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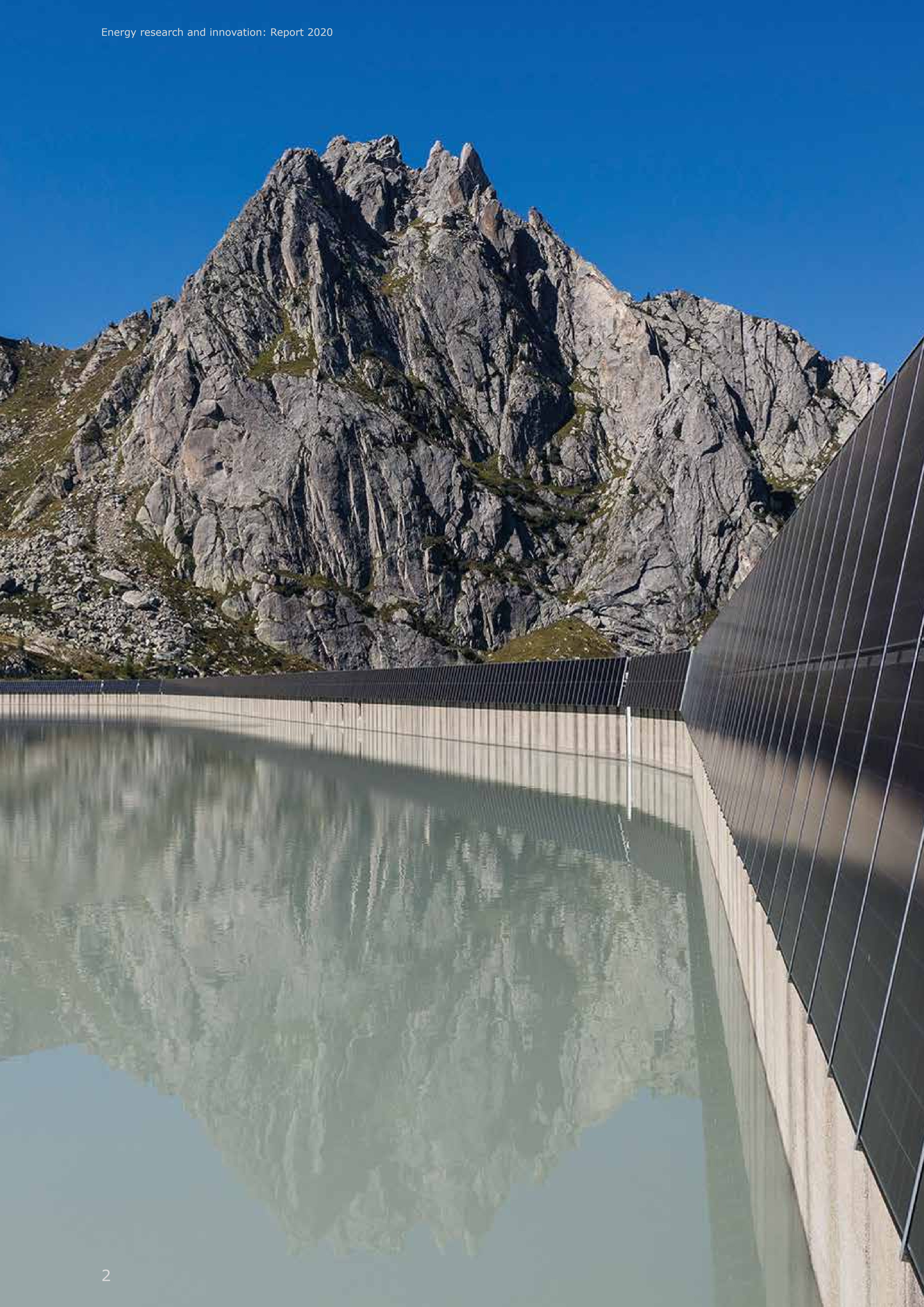
Swiss Federal Office of Energy SFOE

Energy research and innovation
Report 2020



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. A first call for proposals was launched last year. 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).

Swiss Federal Office of Energy SFOE
Section Energy research and Cleantech

(Cover picture) Impeller of a turbocompressor from the Swiss company Celeroton AG. Compact and efficient turbocompressors with appropriate electronics play an important role in fuel cell systems for transport applications (source: Celeroton AG).

(Left) In 2020, the Zurich energy utility ewz commissioned a high-alpine 410 kW PV plant at the Albigna storage dam at an altitude of 2165 metres. Due to its location, the plant is exposed to extreme meteorological conditions. Analysis of the yield data, periodic measurement of the module output, thermal imaging and examination of the overall condition of the plant will provide insights about the long-term reliability of plants at comparable locations (source: ewz).

(next page) Scanning electron micrograph of the surface of a porous titanium layer for Polymer electrolyte membrane (PEM) electrolysis (source: Paul Scherrer Institute PSI, CH-5232 Villigen).

Contents

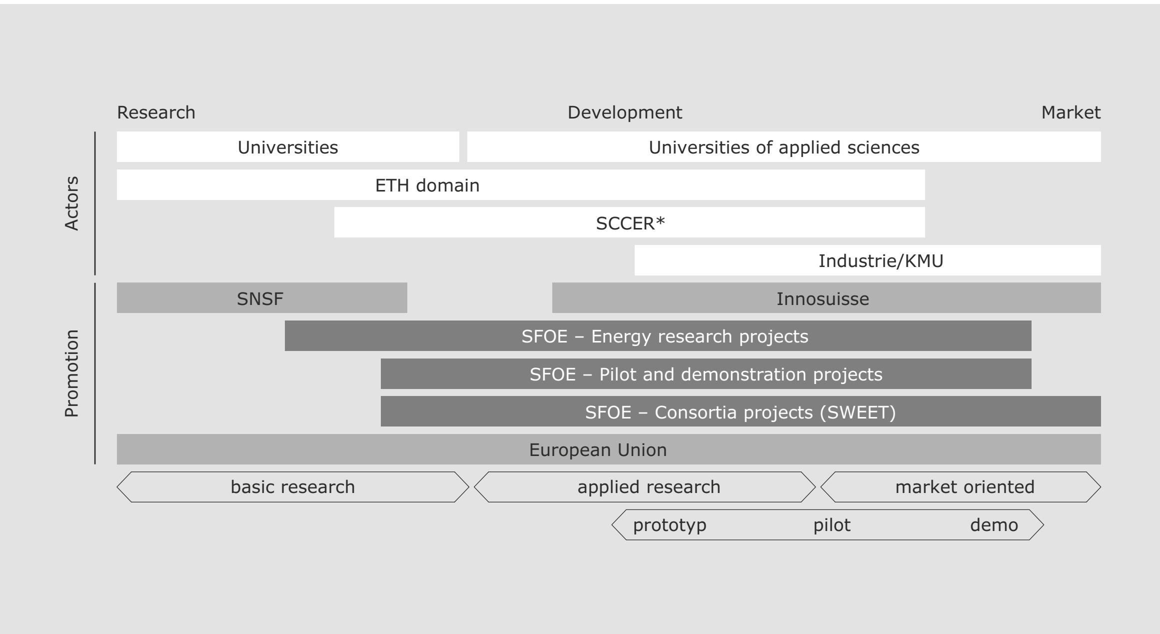
Technology and innovation promotion by the Swiss Federal Office of Energy

The Swiss electorate decided in 2011 to gradually transform the energy system by 2050. In 2019, the Federal Council further decided to reduce Switzerland's greenhouse gas emissions to net zero by 2050. This will necessitate technologies that can compensate for unavoidable emissions – for example from agriculture, industrial production or air traffic. Such so-called "negative emission technologies (NET)" are a key prerequisite for achieving this target. Simultaneously, energy efficiency in buildings, mobility and industry must be increased and the expansion of renewable energy needs to be massively accelerated, while maintaining grid stability.

Energy research is of particular importance in all these tasks. However, researchers must also be offered opportunities to address issues that are important for the Energy Strategy 2050. Appropriate funding instruments are the most efficient way to do so. The Swiss Federal Office of Energy (SFOE) plays a central role here. Following the conclusion of the National Research Programmes (NRP) 70 and 71 on the energy transition at the beginning of 2020 and the expiry of the Swiss Competence Centres in Energy Research (SCCER) end of 2020, the SFOE is the most important Swiss funding body in the energy sector.

With its research and funding programmes, the SFOE covers practically the entire technology spectrum (page 6). The SFOE is following the federal government's energy research concept. The current concept for the period 2021–2024 places an even stronger focus on non-technical research (SSH: social sciences and humanities). Accordingly, technical sciences and SSH are to work closely together from the very conception of research projects. This is the only way to ensure that the knowledge gained is oriented towards later users at an early stage and that the methods and procedures developed are designed in such a way that they are widely accepted and quickly find their way into market. The SFOE has been pursuing this approach for some time: Traditionally, in addition to the various technical research programmes, it also runs a research programme on socio-economic research, which is closely coordinated with the other research programmes.

With its new research funding instrument SWEET ("Swiss energy research for the energy transition"), the SFOE is further strengthening cooperation between the various disciplines (page 6). Inter- and transdisciplinary teams can apply for long-term consortial projects on selected topics. A first call was launched in 2020 and the first consortia projects start in 2021.



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 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 eld of energy e ciency:

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 eld 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 2021–2024", CORE (2020)and "Energy research concept of the Swiss Federal Office of Energy 2021–2024", SFOE (2020).

From the SCCERs to SWEET

Strengthening energy research in Switzerland is a central pillar of the Energy Strategy 2050. In the wake of the Fukushima nuclear disaster in 2011, the Swiss parliament decided to expand energy research in selected research areas. To this end, eight virtual competence centres, so-called "Swiss Competence Centres for Energy Research" (SCCER), were established at Swiss universities in the research areas of industrial processes, buildings and areas, mobility, grids, storage technologies, biomass, energy supply (geothermal and hydropower) and socioeconomics, which were funded by the federal government with more than 250 million Swiss francs. Also in 2013, the Photovoltaics Centre was established at the Centre Suisse d'Electronique et de Microtechnique (CSEM). Between 2013 and 2020, around 800 additional personnel research capacities were built up at the SCCERs. This capacity building was completed at the end of 2020.

New SFOE funding instrument "SWEET"

As a successor to the SCCERs, the work of around 1500 researchers active in the SCCERs is now to be focused on objectives that are important for the Energy Strategy 2050. To this end, Parliament has approved a new research funding programme SWEET, based at the SFOE.

SWEET stands for "SWiss Energy research for the Energy Transition" and is intended to promote consortia working on trans- and interdisciplinary projects over a period of six to ten years through regular calls for proposals. The calls for proposals can be in the areas of energy efficiency, renewable energy, storage, grids or security of critical energy infrastructures. There will be a strong focus on non-technical research – for example socio-economic or socio-psychological research. A total of 136 million Swiss francs is available for calls for proposals from 2021 to 2028. The last research work will be completed in 2032.

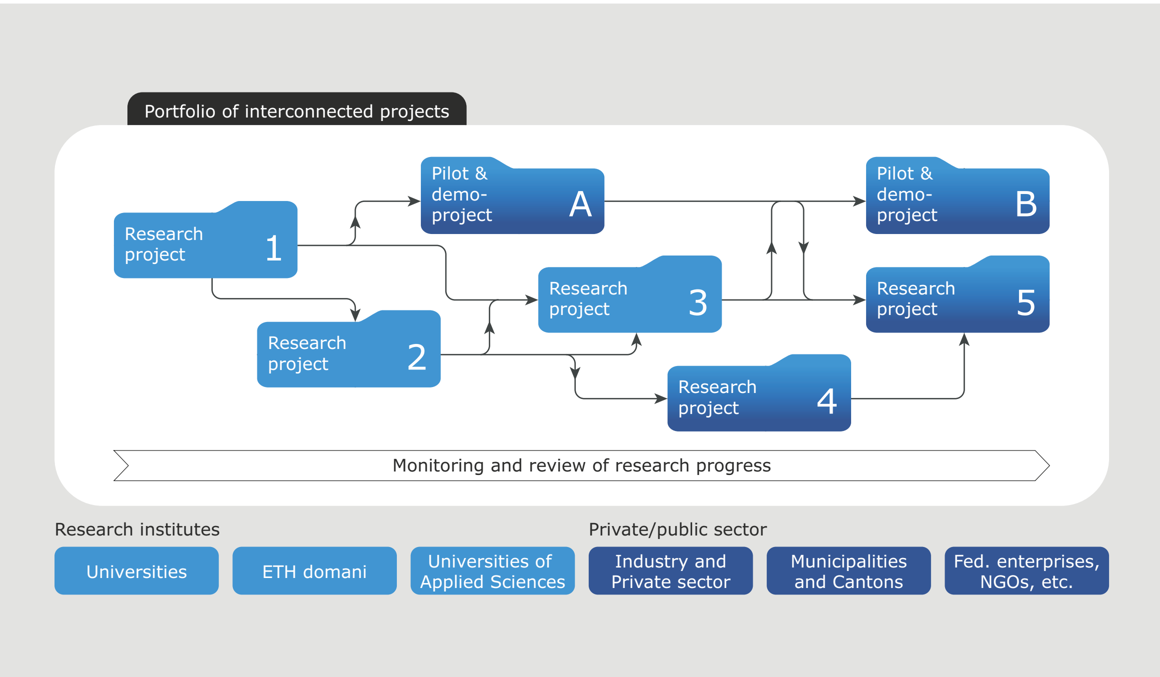
Supported consortia should typically consist of public institutes from the ETH Domain, from universities and universities of applied sciences, but also of private research institutions, companies, organisations and the public sector. In SWEET, no individual projects are funded, but exclusively portfolios of interconnected research projects.

Rolling SWEET calls for tenders

A first SWEET call for proposals was already issued in 2020 on the topic of "Integrating renewable energies into a sustainable and resilient Swiss energy system". This will enable researchers to start research work as early as 2021. A second SWEET call for proposals entitled "Living & Working" was published in spring 2021. It is intended to investigate how energy supply and distribution can be ensured efficiently and cost-effectively and how energy consumption can be minimised in clearly defined geographical (sub)urban areas. New energy-saving potentials are to be identified and quantified by linking the building and mobility sectors and through technology adaptation and behavioural adjustments on the part of consumers. The third SWEET call for proposals is already planned for autumn 2021.

"Game changer" wanted

In order to try out entirely new research approaches, so-called SOUR calls are planned within the framework of SWEET. SOUR stands for "SWEET Outside-the-box Rethinking" and funds short projects lasting six to a maximum of 18 months that pursue radically new and original ideas. SOUR aims to develop promising and unconventional scientific approaches, concepts, theories and ideas and thus stimulate the research community. The small and agile SOUR projects are carried out by a single researcher or a small team. A first call for SOUR was published at the end of January 2021.



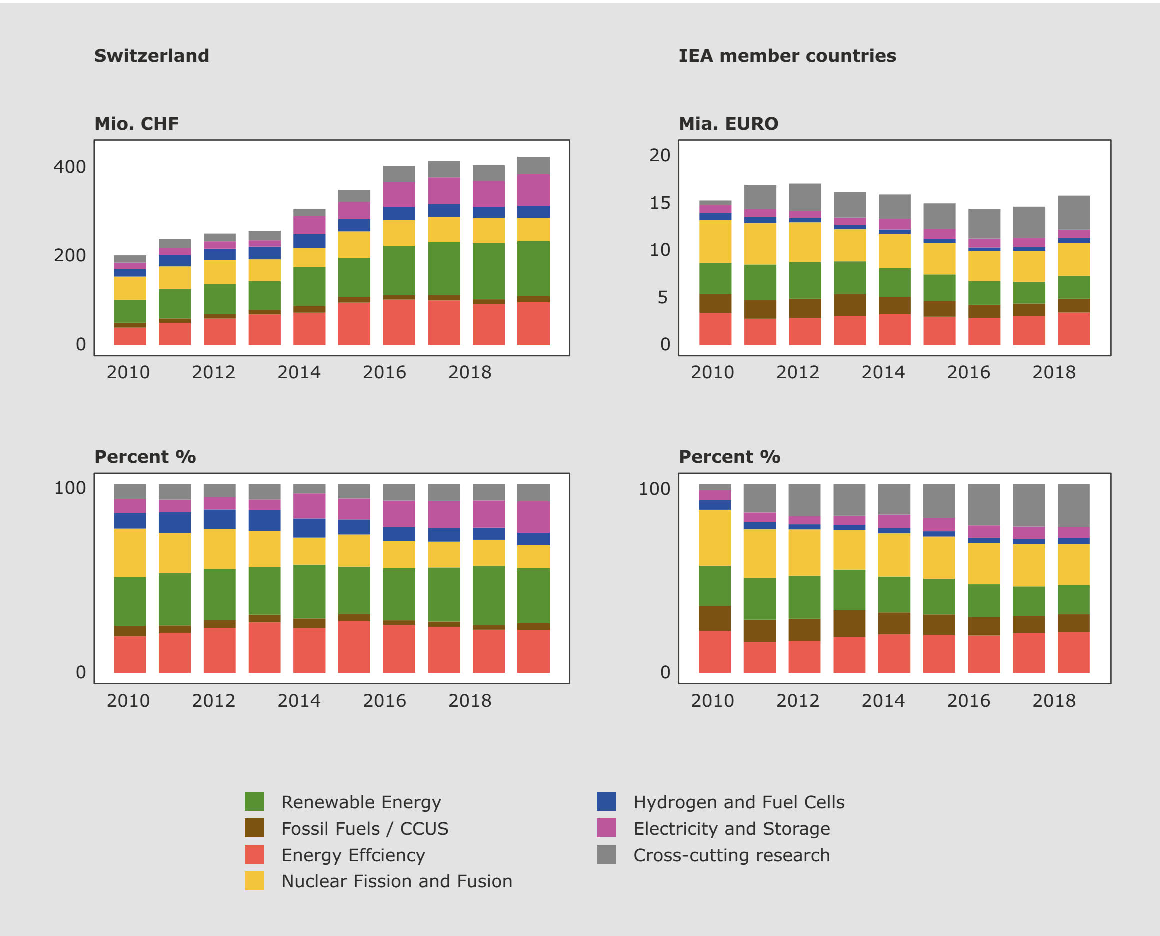
Supported SWEET consortia work on a portfolio of interlinked research projects over several years. It includes SWEET-funded research projects as well as pilot and demonstration projects or third-party projects.

Swiss energy research statistics

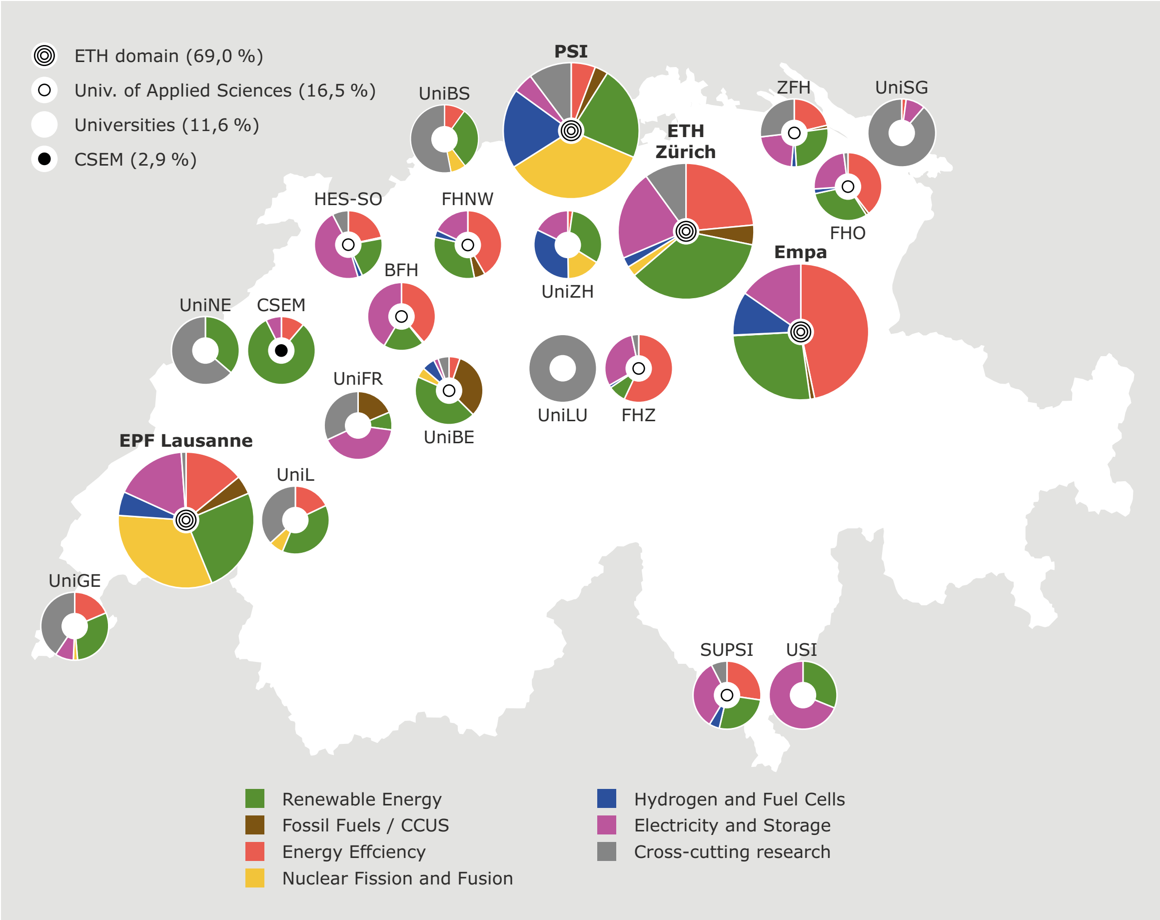
Since 1977, the SFOE has been collecting data for projects funded in whole or in part by the public sector (Confederation and cantons), the Swiss National Science Foundation (SNSF), Innosuisse or the European Union (EU). The survey is carried out by querying databases of the Confederation, the Swiss 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 below 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).

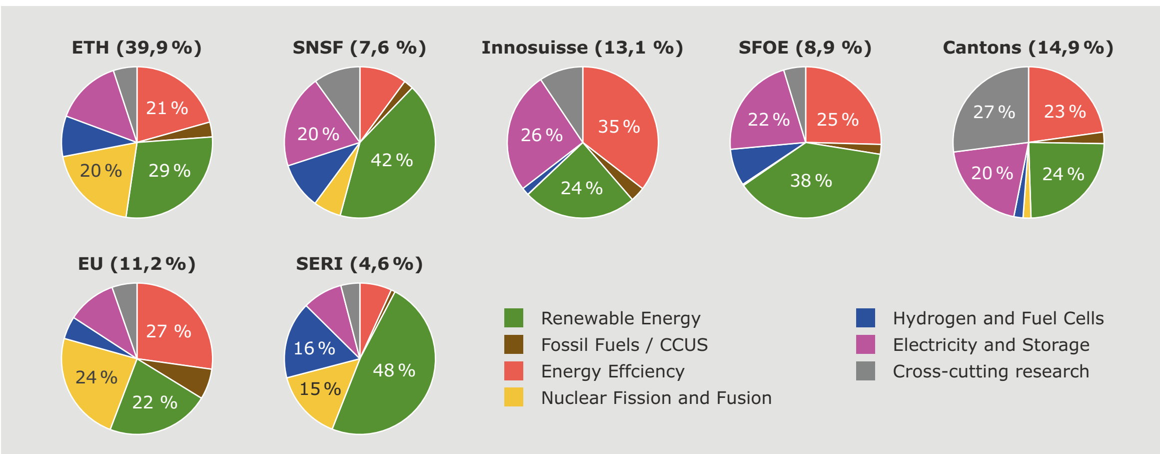
In 2019, the public sector has spent CHF 427 million on energy research. The ETH Domain contributed the largest share of this, 40 % (see chart on next page). Together with the Swiss National Science Foundation, the SFOE was the third largest research sponsor after Innosuisse (13 %) with a share of 9 and 8 % respectively. Of the CHF 37 million spent by the SFOE in 2018, around CHF 17 million went into energy efficiency projects, around CHF 17.5 million into renewable energy projects and around CHF 2 million into projects in the area of social sciences.



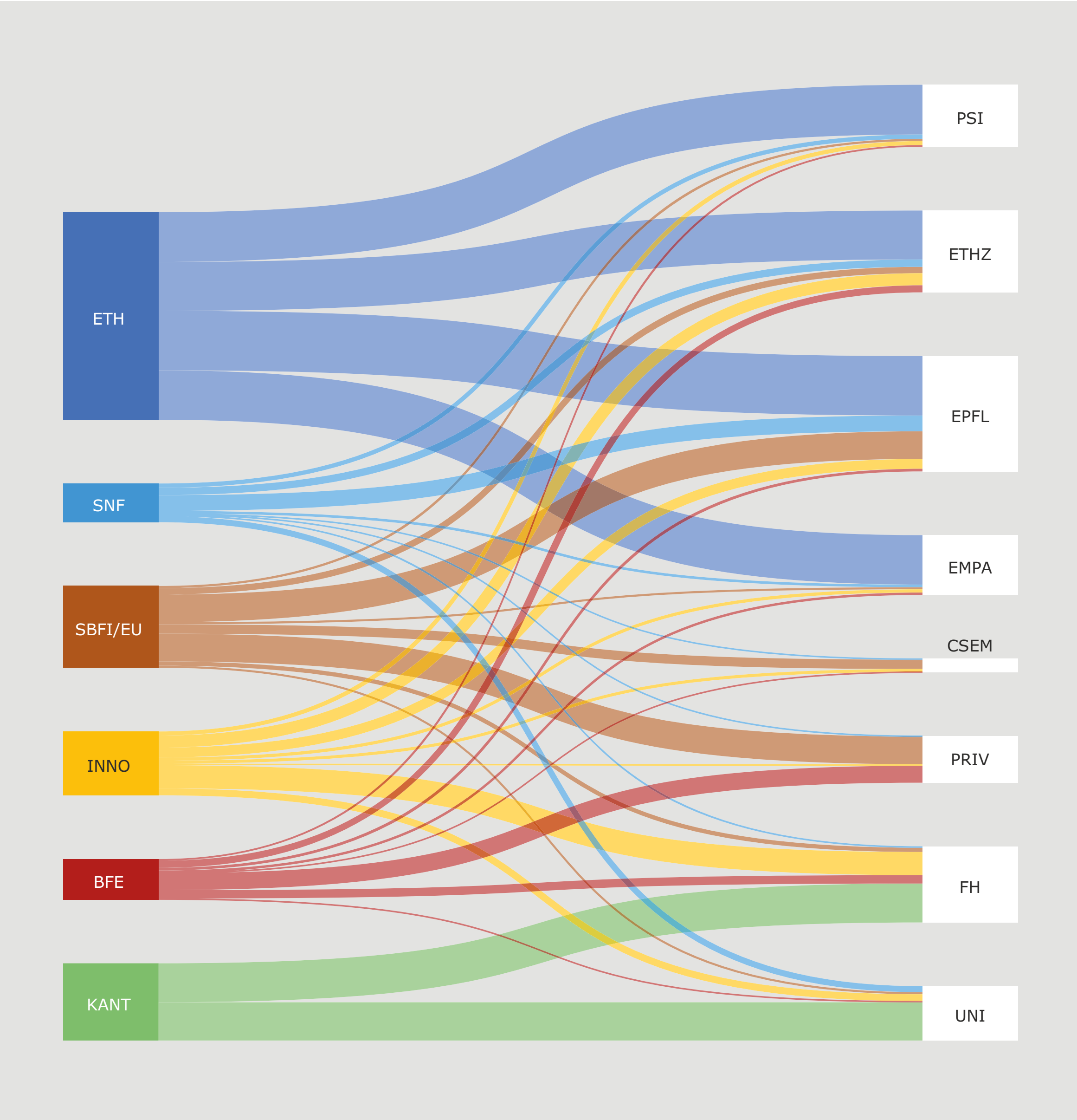
Overview of the public funds spent on energy research in Switzerland and in the member countries of the International Energy Agency IEA. Real values (corrected for inflation) are shown, which for Switzerland range between 0.3 and 0.65 per mille of the gross domestic product. The funds used are broken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



Various energy research topics at Swiss universities (data 2019). The topics are broken down according to the classification of the International Energy Agency. Most of the public energy research (69 % 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.



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.

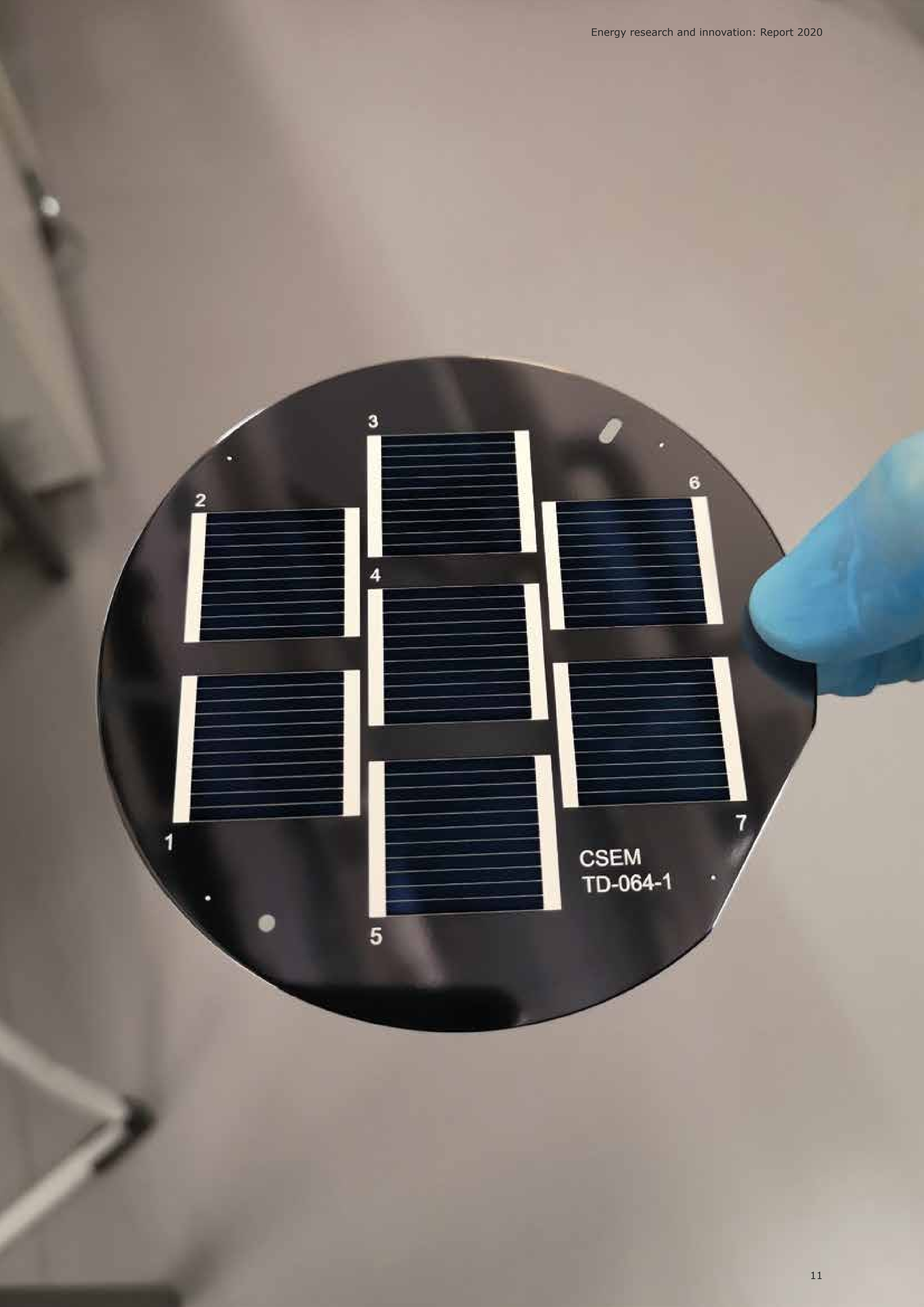


Where does the public funding for energy research in Switzerland come from and where does it go? A large part comes directly from the ETH Domain. Funds from private sources, such as own contributions to Innosuisse projects or pilot and demonstration projects of the SFOE, are not included. Cash flows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

(Left) Tandem solar cells, which combine perovskite and silicon solar cells, offer an interesting approach to further increase the efficiency of solar cells. The Photovoltaic Centre at the Centre Suisse d'Electronique et de Microtechnique (CSEM) is working successfully in this field and developing methods that can be implemented industrially (source: CSEM, private communication).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Energy efficiency

Batteries – key element for the energy transition

Batteries play a central role in energy and climate policy, both to decarbonise motorised transport and as short-term storage for renewable energies to break load peaks. How efficient are deployed battery systems? What contribution could they make to balancing the distribution grids? And how can cells from batteries from electric cars be used economically for "second-life" storage?

Last year, 8 % of all new cars put on the road in Switzerland were pure battery electric vehicles, which corresponds to a doubling compared to 2019. In addition, there are 6 % plug-in hybrids, of which 4 times more were registered. According to the manufacturer, the lithium-ion batteries used in these vehicles have a service life expectancy of at least eight years, which corresponds to a mileage of around 160,000 km. After this time, the capacity of the battery can drop below 80 % of the original, so that it is no longer sufficient to power a vehicle. However, these capacities are quite sufficient for other applications, for example as home storage for solar systems.

The Swiss company Libattion specialises in giving used batteries a second life. Technically, such "second-life" storage devices work well. But are they also economical? One obstacle to large-scale recycling is the testing of the cells. To precisely determine the state of the individual cells of a battery system, a full charging and discharging cycle is required, which takes three to five hours – far beyond the time and effort needed to produce commercially viable "second-life" storage devices. The Centre Suisse d'Electronique et de Microtechnique (CSEM), together with Libattion, has therefore researched alternative measurement methods that allow the condition of battery cells to be reliably estimated within a useful period of time. The findings show that there are good correlations between various measured variables and the state of health (SoH) of the cells. As a result, cells that are suitable for a "second-life" application can be found much more quickly. Depending on the requirements – accuracy of the measurement, robustness of the analysis for different battery types, duration of the analysis or simplicity of the machine processing – different measurement methods are suitable.

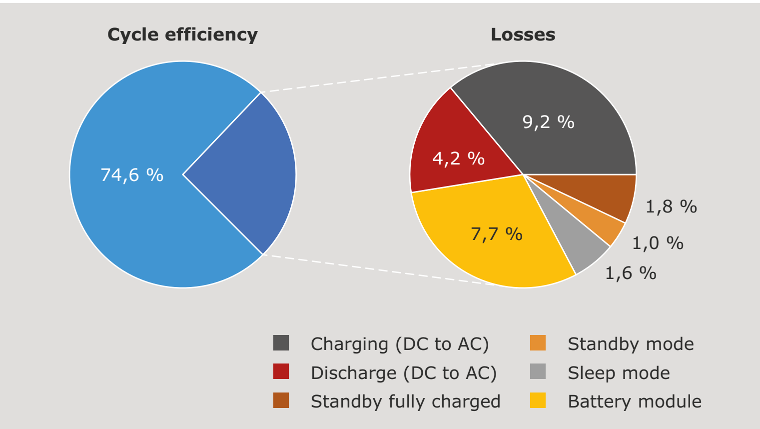
Not only the electromobility battery market is growing strongly, but also the market for home storage in combination with photovoltaic systems. From 2018 to 2019, the installed storage capacity has increased by around 70 % . How efficient are battery storage systems

Every year, approximately 543,000 vehicle batteries are imported in the European Union for traction purposes (pure battery vehicles and plug-in hybrids) , which corresponds to a storage volume of approximately 27 GWh for a standard battery pack of 50 kWh. It is predicted that in 2025, 27 % of these batteries will have a second life in stationary applications, while the remaining 73 % will be available for recycling. Thanks to efficient test procedures of aged battery cells, as developed by the Centre Suisse d'Electronique et de Microtechnique (CSEM) together with the company Libattion, "second-life" applications should become more economical.

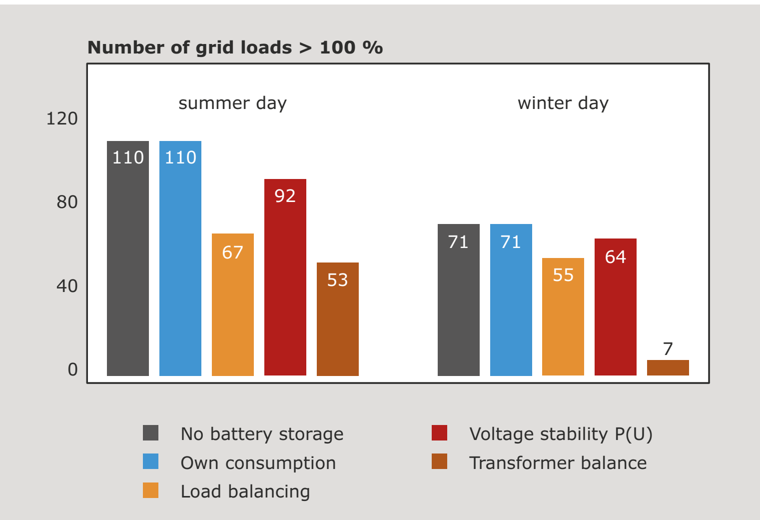
In a SFOE research project, test protocols have been developed that can provide the ageing status of battery cells in a few minutes, compared to the three to five hours required for a complete discharge/charge cycle (source: CSEM).

available on the market? So far, there is no standardised test procedure that depicts realistic operation. The OST University of Applied Sciences has developed such a test procedure, which determines relevant key figures in dynamic operation. The entire battery system, including the battery and photovoltaic inverter, is tested. Photovoltaic production and power consumption are emulated.

Today, home storage systems are mostly used to optimise self-consumption. Sometimes this places a heavy load on the distribution grid. Yet such decentralised storage systems have the potential to stabilise the distribution grid, provided that they are controlled in a "grid-friendly" manner: For example, home storage systems can draw electricity when the voltage in the grid becomes too high and release the energy back into the grid when the voltage drops. Various control strategies are possible. The benefits of "grid-friendly" control for the distribution grid and which incentive systems could promote "grid-friendly" control are under investigation in an ongoing research project with the participation of universities of applied sciences, distribution grid operators and battery manufacturers. Initial results show how grid utilisation changes with different control strategies. In a next step, the benefits will be quantified.



Test result of an alternating current (AC) coupled battery home storage system. A new test procedure from the OST University of Applied Sciences examines batteries in a 3-day test profile that covers all typical operating conditions for the battery. It provides reproducible key figures on the efficiency of the systems under different control approaches such as self-consumption, electricity price and grid use, and indicates at what points losses occur (source: OST-SPF).



The simulation of the grid load for a typical suburban distribution grid in 2035 shows the benefit of grid-serving control of decentralised storage compared to self-consumption-optimised control (blue). Three grid-serving control algorithms were distinguished: load balancing (orange) and voltage maintenance (red) for households with storage and load balancing at the transformer station (brown). The basis is a scenario for the year 2035 without grid expansion, which takes into account the expected increase in photovoltaics, electromobility and battery storage. In summer, photovoltaic production causes feed-in peaks, while in winter it is high electricity purchases that generate large load peaks (data source: BFH Centre for Energy Storage).

For a long time, silicon dominated the world of transistors. Today, compound semiconductors made of various elements play an increasingly important role. Light-emitting diodes based on gallium compounds have replaced other light sources in everyday life. In the field of power electronics, the application of gallium nitride (GaN) and silicon carbide (SiC) transistors allows for an increase in energy efficiency, which is crucial for electromobility and for power generation with renewable energy technologies. The photo shows a wafer with SiC diodes (image source: Bosch).

Efficient driving thanks to efficient semiconductors

From data centres to photovoltaic and wind energy systems or electric vehicles – all these applications involve power electronics that rely on switching elements made of semiconductors. Every switching operation brings losses. These can be significantly reduced with the use of semiconductor materials with a wide bandgap, so-called "wide bandgap" (WBG) semiconductors.

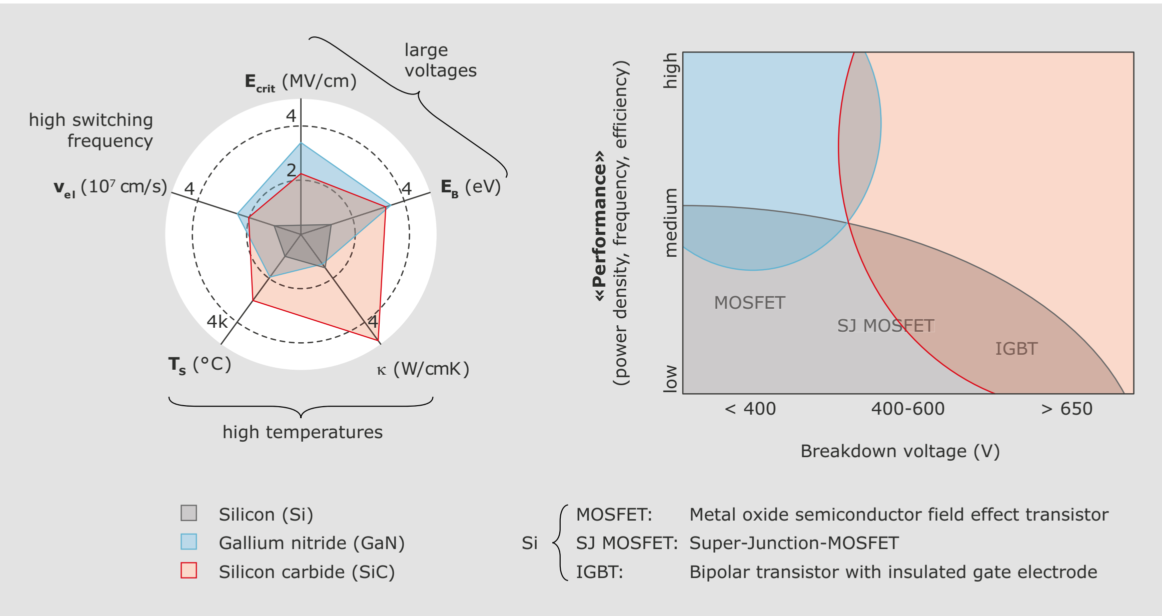
A working group established within the International Energy Agency (IEA) in 2019 on the initiative of Switzerland reveals how much energy could be saved with wide bandgap (WBG) semiconductor components. Applied in wind power and photovoltaic systems, data centres, electric cars and mobile devices, approximately 90 TWh of electricity could be saved globally each year, about one and a half times Switzerland's annual electricity consumption.

The main WBG semiconductors are silicon carbide and gallium nitride. Compared to silicon-based components, WBG power switches (transistors) operate faster, allow a higher packing density and work at higher ambient temperatures. An important advantage is the gain in efficiency: the losses during a switching operation are significantly lower. This comes into play in many applications, for example in converters in electric vehicles. These convert the direct current of the battery into alternating current and feed the drive motor. To control the motor's speed, the semiconductor components switch the voltage on and off at short intervals – several thousand times per second, depending on the concept and application. Each switching operation involves losses. The lower these are, the more efficient the inverter and the greater the distance that can be covered with one battery charge. The higher pack-

Important cost elements in electrically powered buses and commercial vehicles are the powertrain and the energy storage system. As part of a pilot project, a fleet of battery-electric buses is to be equipped with a new power converter based on silicon carbide (SiC) semiconductors, which will be integrated directly into the motor. The efficiency of the power converter has a direct influence on the required battery capacity and thus indirectly on the system costs (source: ABB).

ing density of the WBG semiconductors is also important: Inverters can be made smaller and lighter, which further increases vehicle autonomy.

The power engineering group ABB and bus manufacturer Hess are investigating the potential savings of the technology in such applications. They are developing all the components for the drive train of an electric bus, from the chip to the power semiconductor module to the converter, and are testing the components in practice. In Baden, an electric bus with the new technology will run on a regular line of the Regional Transport Authority Baden-Wettingen. In this way, the energy-saving potential of the technology is to be verified in real life. The field test serves to gather experience, especially for a precise quantification of the possible energy savings. This will allow a well-founded projection of the efficiency potential to be made.



(Left) Compared to silicon, the compound semiconductors gallium nitride (GaN) and silicon carbide (SiC) have a larger band gap (E_B) and a higher critical field (E_{crit}), which enables operation at higher voltages. Thanks to a high electron mobility (v_{el}), the transistors switch faster. A high melting point (T_S) and good thermal conductivity (κ) allow operation at higher temperatures, especially for SiC. (Right) Semiconductor components based on SiC and GaN are increasingly displacing Si components, as these enable significantly higher "performance".

Chicken farms demand a relatively high amount of energy in order to comply with the legal requirements. During a cycle of masting, the temperature curve is precisely defined: from 33 at the beginning, it gradually goes down to 20 degrees Celsius. The relative humidity should never rise above 60 %, otherwise the risk of disease increases. Furthermore, CO_2 and ammonia concentrations in the air must be kept within limits. These requirements demand a high air exchange rate. In two pilot farms, heat recovery technology has made it possible to significantly reduce energy requirements (image source: hiltifarm.ch).

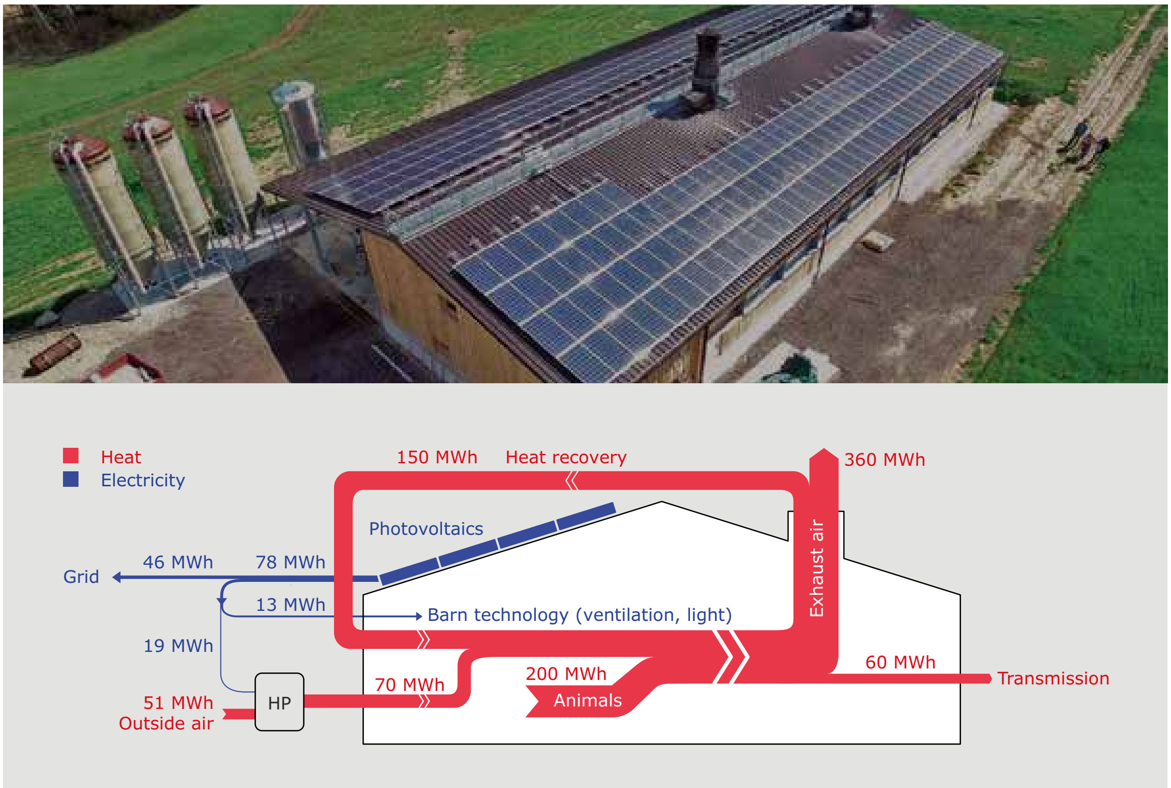
Modern chicken farms: energy-neutral, low-emission, animal-friendly

Chicken farms consume a lot of energy because the barns have to be heated and a constant exchange of air is required. Demonstration projects show that heat recovery and insulation of the building envelope can reduce energy demand by more than 50 %.

A chicken fattening farm with a size of 600 m^2 requires around 160 MWh of electrical energy per year in Switzerland, roughly equivalent to the consumption of 40 four-person households. Insulation and measures for heat recovery, like those used in other buildings, have hardly been used in agriculture so far. There was much suspicion as to whether technical adaptations were worth their investment costs and whether they would function reliably in view of the dusty conditions in farms. However, in view of the about 30 new fattening farms that are built in Switzerland every year and increasing demands on energy efficiency and animal welfare, it is worth taking a closer look at energy-saving measures for such farms.

In the context of demonstration projects, all relevant parameters regarding the stable climate and energy consumption were recorded for one year in two new barns in Hellsau and Zimmerwald. The Swiss meat company Bell Food Group AG and the animal and stable technology provider Globogal AG have independently developed new barn concepts that are to be adopted by farmers in the future. Both concepts rely on own solar power production on roofs, insulation of the building envelope, heat recovery from exhaust air and heat pumps for heating. As a result, the energy demand can be reduced by more than 50 % compared to the empirical values of comparable businesses. Three quarters of these savings are due to heat recovery.

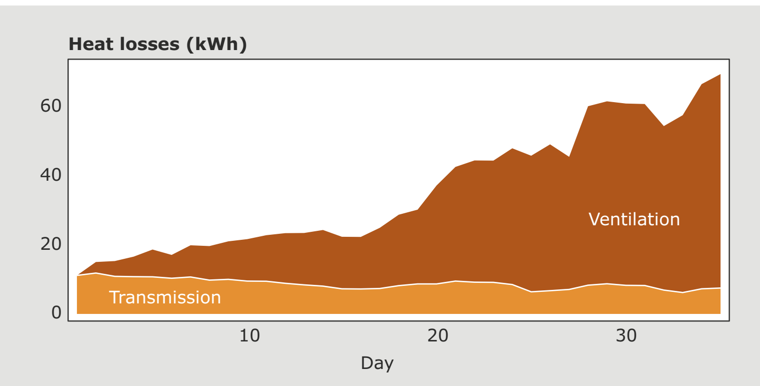
The projects prove that new buildings for poultry farms can meet the requirements of the Minergie standard and that operational safety is



(Top) The Leuenberger fattening poultry house, Hellsau BE, 2019. (Bottom) Energy flow diagram for heat and electricity in a Minergie poultry farm (Data Hellsau).

guaranteed: the heat recovery systems of both manufacturers withstand the dusty exhaust air in continuous operation. The additional investment in the Hellsau project amounted to about CHF 400,000, which is offset by savings in energy costs of about CHF 21,000 per year.

Further optimisations are possible and thus the barn concept seems promising for long-term economic operation. The investment and maintenance costs for the heat exchangers should be amortised within a few years.



Only about 25 % of heat loss occurs through transmission (heat dissipation via the building envelope), the rest is at the expense of constant ventilation. More energy can be saved through heat recovery technology than through insulation of the building envelope.

On both farms, the photovoltaic yield exceeds the farm's own needs by more than twice. The barn in Hellsau has, in addition to the photovoltaic system with an output of 70 kW, a heat storage tank for the heat pump (HP) of 20,000 litres and an electricity storage tank of 18.8 kWh. This allows the farm to cover 87 % of its electricity and heat needs throughout the year. With larger storage tanks, the farm could be almost completely self-sufficient.

In addition to improved energy efficiency, the measures also achieve a better climate in the barn, which benefits the health of the animals and helps the farmers to achieve higher meat yields and better meat quality. The exhaust air scrubbers on the farm in Zimmerwald also recover nutrients from the exhaust air. These are discharged back into the farmers' fields as fertiliser, thus closing the nutrient cycle.

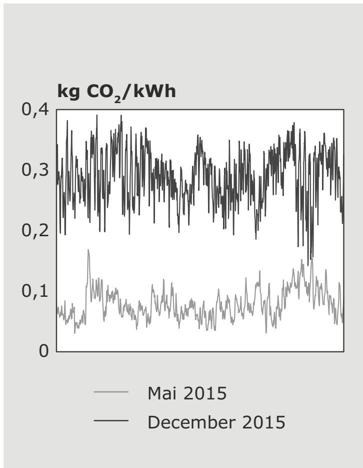
Preparing electrical grids for the future

As a result of the increasing decentralised feed-in of renewable power, battery storage, electric vehicles and heat pumps, distribution grids get used ever more intensively. Furthermore, modern power electronics, used for instance in inverters or chargers, influence the voltage quality. Researchers investigated how these factors affect the grid quality with tests in various distribution grids and in the laboratory, as well as with simulations. In long-term data, no general deterioration of the voltage quality can be determined. However, measurements show that devices with power electronics can influence the grid impedance and thus affect communication via the power grid (powerline communication), which is used for ripple control, among others.

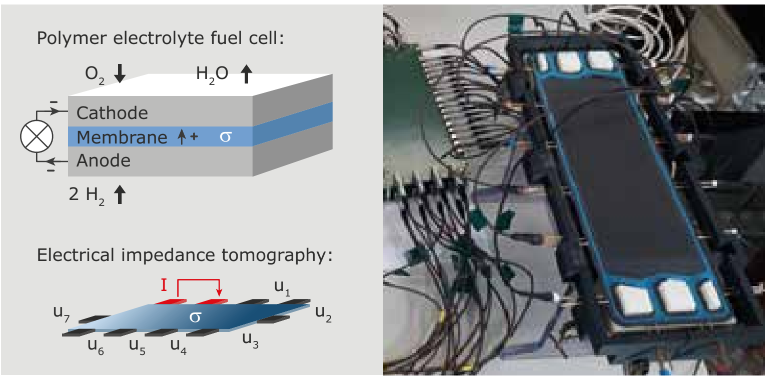
A large number of different influencing parameters make it difficult to compare power quality (PQ) across grids. As part of various measurement campaigns, a PQ index was developed that enables the evaluation of different PQ phenomena using a single key figure (source: Bern University of Applied Sciences BFH).

Dynamic building life cycle assessments

In life cycle assessments for buildings, the Swiss electricity mix is used to calculate the environmental impact associated with electricity consumption – regardless of whether the electricity was consumed in summer or winter, during the day or at night. However, depending on the time of electricity consumption, the origin of the electricity and thus its environmental impact varies. Two recent studies analyse the origin of electricity for different hourly load profiles and show the impact on the life cycle assessment. Based on this data, a new calculation procedure and life cycle assessment methodology were developed for the Swiss building park.



The CO_2 impact of the Swiss consumer electricity mix changes over the course of the year and the day. In summer, the share of electricity from renewable sources such as hydropower and photovoltaics is higher. In winter, when electricity demand from buildings is highest, electricity imports, which also originate from non-renewable sources, account for a larger share (data source: https://doi.org/10.1016/j.dib.2020.105509).



(Left) In order to examine the conductivity distribution σ in fuel cells by electrical impedance tomography, an alternating current I is applied between two electrodes (red) and the resulting changes in the surface potential are measured between pairs of electrodes. Repetition with many different configurations provides data from which the conductivity distribution in the membrane can be calculated. (Right) Experimental setup at the Paul Scherrer Institute.

New diagnostics for fuel cells

Polymer electrolyte fuel cells (PEFCs) are central to the use of hydrogen in the mobility sector. Knowledge about the conductivity distribution within the PEFC membrane is important in this context. The conductivity depends on the membrane humidity, which is influenced by various operating parameters. The point is that the membrane does not dry out locally, which leads to damage. Moreover, partial flooding of the fuel cell by excessive product water must be prevented. Until now, it has only been possible to determine the conductivity within a PEFC membrane using invasive methods that cannot be practically applied. The Paul Scherrer Institute is developing a new, non-invasive method as part of a SFOE project. The method is based on electrical impedance tomography, where the relationship between the conductivity distribution of an object and the potential distribution that can be measured on the surface is analysed.

Renewable energy

A different approach to wind energy

A flying apparatus travels along a circular path at an altitude of 200 to 500 m – what looks like a toy at first glance actually produces electricity from wind energy. Such alternative wind energy concepts, called "Airborne Wind Energy" (AWE), are attracting more and more interest internationally and are also the subject of current research projects in Switzerland.

"Airborne Wind Energy" (AWE) systems use the wind in an unconventional way: a flying device – a small plane, drone or kite – drives a generator on the ground via the unwinding of a rope. Thanks to optimised control and wing shape, more electricity is produced when the flying device rises in the wind than is consumed during recovery. In continuous operation, the flying machine moves along a three-dimensional trajectory in space, where ascent and descent alternate continuously.

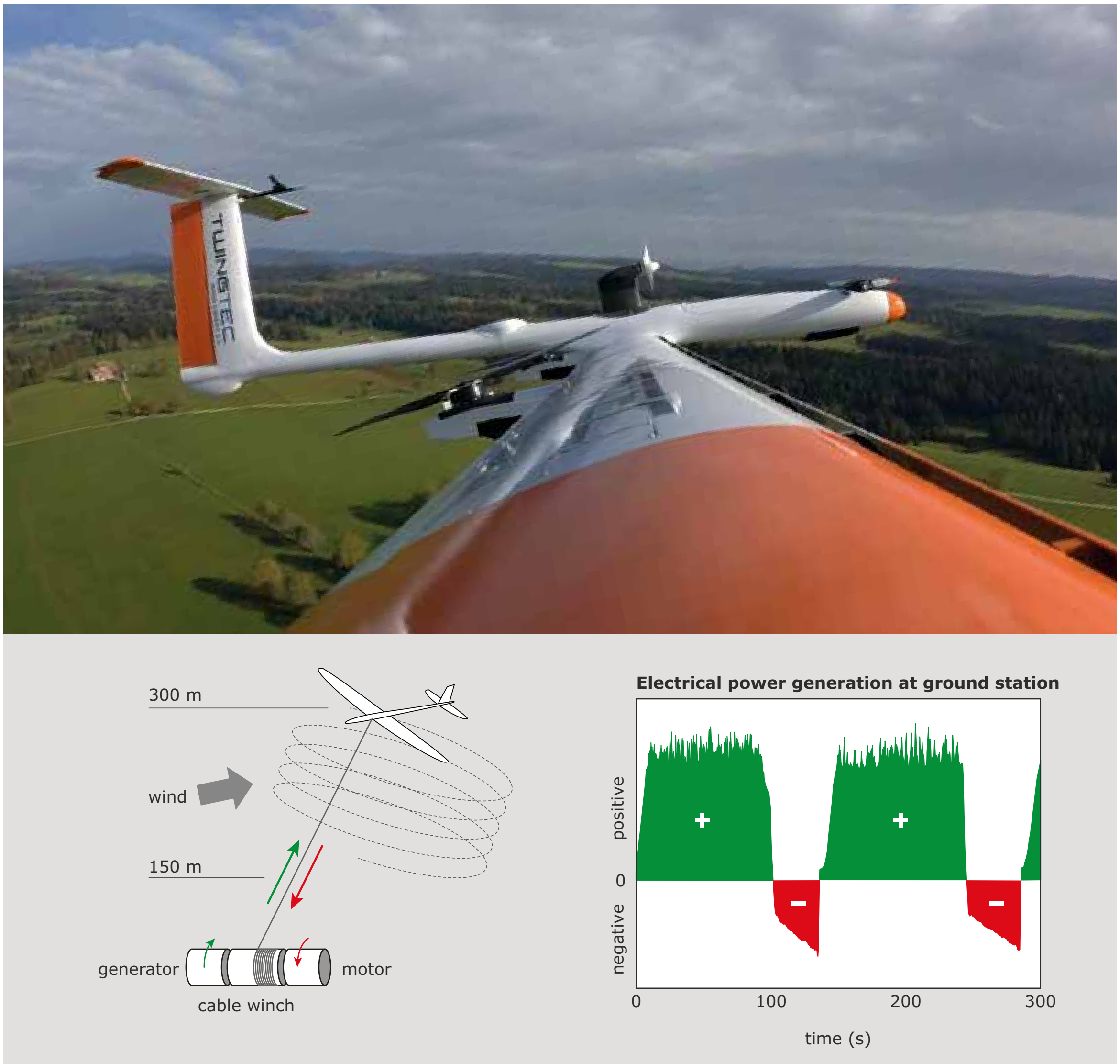
At an altitude of 200–500 m, winds are stronger and more regular than near the ground. Such steady wind conditions can be exploited by AWE systems, which fly in areas well above the height of the largest conventional wind turbines. As a result, variations in generation are reduced. AWE systems are lightweight, require little material and are mobile for use at different sites.

It is still open whether this still young wind energy technology will succeed in the market. Ten years ago, considerable scepticism prevailed, today experts believe the opportunities for this technology are intact. In September 2020, for example, almost 100 experts from research and industry from 18 countries discussed this technology and its potential at a meeting of the International Energy Agency (IEA). According to the IEA, around 60 organisations worldwide are working in this field. In Switzerland, two young companies are active in this area: TwingTec AG and Skypull SA both have pilot systems (see illustration on the left and on the following page) and in the process of developing them to market maturity. The systems will be improved to the point where take-offs, landings and fully automatic continuous operation can run in a stable manner, even in difficult weather conditions.

Other challenges are the long-term durability of the materials and, in particular, the regulatory framework for operation. For example, what

In "Airborne Wind Energy" (AWE), the most efficient part of a conventional wind turbine, the tip of the turbine blade, is replaced by a highly efficient flying object connected to the ground by a cable. Periodically unwinding the rope over a winch generates electricity in a generator. In some systems, electricity is also generated in flight via turbines (generators) that are carried by the aircraft, and the power generated is transmitted to the ground via the cable.

The illustration on the left shows the system of the Ticino-based company Skypull SA. The aircraft is a hybrid of a normal fixed-wing aircraft and a multicopter drone with four rotors. As a drone, the apparatus can thus take off and land even in complex terrain, while at higher altitudes the lift is generated by the wings. In the test phase, the system has a wingspan of 1.3 m, but much larger devices could be built in the future (source: Skypull SA).



Working principle of an "Airborne Wind Energy" system with power generation on the ground: a flying device (drone, glider or kite) connected to the ground with a cable makes use of the kinetic energy of the wind and thus pulls the cable from the coil, which is connected to a power generator. Once a certain flight altitude is reached, the aircraft is recovered to its starting altitude. The net electricity generation in such a "pumping cycle" corresponds to the green area minus the red one. (Top) Flying device of the Swiss company TwingTec AG, which consists of a small glider that can be brought to the initial flight altitude with electric propellers. The area flown over in "pump" mode, which is given by the maximum cable length, may not be entered because of the danger of a cable break (Photo: TwingTec AG).

happens if a helicopter approaches and the pilot does not see the aircraft or the rope? How can the object and rope be made more visible? TwingTec and Skypull are investigating such questions as part of a project supported by the SFOE. The systems of both companies use the collision warning system "FLARM", which was originally developed for sailplanes. It consists of a GPS receiver and a radio module that transmits its current position at close range (a few kilometres) to other "FLARM" devices. Skypull is also working on a camera system that enables their aircraft to detect approaching helicopters, paragliders or small aircrafts. Both companies further investigate how best to illuminate the aircraft so that it can be better seen by pilots of an aeroplane or paraglider. Noise emmission is also an issue, especially during take-off and landing. To this end, Skypull and TwingTec are taking measurements at various places.

The area of application for AWE systems in Switzerland could lie specifically in isolated solutions, for example in mountain huts. Also conceivable would be systems as a supplement in conventional wind farms or – a still visionary idea – as offshore installations in the sea.

Water headrace tunnel of the Gletsch-Oberwald power plant. The water from the Rhone flows through this tunnel to the turbines with a drop of around 300 m. The installed capacity is 14 MW, but with an annual production of 41 GWh, the average output of the power plant is only 4.7 MW. The plant has been built underground to have as little impact on the environment as possible. Only a few Swiss smallscale hydropower plants use the principle of such high-pressure run-of-river power plants. However, they account for a large part of the total electricity production from smallscale hydropower plants (source: FMV).

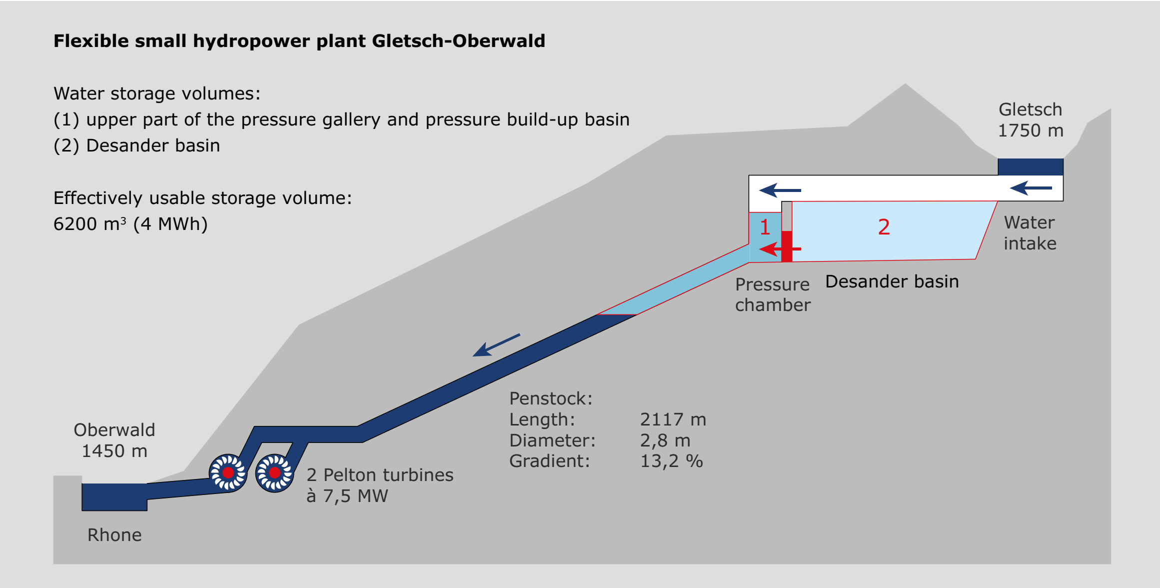
Flexible run-of-river power plants

Depending on the discharge, a hydroelectric power plant on a flowing watercourse produces more or less electricity. If the water level falls below a minimum value, a power plant comes to a complete standstill. Production can be made more flexible if existing volumes in basins and galleries are used as water reservoirs. Valuable balancing energy can thus be gained and a better yield achieved at low discharge rates.

Since 2018, the Gletsch-Oberwald power plant has been supplying electricity for 9,000 households. It uses the difference in elevation of the Rhone between Gletsch (1750 m) and Oberwald (1450 m) to generate power. However, the amount of electricity produced depends on the water flow of the Rhone and cannot be adjusted to the demand. Especially in winter, the Rhone's discharge is often insufficient to operate the turbines at minimum capacity and the water is diverted bypassing the power plant.

Researchers from various institutes led by the University of Applied Sciences Western Switzerland are investigating ways in which run-of-river power plants can be operated more flexibly in order to provide lucrative balancing power. For this purpose, more water is directed to the turbines during periods of high electricity demand than actually flows in from the Rhone. This empties the sedimentation basin and part of the headrace tunnel (see diagram on the following page). When the power demand is lower, these volumes are refilled with water and thus used as storage. These storage volumes can also be filled at low discharge rates while the turbines are temporarily at a rest. This allows electricity to be produced temporarily, even in winter, when the Rhone actually has too little water.

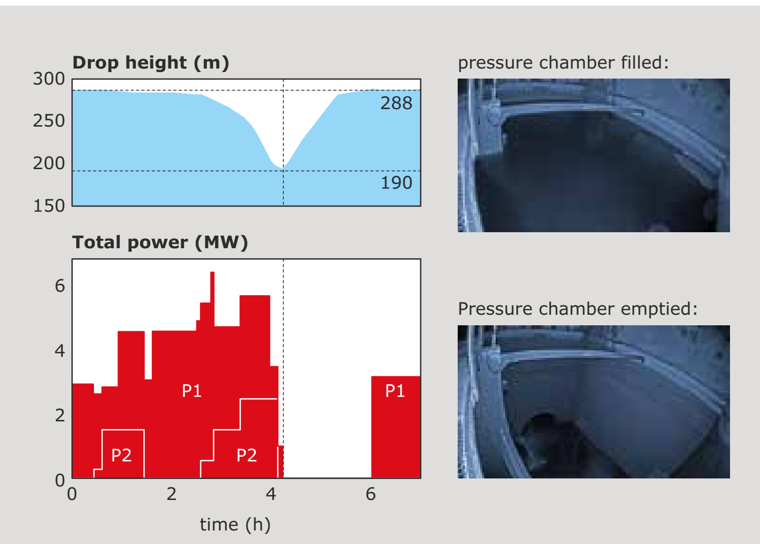
A pilot operation has been successful so far: production in winter could be doubled without major structural modifications, simply by using the existing storage volumes in the settling basin, pressure chamber and part of the headrace tunnel. In addition, the operator was able to offer



At the Gletsch-Oberwald power plant, the water from the Rhone is captured and fed into a desander basin (settling basin for the entrained fines). When the basin is full, the water flows over a partition wall to the pressure chamber and from there into the tunnel, which leads to the turbines in Oberwald about 300 m below. In normal operation, the desander basin, pressure chamber and gallery are filled with water. For flexible operation, the (1) volumes of part of the pressurised water gallery and the pressure chamber and (2) the volume of the desander basin can be used. The water content of these volumes can be controlled with the operation of the turbines and by opening and closing a gate (red) in the valley-side partition wall of the desander basin. The water level in the pressurised water tunnel can only be lowered to a limited extent, as the geometry of the water jet hitting the Pelton turbine is no longer correct if the water pressure is reduced too much, and the turbine loses efficiency and ages more quickly.

balancing power with a capacity of around 1.5 MW throughout the year. With good forecasts of runoff volumes and electricity demand, the power plant operator can control production and thus achieve better prices, which decisively increases the profitability of the power plant.

However, due to this flexible use, higher fluctuations in discharge are to be expected in the natural flow of the Rhone downstream of the power plant. From a water ecology point of view, this so-called hydropeaking can be problematic. However, accompanying ecological studies have shown a low impact on aquatic life. In order to keep the impact on the river ecology as small as possible, the power plant is controlled in such a way that the discharge peaks are no more than 1.5 times as large as the base discharge. In winter, the discharge is even flattened due to the lower number of shutdowns and restarts. Nevertheless, for each power plant that is to be operated in this way, clarification is required in advance as to whether changing discharge volumes could have a negative impact on the ecosystem.



The use of water reservoirs in the power plant made it possible to produce peak energy for four hours. During this time, the reservoirs were emptied and the water level in the pressure tunnel was lowered to 190 metres. In the following three-hour phase, the reservoirs filled up again, with little or no electricity being generated. The purpose of the tests was to analyse the different speeds at which the level was lowered and filled in the headrace tunnel and the effects on the Pelton turbines. (P1 = Pelton turbine 1, P2 = Pelton turbine 2) (Source: according to final report SFOE project "SmallFLEX").

With machine learning, solar plants can be identified in aerial photographs. The result here shows a section of the city of Basel with photovoltaic installations marked in red and solar thermal installations marked in yellow.

Airborne solar statistics

Anyone flying over Switzerland with the "Google Earth" software will immediately recognise roofs with solar installations. Nevertheless, no one knows exactly where systems are installed. It would be fascinating to systematically identify photovoltaic and solar thermal collector panels from aerial photographs. Researchers at the University of Applied Sciences and Arts Northwestern Switzerland (FHNW) have dared to do so with the help of machine learning.

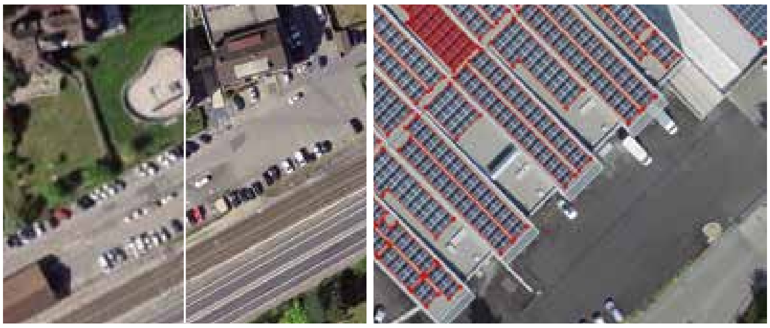
How many solar systems are installed in Switzerland? How much electricity and heat do they produce? Such figures are estimated today on the basis of market surveys and average annual yields. However, they are fraught with uncertainties. For example, sales figures do not reveal where the photovoltaic modules and solar thermal collectors are installed and with which orientation and inclination. These factors have a considerable influence on the annual production.

Could this data be recorded more accurately thanks to digitalisation? Researchers at the FHNW came up with the idea of automatically detecting photovoltaic panels and solar thermal collectors on aerial photographs. Similar approaches are also being pursued at other research institutions in Switzerland and abroad.

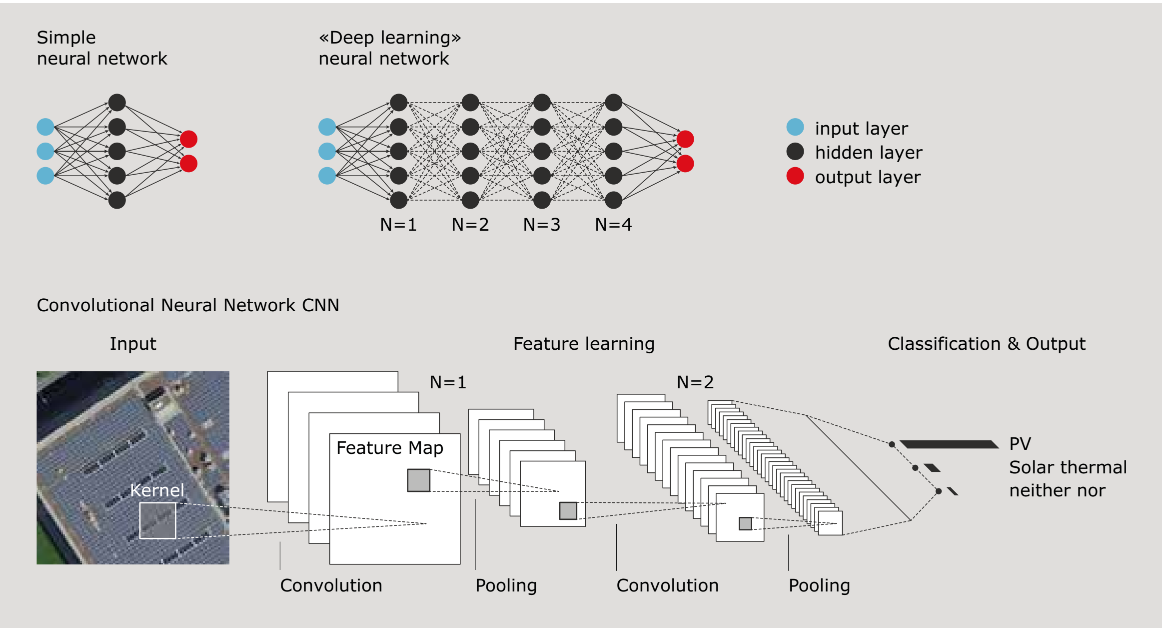
Automatic detection is only possible thanks to high-resolution aerial photographs from the Federal Office of Topography swisstopo. The images, which are free of distortions (orthoimages), cover the whole of Switzerland with a ground resolution of 10 cm in the lowlands and 25 cm in the Alps and are updated every three years. In addition, swisstopo has 3D models of all Swiss buildings. This information can be used to determine the orientation and inclination of roofs in order to calculate the area of solar installations and, in a further step, their production.

Machine learning methods are used by the researchers to analyse the aerial images. By means of aerial photos on which solar plants were marked and assigned by hand, the computer "learns" to recognise the solar surfaces as such. In the process, the algorithm does not simply search the aerial photos for predefined images, but derives its own patterns and laws from the training data.

The more learning material the algorithm receives, the better it gets. The software of the FHNW, which was fed with 30,000 training data, already achieves a remarkable performance: 92 % of the detected photovoltaic installations were indeed photovoltaic plants. The algorithm has somewhat more difficulty with solar thermal collectors: 88 % are correctly assigned. However, the algorithm still does not recognise all solar surfaces. The rate gets worse with increasing accuracy the algorithm has to determine whether the modules are photovoltaic or solar thermal. Absolute area data can therefore not yet be derived precisely with the method. However, it is possible to make statements about the geographical distribution of solar installations or about changes over time if the analysis is repeated regularly.



A decisive prerequisite for the identification of solar installations on aerial photographs is a correspondingly high resolution. The Federal Office of Topography swisstopo now provides images with a resolution of 10 cm. The left image illustrates this in comparison to the previous resolution of 25 cm (left part of the image). In order to train the neural network, a total of 7,839 images were prepared where photovoltaic and thermal plants were marked with polygons (source: FHNW).



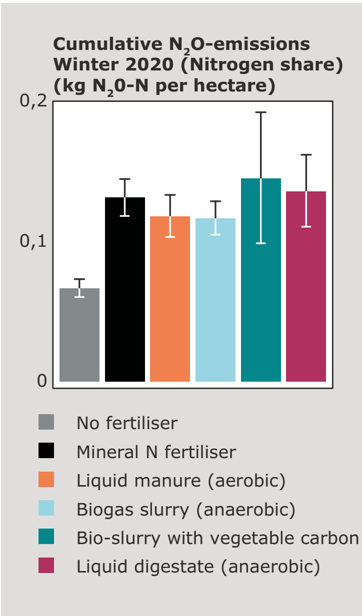
Artificial neural networks are used to recognise solar plants in aerial photographs. These networks are made up of different layers of artificial neurons (nodes) that are connected to each other. So-called weights define how strongly the individual neurons depend on each other. The weights in the hidden layer are adjusted by means of predefined "learning material" to make the result in the output correspond as closely as possible to the input. If there are several intermediate layers, this is called "deep learning" networks.

In a convolutional neural network (CNN), intermediate layers are made up of (1) a convolutional layer, where mermals are scanned with filters (kernel) and the information is mapped onto different feature maps, and (2) a pooling layer, where unnecessary information is removed. At the end, there is a classification and the output of the probability that the object belongs to a certain class. In this research project, a relatively new method (Faster R-CNN) was used. In an R-CNN, an image is first examined for possible objects with a search algorithm, which then suggests image regions that contain an object with a certain probability. The R stands for "region based". Faster R-CNN builds on this and corresponds to the current state of research.

"Big Data" for solar forecasting

The amount of electricity a photovoltaic system generates depends on the weather. In the reverse sense, the current weather situation at a location can be derived from the production data – photovoltaic systems could thus serve as decentralised weather stations to predict production. To this purpose, researchers at the Centre Suisse d'Electronique et de Microtechnique (CSEM) have developed a self-learning algorithm that was trained with real and simulated production data. The production forecasts calculated for three hours were comparable or even better than those based on meteorological data. The algorithm also proved to be robust against errors and gaps in the production data transmitted by the photovoltaic plants.

The basic idea behind solar forecasts based on "Big Data" is to make events in past PV production (e.g. clouds) informative for predicting production at other locations. The figure shows an example of a set of PV production locations for the prediction of a plant in central Switzerland.



Climate impact of fertilisers from biogas plants

Slurry and digestate from biogas plants are valuable fertilisers. Recently, the use of vegetable carbon has also come into focus. Its production by means of pyrolysis not only yields renewable energy, but the plant carbon itself is also said to improve the soil and bind CO_2 in the long term. How do organic fertilisers from biogas plants and plant carbon behave in the field? Do they lead to higher or lower greenhouse gas emissions than other fertilisers? This is one of the decisive factors in determining whether energy production from biomass has a positive effect on the climate in the long term. This question is being investigated by an overarching research project of the Federal Offices for Agriculture, Environment and Energy.

Cumulative nitrous oxide emissions with different fertiliser applications for winter barley. The type of fertiliser has no significant influence on emissions. Rather, they increase with greater precipitation and higher soil temperatures.

Hybrid (PVT) modules consisting of photovoltaic and thermal collectors are installed on the building of the company Oblamatik in Chur. The building also features a thermally active foundation plate. During heating season, it serves as a source of heat for the heat pump and is actively regenerated via the PVT system and passively regenerated via the ground. In cooling mode, the slab and the surrounding soil absorb building heat. Overnight, the concrete slab is cooled down via the PVT system. The 384 m2 absorber surface of the PVT modules transfers heat to the air via convection and to the cold sky via radiation exchange (source: Oblamatik).

New terrains for solar thermal energy

How to store solar heat seasonally? Various approaches are being investigated in several pilot and demonstration projects. One way is to feed the heat into the ground via geothermal probes from heat pump heating systems. This reduces the cooling of the ground and the heat is available again in winter. With new materials for borehole heat exchangers, the heat transfer between the probe and the ground could be improved, both during heat extraction and during heat recovery. In addition to the ground, building components can also be used as heat reservoirs. Geographically, such solutions seem particularly promising in locations with high irradiation and high heating requirements.

Socioeconomics

The mobility turnaround in our minds

Electric vehicles are on the rise. How to get even more people to buy an electric vehicle is being investigated in several current studies.

Road traffic is responsible for about one third of CO_2 emissions in Switzerland. Electric vehicles are key with regard to reducing these emissions. And indeed, electric vehicles are becoming increasingly popular: sales figures in the vehicle market have been below the long-term average since the start of the Covid 19 pandemic, but sales of electric and hybrid vehicles are increasing significantly. Still, only about 8 % of new registrations have a purely electric drive. Where should we start to convince customers even more of the benefits of electromobility?

A study by ETH Zurich investigated how people who own a vehicle themselves perceive electromobility and government incentive schemes for the latter. The approval and possible purchase intentions increased significantly in the course of the study after the participants had received more knowledge about electromobility and some were also able to test drive electric vehicles. Information about already installed public charging stations as well as own experiences with an electric car had a positive effect on purchase intentions.

Another study by the University of Geneva also showed that many drivers underestimated how large the share of journeys that can be covered by an electric car is. Information on this can have a positive effect against the so-called range anxiety. According to another study by the University of St. Gallen, product bundles of electric vehicles and charging services can positively influence customer acceptance of electromobility. In another piece of work, the University of St. Gallen also investigated which marketing and communication measures can influence the purchasing process in order to support electromobility. Here, the role of the vehicle salesperson proved to be central, with the manner of communication being very important in the sales process.

(Left) The network of charging stations for electromobility in Switzerland is already relatively dense by international standards. At www.ich-tanke-strom.ch users can see in real time which charging stations are currently free (image source: map.geo.admin.ch).

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. https:// www.iea.org/tcp), see page 34.

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

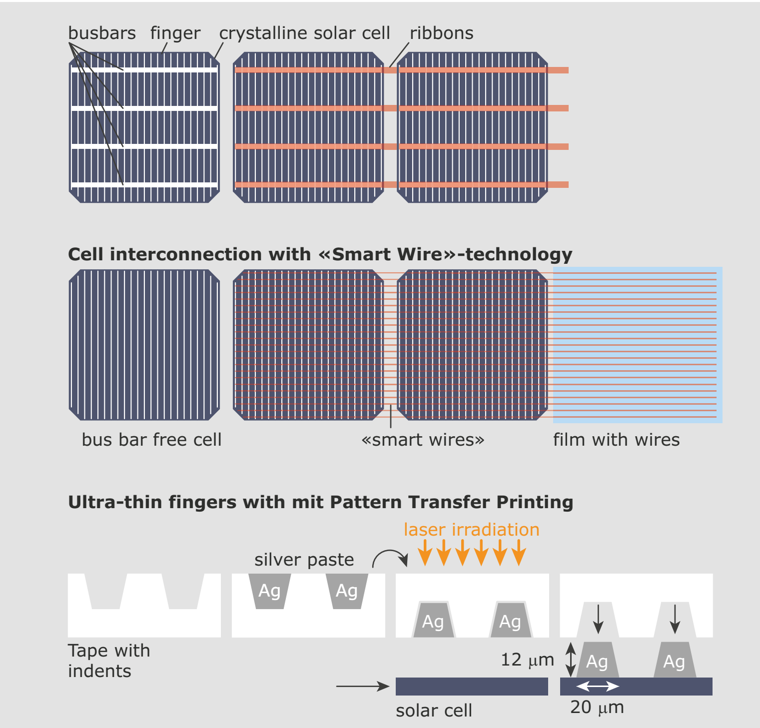
(Left) Hydrogen mobility in Switzerland is gaining momentum, with around 50 fuel cell trucks already on Swiss roads. The filling station network is also being steadily expanded on the basis of private initiative. For this purpose, hydrogen logistics are carried out via containers where hydrogen is stored under pressure. In the area of the use of hydrogen for heavy transport, Swiss stakeholders are playing a pioneering role internationally and the activities are receiving a great deal of international attention (photo source: Hydrospider AG).

Less silver – lower-cost photovoltaics

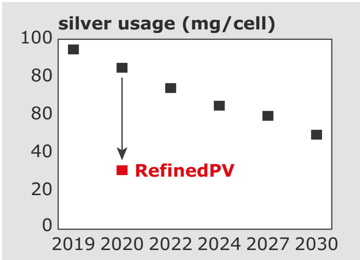
Prices in photovoltaics have been falling for years. It is all about increasing efficiency and reducing manufacturing costs. In a European project, the focus was on the cost reduction that can be achieved by saving expensive components (silver) through innovative contact and connection technology for solar cells.

Thanks to rapid market development, prices for photovoltaics have fallen by 80 % in the last ten years. Today, solar power is one of the cheapest renewable energies. One starting point to further reduce costs is to lower the amount of silver in the conductive pathways that collect and transport the electricity from the cells: Fine fingers collect the current in the cells and conduct it to the busbars. Individual solar cells are connected to each other by so-called ribbons. In recent years, new approaches have been developed that use less material and where the conduction losses are smaller. The Swiss company Meyer Burger uses its "Smart Wire Connection Technology" (SWCT) for this purpose, where numerous fine wires are attached to the cell across the contact fingers and connect neighbouring cells to each other. To reduce silver consumption in the contact fingers, the Israel-based company Utilight has developed a new technology that allows ultra-thin wires (20 µm) to be deposited on the solar cells, hardly possible with standard screen printing processes.

In a joint project within the framework of the European SOLAR-ERA.NET network, these two companies have combined their technologies together with the German research centre ISC Konstanz. On the cell side, it was possible to reduce the consumption of silver to 28 mg per cell, a value that is years ahead in terms of technological development over time. Meyer Burger manufactured solar modules from the fine-line metallised cells using SWCT interconnection technology and indium-free wires, and tested them according to standard norms. The maximum module power achieved with these cells is 310 W (60-cell module) and thus exceeds commercial 3-busbar modules by more than 15 W.



To contact crystalline silicon solar cells, metallic fingers and busbars are printed on the cells as current busbars. In recent years, technologies have been developed to connect cells without busbars and to reduce the width of the contact fingers. Both help to improve performance, as the cell is less shaded and there is less ohmic loss. Furthermore, silver is massively saved, which is a relevant cost factor.



Silver consumption for silicon solar cells (monofacial, p-type) according to the International Technology Roadmap for Photovoltaic (ITRPV, 2020).

SOLAR ERA-NET

Procekt "RefinedPV"
(Reduction of Power Losses by Ultra-fine Metallization and Interconnection of Solar Cells)

Project duration: 2017–2020

Swiss participation:
Meyer Burger Technology AG

Hydrogen with negative CO_2 emissions

Net zero greenhouse gas emissions by 2050: Hydrogen and the binding and storage of CO_2 play a decisive role in achieving this goal. In a broad-based European research project with Swiss participation, researchers were investigating what this path could look like.

Heat pumps are not suitable for high process temperatures, and battery-powered vehicles reach their limits when transporting heavy loads. In order to decarbonise these areas, hydrogen should be used. How can hydrogen be made available that has been produced with low CO_2 emissions? In the European “Elegancy” project with 22 partners, the extraction of hydrogen from natural gas with simultaneous capture and storage of the CO_2 released in the process was investigated.

The researchers see great potential in the production of hydrogen from biomass. This allows “negative CO_2 emissions” to be realised in order to compensate for emissions in other sectors such as agriculture or air traffic. Hydrogen is obtained from biomass either by steam reforming biogas produced from biowaste. Or wood is converted into synthetic methane or hydrogen by gasification. In both cases, CO_2 can be captured and permanently stored underground. The CO_2 extracted from the atmosphere by plants during growth is not released again and the CO_2 balance is neagtive.

Special attention was paid to the storage of CO_2 underground. Are there suitable storage sites in Switzerland that have sufficiently large capacities and are impervious to gas leakage? The researchers have developed a screening methodology to determine potential storage sites. The aim is to quantify the most important geological properties required for CO_2 injection and to assess their uncertainties. Three sites were investigated for their potential – one of them in the Entlebuch, where natural gas was once produced. Such former gas deposits, which are numerous in the North Sea, are particularly well suited as sinks. Where natural gas once accumulated, it can be assumed that the subsoil is dense.

At the Werdhölzli site of Biogas Zürich AG, biogas is produced from organic waste and fed into the gas grid. In the future, also hydrogen could be produced from this biogas. If the CO_2 were captured and stored in the ground in the long term, emissions would even be negative (Source: Energie 360° AG / Daniel Hager Photography).

ERA-NET ACT

Project “Elegancy”
(Enabling a Low-Carbon Economy via Hydrogen and CCS)

Project duration: 2017–2020

Swiss participation:
ETH Zürich,
Paul Scherrer Institut PSI,
Climeworks AG

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 side) Drone of the company TwingTec AG for an alternative wind energy concept, see report page 21 (source: TwingTec AG).

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