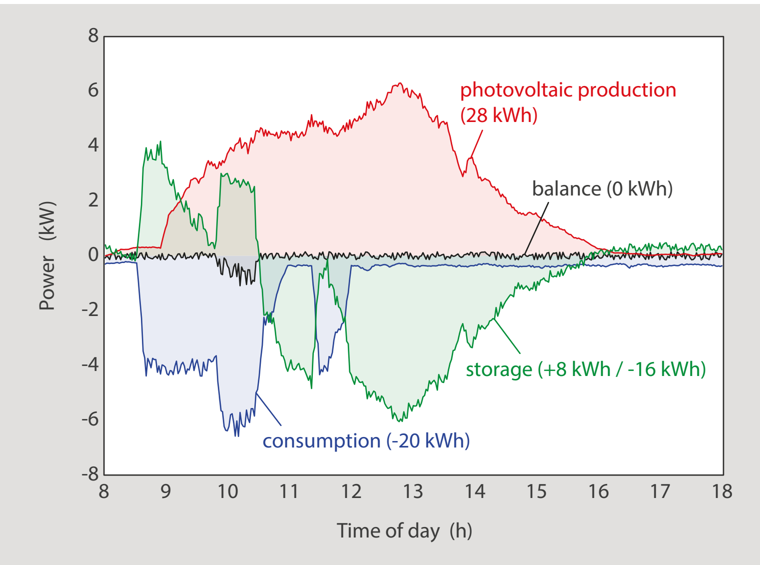
At the University of Applied Sciences of Western Switzerland in Valais (HES-SO Valais Wallis), a fully functional microgrid is being demonstrated, where components for electricity generation, storage and consumption are integrated. These components are coupled via an innovative intermediate circuit (bus) based on 700 V DC voltage. The peak power of 20 kW generated by photovoltaics is dimensioned to a level relevant for industrial applications (Source: Christoph Ellert, HES-SO Valais Wallis).

researchers are partners in this project and are focusing on the integration of photovoltaics, battery storage and industrial motors. As part of a related Swiss pilot project, researchers from the Centre Suisse d'Electronique et de Microtechnique (CSEM) built a small DC microgrid at the Neuchâtel wastewater treatment plant, an interesting location since many processes with high energy consumption are linked together electricity is generated locally. In test operation, the microgrid in Neuchâtel provided revealing data and demonstrated the ability to increase local consumption and smooth generation peaks.

DC/DC converter for individual photovoltaic modules on the roof of the HES-SO Valais Wallis. Each of the 45 modules is connected to the DC bus via its own converter with integrated maximum power point tracker. The efficiency of the individual converters is 97 to 98 % (source: HES-SO Valais Wallis).



Low-voltage electrical distribution systems typically function with alternating current (AC) technology. Systems based on direct current (DC) with voltages between 300 and 750 V are particularly interesting for industrial applications. A DC bus is connected to the local AC distribution network with a single front-end unit. By eliminating additional AC/DC conversions between DC sources (photovoltaic) and DC loads (variable speed drives for motors, pumps, compressors) or storage (batteries, electrolysis), efficiency is increased (graph according to HES-SO Valais Wallis).

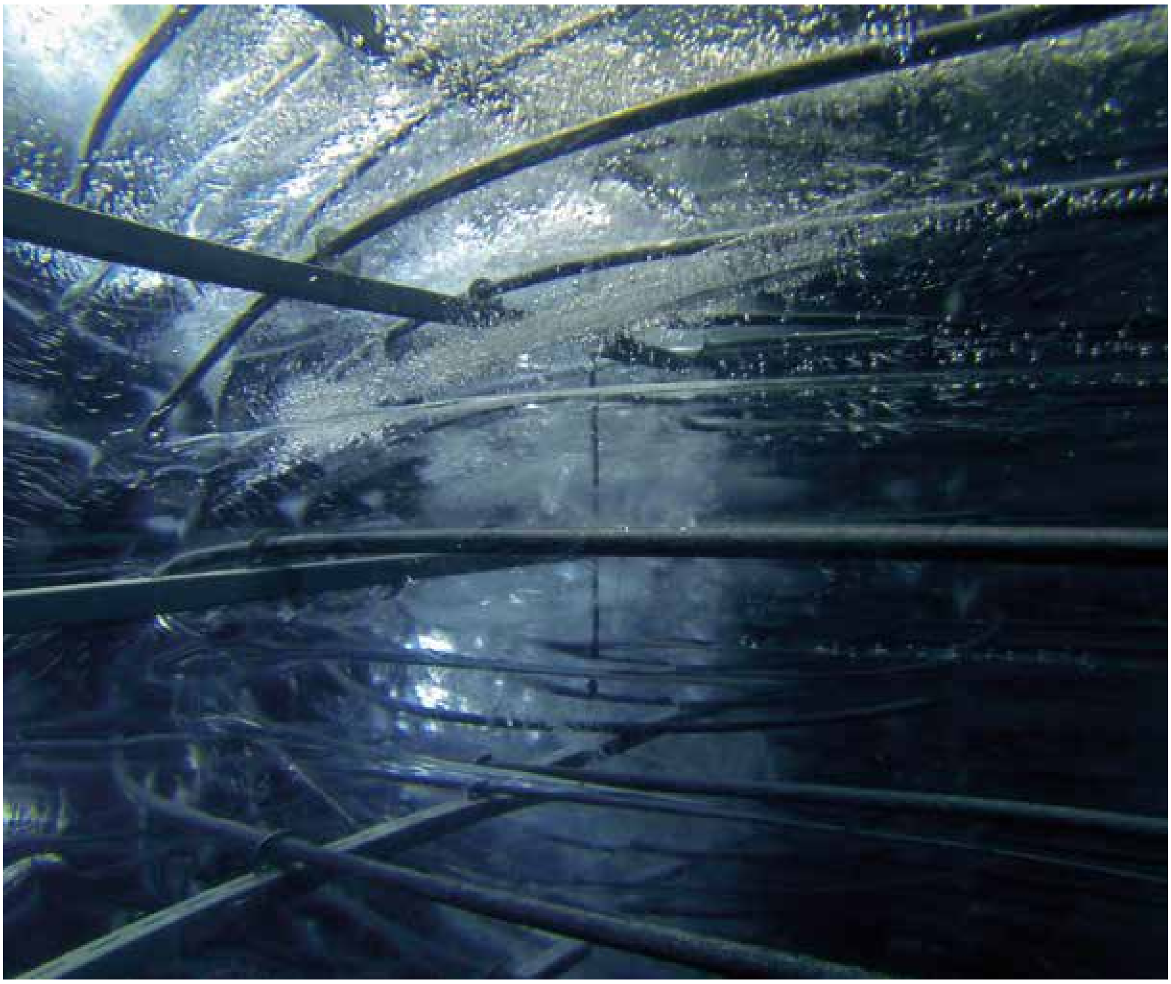


A project at the University of Applied Sciences in Sion (HES-SO Valais Wallis) demonstrates the technical and economic advantages of a DC microgrid on an industrial scale. Meteorological and consumption forecasts allow a smoothing of the performance profile. The example on the left shows the performance of the control algorithm for a complete smoothing of the DC/AC balance despite strongly fluctuating PV power generation. The kWh-numbers in brackets indicate the integrated power over the day (graph based on data from HES-SO Valais Wallis).

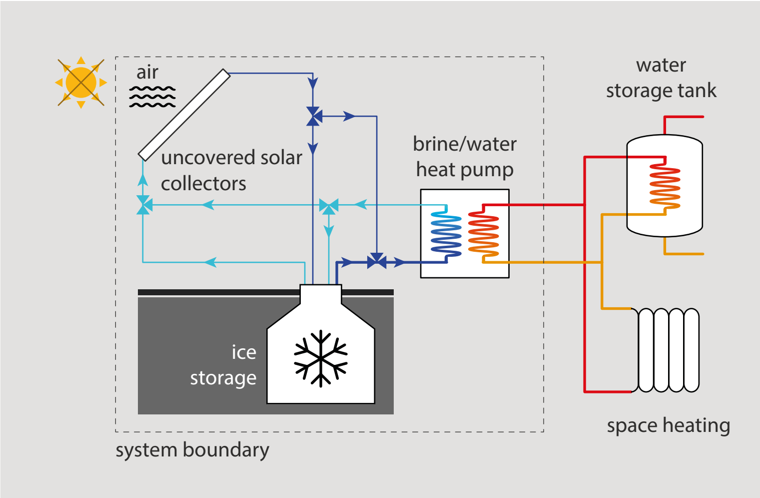
Sunny support of heat pumps

The decarbonisation of heat is a central concern of the Swiss Energy Strategy 2050. For this purpose heat pumps, already standard in new buildings today, offer great potential. How can they be operated efficiently and supplemented with solar energy? The University of Applied Sciences in Northwestern Switzerland has investigated various approaches to heat pumps that operate without geothermal probes.

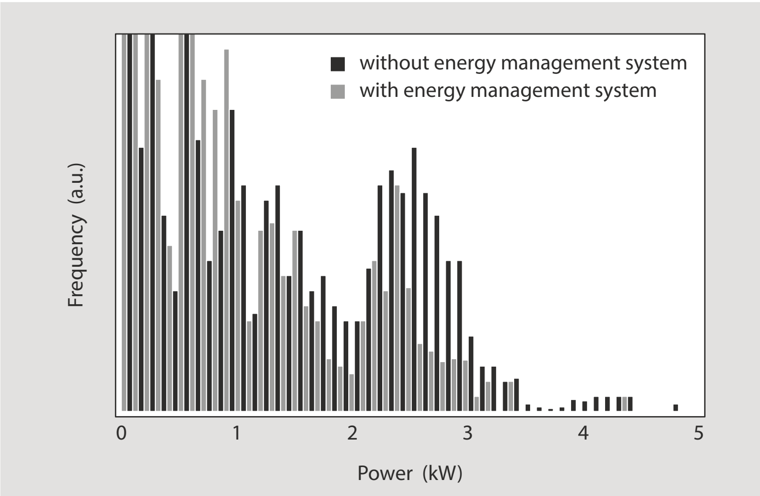
The combination of photovoltaics (PV) and heat pump is widely used in multi-family houses and apartment buildings. To make better use of local PV electricity generation, such systems can be supplemented with a larger heat storage tank or a battery. A battery allows the heat pump to be operated with local electricity even when the sun is not shining and the amount of electricity drawn from the grid is reduced. The balance looks even better with an intelligent energy management system (EMS). It controls the heat pump according to the amount of solar power available instead of the heat demand: while the sun is shining the heat storage tank is charged. To increase its capacity, the storage tank is heated up more than usual. Simulations by researchers at the University of Applied Sciences Northwestern Switzerland (FHNW) show that a residential building with an air-to-water heat pump draws less electricity from the grid thanks to the EMS. However, the total electricity consumption is higher because the efficiency of the heat pump for achiev-



Underground ice storage system with a heat sink capacity of 30,000 kWh. Ice storage systems are latent heat storage systems with water as the storage medium, where the latent heat is used as storage during the phase transition from ice to water and vice versa. In the temperature range above 0 °C, they can also serve as sensitive heat stores (source: SCHNEPF Planungsgruppe Energietechnik, Nagold, Germany).



Test arrangement for a heat pump with heat supplied from a solar collector (uncovered tube absorber) in combination with an ice storage tank. The ice storage tank simultaneously serves as a heat storage tank for solar heat (graphic according to FHNW).



Heating system with an air-to-water heat pump, a photovoltaic system, a battery and an intelligent control system that relieves the grid. An energy management system reduces the frequency of high supply and feed-in capacities, a relevant parameter for the network operator (graph based on data from FHNW).

ing higher temperatures in the storage tank is lower. From the point of view of the grid operators, an EMS has advantages because high supply and feed-in capacities occur less frequently.

One way to use solar heat is to use solar absorbers in combination with an ice storage tank, a concrete tank a few meters in the ground. The water contained in such a tank is heated more by the surrounding soil and to a lesser extent by the solar absorbers. In the cold season, heat from the storage is extracted by the heat pump via an inserted pipe system. If the water around these pipes reaches the zero degree limit, ice crystals form. During phase transition from liquid to solid latent heat is released. As long as the ice reservoir does not freeze completely, the heat energy of the phase transition can be used. As model calculations show, the heat pump nevertheless draws only a small part of the heat from the ice storage tank, the largest part originates directly from the solar absorber.

In comparison with an air-to-water heat pump, the system with solar absorber and ice storage has a significantly higher annual performance factor, which is equivalent to a system with ground probes. The gain in efficiency is not only due to the storage tank, but above all to the fact that the solar absorber does not require a fan to suck in ambient air. This also reduces noise emissions. The effect of the ice storage is to extract heat from the ground, a positive and important side effect. It therefore behaves like geothermal probes.

Hydrogen on Swiss roads

Decarbonisation of mobility is essential to achieve the climate targets as this sector is responsible for around a third of greenhouse gas emissions in Switzerland. In addition to battery electric mobility, hydrogen mobility is a climate-friendly alternative to fossil drive technologies, especially for heavy duty transport. Swiss players are pioneers in this area.

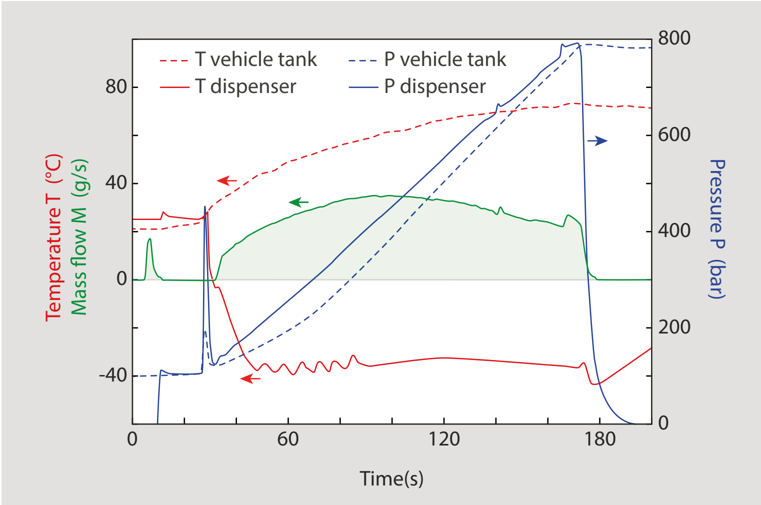
If only water vapour escapes from the exhaust a fuel cell vehicle is on its way: a fuel cells converts hydrogen (H_2) and oxygen (O_2) into electricity, which in turn drives an electric motor. If the hydrogen is produced by electrolysis using renewable electricity (green hydrogen), this technology has great potential for CO_2-free mobility. In particular, this applies in particular to heavy-duty road transport, where hydrogen offers high energy storage densities that are not possible with batteries.

Hydrogen mobility in Switzerland is currently being pushed by private initiative. In 2018, the H2 Mobility association was founded, gathering a large number of important players from the transport sector and filling station operators to establish a nationwide filling station infrastructure for hydrogen. Thanks to fuel cell trucks, with hydrogen consumption that is a factor of 30 to 50 higher than that of passenger cars, it is possible to achieve profitability at the filling stations. Fuel cell trucks are being introduced to Switzerland as part of a joint venture between the Korean manufacturer Hyundai and the Swiss company H2energy. The first of up to 1000 trucks will arrive in Switzerland in 2020.

A second joint venture between H2energy, the energy utility Alpiq and the industrial group Linde guarantees the production of green hydrogen", which is supplied to filling stations in Switzerland - six new hydrogen filling stations are planned for 2020. To this end, a 2 MW electrolysis plant at Alpiq's run-of-river power station “Gösgen” will soon go into operation.

The chain – production of green hydrogen, construction and operation of a public hydrogen filling station and the use of a fuel cell truck – has been demonstrated on a pilot scale in recent years as part of larger pro-

Prototype fuel cell truck developed by Esoro in cooperation with Swiss Hydrogen: Successful drive-off test at a slope of 30 % and a total weight (truck plus trailer) of 35 tons (source: Esoro).



Since 2016, fuel cell vehicles can be refuelled in Switzerland with 700 bar hydrogen. In accordance with the SAE J2601 protocol, such a refueling takes only a few minutes. To prevent the temperature in the vehicle tank from rising too much, the hydrogen must be pre-cooled at the filling station. The mass flow during such a refuelling corresponds to a power flow of more than 5 MW (Source: Empa, graph based on Empa data).

jects supported by the Swiss Federal Office of Energy. In 2016, for example, the first publicly accessible hydrogen filling station went into operation in Hunzenschwil, where vehicles can be refuelled with hydrogen at 350 (for trucks) and 700 bar (for passenger cars) in just a few minutes. In the period 2017 to 2019, hydrogen consumption averaged 80 kilograms per week. As part of this project, a further filling station for 700 bar refueling was built at Empa.

In that context, a Swiss guideline for hydrogen filling stations was drawn up, which outlines the approval process for future filling stations.

As a world first, a fuel cell truck with a registration over 35 tonnes has been in use at Coop since 2016 as part of another SFOE project. This truck was developed by Esoro in close collaboration with Swiss Hydrogen, which designed the integration of a 100 kW fuel cell stack. A lithium-ion battery of 120 kWh is installed as a buffer storage. This vehicle can also be used for demanding routes of up to 375 km in length and with several passes in the Jura.

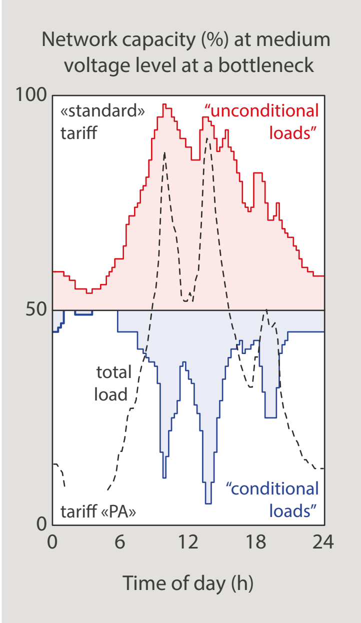
A 2MW electrolyser plant at the run-of-river power plant "Gösgen" will go into operation in 2020 to produce "green hydrogen" for fuel cell trucks. The picture shows tank containers, where the hydrogen produced is temporarily stored and which are used to supply the filling stations in Switzerland with hydrogen (Source: Hydrospider).

In a third pilot project, the production of "green hydrogen" was tested at the run-of-river power plant of Eniwa in Aarau on a scale of 180 kW electrolysis power. The hydrogen produced at this site is transported by a trailer with a storage volume of 223 kg of hydrogen at 200 bar to the filling station in Hunzenschwil some 20 km away, on average every 20 days. It is temporarily stored there in a stationary tank at 50 bar. Given the limited size of such an intermediate storage facility, operation of the filling station could be limited. In future, mobile hydrogen storage units with 350 bar nominal pressure will be used, allowing them to be transported as standardised containers. In parallel to the general operating experience, the aim of this project was to demonstrate dynamic control of the electrolysis during the 5600 hours of operation in order to be prepared to provide regulating power for system services in future plants.

Reduced network load thanks to flexibility

The expansion of renewable energy is pushing the existing power grid to its limits in some places. Rather than expanding the grid infrastructure, the PowerAlliance (PA) project uses the redundant capacity of the medium-voltage grid to supply units that tolerate a lower level of supply security. This includes, for example, Power-to-X systems that can be switched off as soon as the reserve capacity in the network is needed. Customers specify these conditional loads in a schedule for the subsequent day and in return benefit from a more favorable tariff. In another project, a local market for decentralised flexibility has been tested on a technical basis, where biogas and photovoltaic plants as well as storage systems are intelligently integrated. A special tariff system rewards grid-compatible behaviour.

Network capacity in the category "unconditional loads" (red) with high supply security and "conditional loads" (blue), with lower supply security and thus benefiting from a reduced tariff (e.g. electrolysers or batteries). This split enables the intelligent use of idle grid reserves.



Electricity storage with compressed air

In compressed air storage, the electricity to be stored drives a compressor which compresses ambient air to be stored in a cavern. During discharge the compressed air expands in a turbine and an attached generator generates electricity. In adiabatic compressed air storage systems, the compression heat is additionally stored in a thermal storage unit, resulting in increased overall efficiency. Such compressed air storage systems can efficiently compensate for fluctuations in electricity production – presupposing that the cycles of compression and expansion are not too short. A simulation model developed by the University of Applied Sciences of Southern Switzerland (SUPSI) and ETH Zurich together with industrial partners confirms this. Since standard combined compressor/expander units are relatively inefficient, these two components need to be optimized independently.

Air conditioning with the underground

More than 100,000 geothermal probes are in operation in Switzerland, primarily to heat buildings. When they are used to cool in summer, this is known as "geocooling". A welcome bonus is the regeneration of the ground after the winter heat extraction, enabling a large proportion of the heating energy to be restored. Thereby, the significant gap between high indoor and low underground temperatures is exploited. The available cold corresponds roughly to 30 times the energy used, as shown by studies conducted by the University of Applied Sciences of Southern Switzerland (SUPSI) at a site in Lugano.

Impeller of a 3-stage air compressor (source: MAN, Augsburg).

A building in a central location in Lugano is heated and cooled using geothermal probes (source: SUPSI).

Renewable energy

Solar fuels for aviation

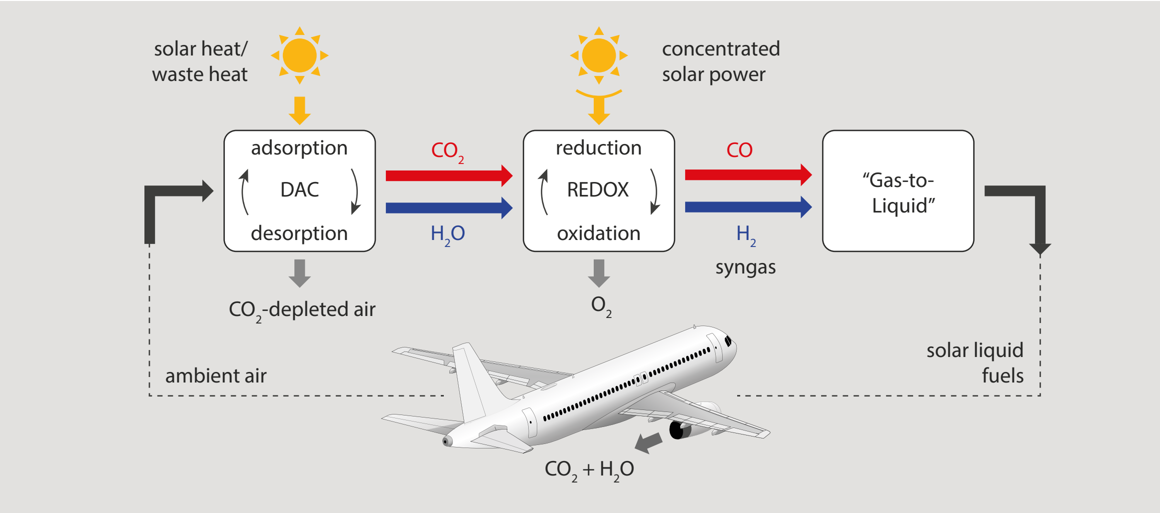
Including international air traffic, the transport sector accounts for around 40 % of Switzerland's greenhouse gas emissions. Even though today's aircraft are at least 50 % more efficient than 30 years ago, this sector poses major challenges for energy and climate policy due to its rapid growth. Swiss players are world leaders in the development of renewable liquid fuels with concentrated solar energy and are supported in their endeavours by the SFOE. The aviation industry is showing great interest in this subject, as underlined by recent joint declarations of intent with the Lufthansa Group.

For the first time, researchers from the Chair of Renewable Energy Sources at EHT Zurich (Prof. Steinfeld) were able to demonstrate the production of liquid hydrocarbons – of which all common fuels are composed – from concentrated sunlight and ambient air under real field conditions. A high-temperature solar reactor in a solar mini-refinery on the roof of ETH Zurich splits carbon dioxide (CO_2) and water (H_2O) obtained directly from the air and produces syngas – a mixture of hydrogen (H_2) and carbon monoxide (CO). This mixture can be processed into liquid hydrocarbons such as methanol or kerosene by established “gas-to-liquid” technologies. The solar-powered process chain (see figure on the following page) makes use of the entire solar spectrum and offers a thermodynamically favourable way of producing solar fuels.

The technology for direct recovery of CO_2 and H_2O from ambient air is based on thermally driven cyclic adsorption and desorption, employing an amine functionalized sorbent. The synthesis gas is then produced in a solar redox unit, which thermochemically splits CO_2 and H_2O via a reduction-oxidation (redox) cycle process using cerium as redox material. In a first (solar) step, oxidized cerium is thermally reduced with concentrated solar energy, whereby oxygen is released. In a second (non-solar) step, the reduced cerium oxide then reacts with CO_2 and H_2O to produce the syngas. The cerium is re-oxidized and ready for further cycles. In ETH Zurich's solar mini-refinery unit, the absorption of solar energy (receiver) and the thermochemical reaction take place in the same reactor. Two identical solar reactors are used to carry out both reactions – the solar reduction and the non-solar oxidation – mutually in parallel.

Two ETH spin-offs have emerged from Aldo Steinfeld's research group: Climeworks and Synhelion. In recent years, Climeworks has successfully developed the process described above into a product. The company Synhelion is working on commercializing the technology for the production of solar fuels. To implement this technology, Synhelion's concept separates the absorption of solar energy, the storage of high-temperature heat and the thermochemical reaction in order to optimize overall efficiency. A newly developed high-temperature solar receiver exploits the principle of

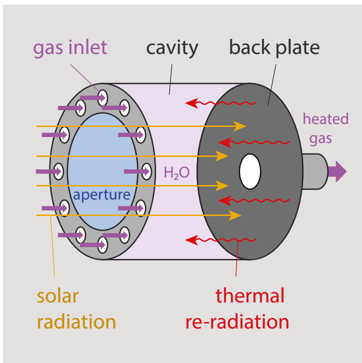
Solar mini-refinery on the roof of ETH Zurich for the production of solar fuels from air and solar energy (source: ETH Zurich).



In 2019, ETH Zurich was able to demonstrate for the first time the production of solar liquid fuels based on water and carbon dioxide extracted from the air and using concentrated solar energy. The technology developed at ETH Zurich was demonstrated on a mini-refinery directly on the roof of ETH Zurich and on a larger scale on a solar tower in Madrid as part of an European project. Renewable liquid fuels are particularly important for aviation, as there are few or no technical alternatives (graph according to ETHZ-PREC).

the "greenhouse effect": the volume of gas in a cavity absorbs the thermal back radiation of the black back plate heated up by concentrated solar radiation. The gas (e. g. steam or CO_2) serves as heat fluid and can – coupled with a thermal storage – continuously supply the thermal energy required for the thermochemical decomposition of CO_2 and H_2O in a non-solar reactor.

After this novel receiver concept has been thoroughly investigated in theory together with researchers from the University of Applied Sciences of Southern Switzerland (SUPSI), a first pilot reactor on a 200 kW scale was tested very successfully in 2019 on the 300 kW solar simulator of the German Aerospace Center (DLR). Temperatures of over 1550 °C were achievable with steam as absorber gas.



(Top) Novel solar receiver concept from the company Synhelion with radiative heat transfer (graphics after Synhelion). (Upper left) A 200 kW pilot reactor (source: Synhelion) was successfully tested in 2019 on the solar simulator of the German Aerospace Center (lower left, source/credit: DLR/M. Hauschild) and temperatures of over 1550 °C were reached.

“Biochar” from waste

Hydrothermal carbonization (HTC) is the process of carbonizing biomass under heat and pressure. This process allows organic residues to be used for energy generation and returns plant nutrients to the soil.

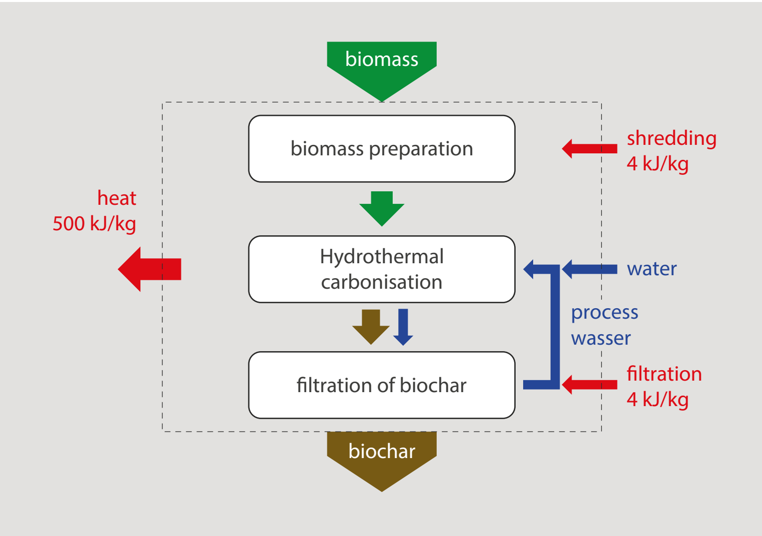
In Switzerland, large quantities of organic residues such as sewage sludge, liquid manure, green waste or food waste are accumulated, which are rich in nutrients and which can be recycled both materially and energetically. Widely used are fermentation plants that produce biogas from wet biomass. These plants usually do not completely convert organic carbon into the energy carrier biogas.

If a complete energetic use of the organic substance is aimed at, hydrothermal carbonization (HTC) offers an attractive alternative. With this procedure, which in principle corresponds to an accelerated formation of lignite, moist biomass is converted in an environment-friendly and climate-friendly manner into a hydrophobic and coal-like product that is hygienically harmless from an epidemic point of view. Thus, almost all the carbon is available for potential energetic use in a combustion or gasification process. Alternatively, due to its high adsorption capacity, coal can be used as a soil conditioner and as an agricultural auxiliary material. Depending on the initial substrate, phosphorus either remains in the majority of the coal or is transferred into the process water. The HTC treatment of sewage sludge offers a possibility for effective phosphorus recovery.

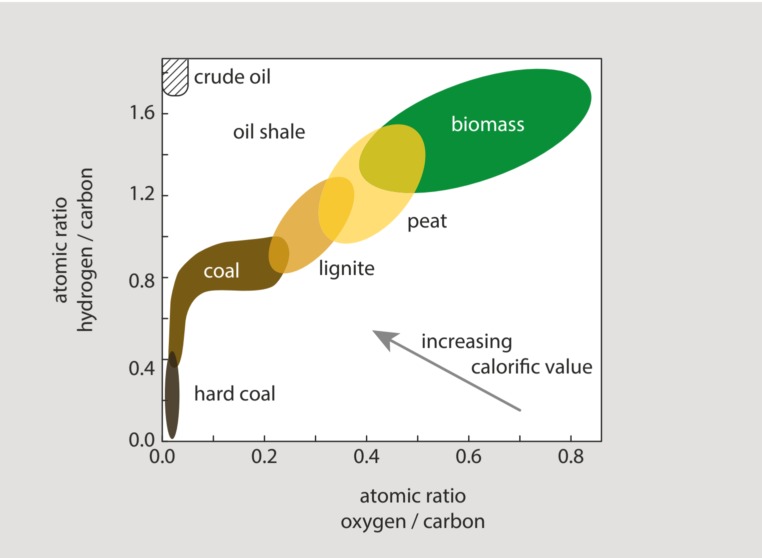
By means of hydrothermal carbonisation, organic residues can be converted in an ecologically, climate- and hygiene-friendly way to be used for energy generation or as plant nutrients for agriculture. The figure shows carbonisates from slurry in pellet form with an energy density of 10-12 GJ/m³ (source: FHNW).

At the "Rheinmühle" innovation campus in Chur, a continuously operating HTC reactor was implemented as part of a SFOE pilot project. In this reactor, biomass, which consists mainly of carbon, oxygen and water, is carbonized under pressure at temperatures of 180 to 240 °C. Long, organic hydrocarbon molecules are split into shorter ones. The reactions release heat that can be used as process heat. Furthermore, the process water obtained can be fermented anaerobically.

The pilot plant is intended to demonstrate an electricity and heat generating processing path for liquid manure, sewage sludge and catering waste for the first time in Switzerland. The optimisation of the individual process steps is being scientifically monitored and documented. Since January 2018, the plant has been processing 10 tonnes of biomass per day. About 1000 m³ of liquid manure from a livestock farm and about 100 tonnes of sewage sludge from the Chur wastewater treatment plant are to be processed separately in this way every year. The HTC coal produced serves as storable fuel for gasification and combustion systems. After some initial difficulties, the plant is now operating stably. At present, the exhaust gas limits (NO_x and SO_2) are still being exceeded during combustion tests in laboratory plants with the HTC coal. If used in modern waste incineration plants or cement works, these pollutants would be eliminated in flue gas filters anyway. HTC coal obtained in this way is an interesting solid fuel due to its calorific value comparable to that of wood.



Hydrothermal carbonization (HTC) is an exothermic chemical process to convert wet biomass into biochar. In this process the proportion of carbon and thus the calorific value is strongly increased. The process takes place under pressure (20 bar) and at temperatures of around 200 °C. Carbon balance: up to 90 % of the carbon from the initial biomass can be thermally utilised in the form of biochar. Energy balance: depending on the initial substance, 60–90 % of the gross calorific value of the input material is available in the resulting HTC coal (source: according to ZHAW/Aqua and Gas 2014).



Different stages of carbonization (formation of coal) from biomass (cellulose/wood) through peat and lignite to hard coal and anthracites in the van Krevelen diagram, where the atomic ratio of hydrogen to carbon is plotted versus the atomic ratio of oxygen to carbon.

An alternative to air-to-water heat pumps

Photovoltaic thermal systems (PVT) make optimum use of the roof surface of a building: they generate both electricity and heat that can be used in a heat pump. This ecologically and economically sound combination was investigated in a project by the Zurich University of Applied Sciences (ZHAW).

When it comes to renewing heating systems in single-family homes, owners often choose air-to-water heat pumps – a vital contribution to decarbonising heat supply, provided that renewable electricity is used. However, such systems have the disadvantage that they are not very efficient and generate noise, especially in winter when outside temperatures are low.

In the SFOE funded "L-Sol" project, researchers from the Renewable Energies group at the Zurich University of Applied Sciences (ZHAW) investigated a new type of system in which PVT hybrid modules supply both electricity and heat for the heat pump.

These modules are a combination of photovoltaic (PV) and solar thermal (T) modules. The heat pump is based on a low-temperature buffer tank as heat source, which can be loaded with heat from uncovered (uninsulated) PVT collectors. This allows efficient use of heat at low temperature levels and the PV modules have a higher efficiency due to lower temperatures. Initial system simulations are promising: in new buildings and energetically renovated single-family homes, electricity consumption will be some 5 to 30 % lower compared to an air-to-water heat pump. The PVT modules run without noise and therefore do not disturb any neighbours. Since no ground work is required, the system is particularly suitable for existing

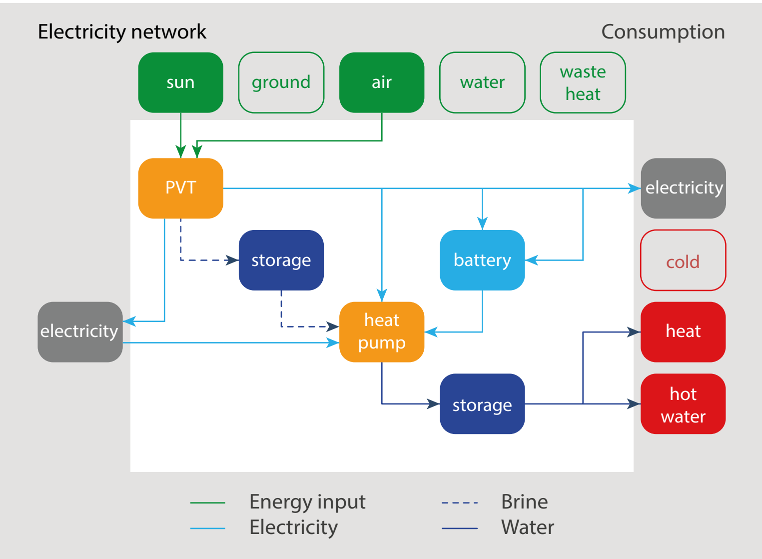
Hybrid photovoltaic thermal modules (PVT) on the roof of the linth-arena sgu (source: ZHAW).

buildings and for locations where no ground probes or groundwater extraction is possible.

Günstig ist sie nicht, diese innovative Technik. Die Gesamtkosten lassen sich über 20 Jahre jedoch auf das Niveau eines Luft-Wasser-Wärmepumpensystems senken, wenn ganz normale PV-Module rückseitig mit Wärmetauschern nachgerüstet werden. Diese erbringen zwar einzeln betrachtet eine um 20 % geringere Wärmeleistung als originale PVT-Module, im Gesamtsystem kommt dies jedoch wegen der entsprechend längeren Laufzeit kaum zum Tragen – somit überwiegen die Vorteile der wesentlich geringeren Investitionskosten.

This innovative technology is not cheap. However, the total costs can be reduced over 20 years to the level of an air-to-water heat pump system if normal PV modules are retrofitted with heat exchangers on the back. Although they provide 20 % less heat output than original PVT modules, this is hardly noticeable in the overall system due to the correspondingly longer running time - thus the advantages of the significantly lower investment costs outweigh the disadvantages.

A dimensioning matrix developed in the project offers planning assistance: It shows the area of application and allows an initial, rough dimensioning of the components. A typical system for a single-family house comprises 15 to 30 PVT modules, a buffer storage tank, a heat pump and a 600 litre reservoir.



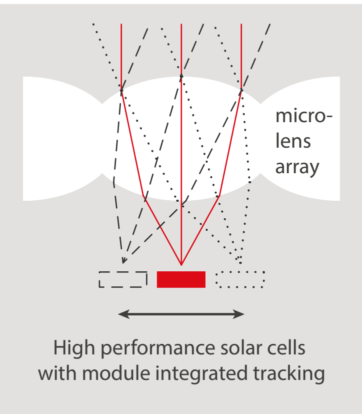
Overview of the "L-Sol" system: Sun and air (green) serve as ambient heat sources, PVT hybrid collectors generate electricity and produce heat, a heat pump provides the required temperature level (orange). Thermal storage tanks are shown in dark blue and electrical energy in light blue. (Displayed according to the classification of the IEA program SHC Task 44 "Solar and heat pump systems" according to data from the ZHAW).

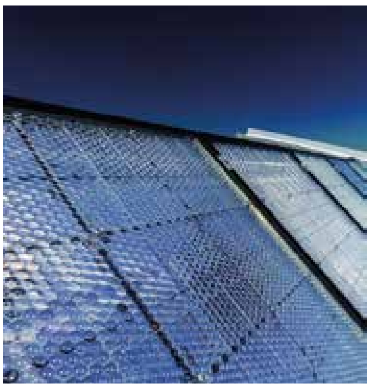
Electricity and heat for a heat pump: In this example a conventional PV module was retrofitted with a heat exchanger (source: ZHAW).

More solar energy from the same area

The start-up Insolight develops photovoltaic modules that use optical micro-lenses to concentrate and focus sunlight on high-performance solar cells. To ensure that the bundled light rays hit the cells at any angle of incidence, the rear wall of the module with the embedded solar cells is tracked by a few millimetres during the course of the day. Although this innovative solution is technically complex, considerably fewer modules are needed to achieve the same electricity yield. The energy production costs could therefore be lower. On roofs with limited space, such modules can produce significantly more energy than standard modules.

Direct solar radiation is concentrated on high-performance cells using a planar optical concentrator system with a large number of individual lenses (source: Insolight).





Potential of complex wind conditions

In general, wind conditions are determined by large-scale weather phenomena. In Switzerland, however, wind conditions are also strongly influenced by the complex local terrain. For example, in parts of Switzerland the wind often blows when other regions of Europe are calm - and vice versa. ETH Zurich researchers are using model calculations to investigate whether such correlations can at best be used specifically to compensate for other production by wind and other variable renewables. E. g., their analysis shows that wind speeds in the Léman region and at the Rhone knee in Valais are significantly higher in high-pressure weather conditions than in neighbouring flat regions. Anticyclic production patterns can provide an incentive for the construction of new wind turbines in Switzerland, even if the average wind speed alone would be insufficient.

In Switzerland, wind conditions are strongly influenced by the complex terrain (source: pixabay.com).

Aluminium extends summertime

It is something like the "missing link" of a renewable energy supply: the storage of the surplus of solar power in summer, which will be generated in the future. A project at the Institute for Solar Technology (SPF) at the University of Applied Sciences in Rapperswil is focusing on an aluminium-based chemical energy storage cycle: aluminium oxide can be reduced to elemental aluminium using Hall-Héroult electrolysis. Thanks to the high chemical energy storage density, aluminium can be stored and transported as a storage material in granulate form for months without loss. Energy can be generated from aluminium by oxidative reaction with water (steam). This releases hydrogen, which generates electricity and heat in a fuel cell. Initial tests with a functional model at SPF have been very promising.

(Right) Laboratory prototype of an aluminum converter for hydrogen production in combination with a 12 W fuel cell (source: SPF).

Socioeconomics

Social factors when deciding in favour of solar systems

In order to significantly increase the share of renewable energy, it is essential that many individuals decide to generate their own energy. An important element in decision-making processes is what the neighbours do.

In view of the ambitious timetable of the Energy Strategy 2050, it is important to find new ways of getting the population excited about renewable energy sources. Previous studies have already shown that, not only financial incentives in the form of subsidies or taxes, but also “social contagion” has an influence on the development of new photovoltaic systems. Social contagion" refers to the phenomenon of people consciously or unconsciously adopting a behaviour or way of thinking that they observe in others. A distinction is made between two forms: word-of-mouth propaganda and imitation. With word-of-mouth propaganda, owners of photovoltaic systems provide information. This helps to overcome the uncertainty that accompanies an investment. Imitation is a more subtle form of contagion, in which one feels under pressure to go with the norm.

Previous studies on “social contagion” in the field of solar energy were limited to private households. Now the Geneva University of Applied Sciences (HES-SO Genève) has examined not only households but also companies and farms, and distinguished between different types of photovoltaic systems (roof-top, building-integrated and ground-mounted). Around 60,000 systems were examined throughout Switzerland, installed between 2006 and 2015.

Results show that not only private individuals, but also companies and agricultural enterprises can be convinced by “social contagion” of photovoltaics. However, the contagion effect is highest among private individuals. Companies and farms are more likely to be influenced by installations from other companies than by installations on private roofs. Important factors are the proximity, size and age of the “model installations”: new installations are built in particular when systems are installed in their immediate vicinity. Large installations have a greater impact. And building-integrated installations have a stronger imitation effect than roof-mounted installations – possibly because they are more visible.

Development and testing of a new type of photovoltaic system technology for the alpine region on a roof in St. Moritz. With vertically arranged bifacial modules, the disadvantages of standard inclined photovoltaic systems can be avoided: the loss of electricity production in winter (when it is needed most) due to coverage by snow, massive support structures and the risk of damage to PV modules and mounting structure due to high snow loads (source: reech).

International

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. www.iea.org/tcp), see next 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, etc.).

(Left) Part of the interior of the hydrogen filling station at Empa in Dübendorf with hydrogen fittings, two compressor stages (right 440 bar, left 900 bar), hydrogen buffer storage for electrolysis and two final hydrogen storage tanks for refuelling at 440 and 900 bar respectively (source: Empa).

(page 31 upper) As part of a project supported by the SFOE, Empa researchers are working with the company Solaronix SA to develop a new process for large-scale production of perovskite solar cells using a slot die technique. In this kind of solar cell the light-absorbing layer has a perovskite crystal structure of the form ABX_3, where A and B represent two very different sized, positively charged ions (cations) and X stands for a negative ion (anion). Five different layers consisting of different materials must be deposited during the production of perovskite solar cells. Empa's method allows these layers to be applied directly one after the other, whereas in the screen printing process used so far, the different layers must each be dried and compacted individually (source: Empa).

(page 31 lower) The components forming the perovskite crystal are infiltrated as a precursor solution (ink). This is typically done by semi-automatic pipetting, which is not very precise. Empa has therefore developed a "drop on demand" infiltration of the precursor ink by means of ink jet printing, which allows better control of the process parameters during infiltration (source: Solaronix SA, Empa).

Technology Cooperation Programmes of the IEA

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

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

Demand Side Management (ieadsm.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)

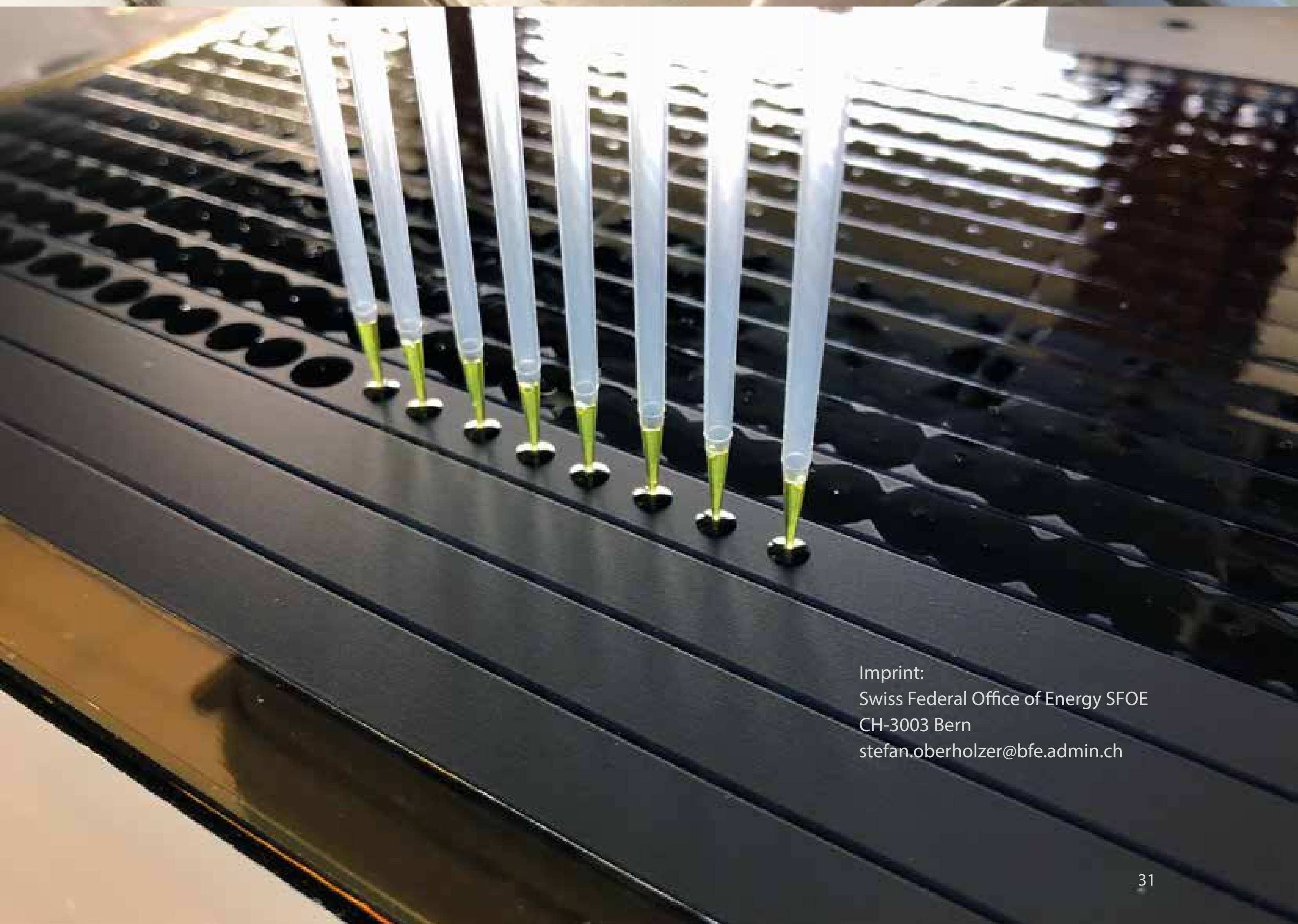
Further international cooperation

DACH-Cooperation Smart cities and communities

International Partnership for Geothermal Technology

DACH-Cooperation Smart grids

Fuel Cells and Hydrogen Joint Undertaking



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