Energy Funding Programme 2013–2020

FINAL REPORT

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

Content

Prefaces

André Kudelski
President of the Innosuisse Board
Matthias Egger
President of the Research Council SNSF

Since prehistoric times, energy has been linked fundamentally to innovation. This may have started with the domestication of fire, which revolutionized the way of life for early humans by providing, among other things, heat, light and security, and proved to be a key differentiator from other living species on Earth. For millenniums, energy was a key driver for progress in agriculture, transportation, automation and industrial development. By fuelling improvements in productivity, energy provided humans more time to think outside of the box.

For much of our history, the primary goal of humankind in this field was to find energy in abundance and at cheap prices, but this has changed due to the growing impact of humans on our planet. While energy needs remain high, especially with the growing global population, the challenge now is to ensure that the energy we use is renewable. This is in order to secure the supply in the future and to avoid collateral damage like climate change.

Lowering energy consumption for everyday life as well as ensuring the renewability of energy sources present a real opportunity for Switzerland. This helps reduce dependency on fossil fuels, which are not a Swiss natural resource. Designing devices that consume less power also has other virtues for the information technology sector by enabling faster calculation times and longer battery life, which are key for higher performance and comfort of use.

The scientific work and networks established in the SCCER and Joint Activities are an excellent stepping-stone to address the complexity that comes with the systemic challenge of energy transition. The Energy funding programme has increased the capacities in both academia and the economy. It thus provided the impetus that will lead to more excellent research and tangible solutions in practice.

The Swiss energy research landscape benefitted from the joint strategic steering of the Energy funding programme by Innosuisse and the Swiss National Science Foundation (SNSF) and from the valuable advisory support by the Swiss Federal Office of Energy (SFOE). This cooperation facilitated the transfer of information and better coordination of the support for energy research and development.

The present report provides insights into nearly eight years of coordinated energy research in Switzerland from the point of view of the experts who accompanied the SCCER and Joint Activities. These experts formulate recommendations for further steps to be taken to favour the implementation of the Energy Strategy 2050. Innosuisse and SNSF, without explicitly commenting on the content, consider these recommendations to be a valuable contribution to further discussion on this important issue.

Benoît Revaz
Director of the Swiss Federal Office of Energy

Switzerland's decision in the wake of Fukushima to phase out nuclear energy will require a significant increase in energy research. Eight Swiss Competence Centers for Energy Research (SCCERs) were set up between 2013 and 2020 to expand the human research capacities as required for this purpose. They were to provide scientific answers to key questions relating to the Energy Strategy 2050.

What are the conclusions we can draw today? The track record of the SCCERs is convincing. They have fulfilled their task not only of producing further "scientific reports", but also of presenting the many findings obtained in a wide variety of White Papers and in such a comprehensible way that the conclusions and recommendations form a useful basis for politics and administration.

The fact that the federal government did not simply provide more funding for research projects, but deliberately invested in the establishment of new research teams, was a well-thought-out move. The conditions attached to this have led to the formation of cross-functional teams in the SCCER disciplines. Technical and non-technical researchers have come together and learned to jointly identify and address problems. Former silos have become interdisciplinary think tanks.

We can build on that today. The new funding instrument Swiss Energy Research for the Energy Transition (SWEET), which is based at the Swiss Federal Office of Energy, creates the possibility of funding interdisciplinary and transdisciplinary consortia projects, each of which will run for a period of six to eight years and provide comprehensive answers to broadly formulated questions from a systemic perspective. The collaborations established among the SCCERs are an important prerequisite for this.

Preamble

Dr. Adriano Nasciuti
President of the Steering Committee

To support the realisation of the Energy Strategy 2050, the Federal Council and Parliament created a novel concept to strengthen research and innovation – the Energy Funding Programme. The core of this programme was the creation of eight Swiss Competence Centers for Energy Research (SCCERs), covering seven action areas. These action areas were defined in the Dispatch to Parliament on the action plan "Coordinated Energy Research in Switzerland – measures for the years 2013–2016" (see page 17).

This final report provides an overview of what has been achieved, using selected examples of activities and results.

All the SCCERs simultaneously addressed challenges at different stages of the knowledge and value creation chain in coordinated fashion. In addition, the research and development activities involved multiple higher education institutions (HEIs) per SCCER. This enabled the different HEIs to benefit from each other's strengths. The active involvement of private and public implementation partners from the outset promoted effective technology transfer and helped to focus research on products and services relevant to Swiss business and society. Thanks to the long-term design of the SCCERs, the partners got to know and trust each other. Consequently, valuable exchange took place between partners concerning experiences, information and even data.

One key component of the programme was the promotion of cooperation between different disciplines, which is essential to addressing systemic challenges like the transformation of the energy system in Switzerland. For example, the increasing share of renewable energy from intermittent sources means that the electricity system requires different technologies for storage and flexible use of energy. To develop these technologies and integrate them into the system necessitates collaboration between researchers and implementation partners from the fields of electrochemistry, the power system, etc. New business cases are also needed, along with a supportive legal framework and public acceptance. Technological, social, legislative and economic research and innovation should therefore complement each other.

Many of the challenges facing Switzerland are highly complex and require a systematic approach in order to be addressed successfully. The experience of the Energy Funding Programme shows that it is worth investing in coordination and collaboration across different HEIs and disciplines. Ultimately, the overall achievement is greater than the sum of the individual projects' results.

The SCCER Steering Committee has strategically supported the SCCERs. Additionally, 31 experts evaluated the SCCERs' and JAs' activities and results annually. The SCCER Steering Committee would like to take the opportunity to thank the experts and in particular Stefan Nowak, who chaired the panel of experts over the last four years, for their highly valued work during the eight years of the Energy Funding Programme.

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Prof. Dr. Anna Fontcuberta i Morral
EPFL (National Research Council of the SNSF)

Prof. Dr. Marcel Mayor
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Benoît Revaz
Benoît Revaz, Director of the Swiss Federal Office of Energy (Advisory)

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was President of the Steering Committee from 2013 to 2017.

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ETHZ

Prof. Dr. Marc Gruber
EPFL

Dr. Matthias Kaiserswerth
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Martin Müller
m2c GmbH

Dr. Martin Riediker
Touchless Biometric Systems

Prof. Dr. Frank Scheffold
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Prof. Dr. Paul Söderlind
University of St. Gallen (HSG)

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Executive Summary

Dr. Stefan Nowak
Chair of the SCCER Evaluation Panel

The SCCERs significantly increased the level of cooperation between the different types of research institutions involved in the programme, i.e. between the ETH Domain, universities of applied sciences and other universities.

Following the reactor disaster at Fukushima Daiichi, the Swiss Parliament approved the Federal Council's Dispatch on the action plan "Coordinated Energy Research in Switzerland – measures for the years 2013–2016"[1]. The goal of the action plan was to strengthen research and development in order to support a fundamental transformation of the Swiss energy system by 2050, with nuclear energy production being phased out. The most important measure introduced by the dispatch was the creation of eight Swiss Competence Centers for Energy Research (SCCERs) covering seven thematic action areas[2] under the Energy Funding Programme. These were intended to bring together researchers from all types of research institutions and received CHF 72m in funding for the years 2013–2016.

In the first funding period (2013–2016), the SCCERs were able to significantly expand their research capacity in the specified thematic areas and thus lay solid foundations for their application for the second funding period (2017–2020). Based on the insights from the first funding period, research strategies were partially adapted, work plans changed and, in some cases, new research groups included. Certain projects were also transferred to industry. As a result, while the proposals of all eight SCCERs were approved for the second funding period, research did not simply continue. From 2017, the Commission for Technology and Innovation CTI, the predecessor organisation of Innosuisse, provided CHF 111.9m in funding to support the continuation of the SCCERs' activities, along with an additional CHF 7.7m for the creation of six projects involving researchers from two or more SCCERs. These Joint Activities (JAs) covered topics at the interface between the thematic areas of the SCCERs and aimed to answer research questions from a more systemic perspective.
In addition to the CTI/Innosuisse funding, the participating higher education institutions (HEI) contributed CHF 251.2m (2014–2020[3]) to the financing of the SCCERs and JAs. Researchers also received CHF 149.4m from competitive federal funds and contributions of CHF 130.2m from

[1] Federal Council (2012): Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

[2] The seven action areas were: Efficiency; Grids and their components/energy systems; Storage; Power supply (supply of electrical energy); Economy, environment, law, behaviour; Efficient concepts, processes and components in mobility; and Biomass.

[3] Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

industry partners and international projects. Overall, a total of CHF 724.6m was available for Swiss energy research under the Energy Funding Programme from 2014 to 2020[4].

Looking at the different SCCERs individually, the **SCCER Future Energy Efficient Buildings & Districts (FEEB&D)** dealt with energy efficiency and CO_2 emissions in the built environment. With regard to single buildings, it developed coloured solar panels, a more efficient insulation material, dynamic glazing for windows, vision-sensing technologies for blinds and lighting control, along with predictive control of multiple energy subsystems. It created a smart and powerful IT tool to define the optimum configuration of decentralised multi-energy systems in specific situations, and a comprehensive spatiotemporal database reporting energy demand and renewable energy potential for Switzerland at high resolution.

The **SCCER Efficiency of Industrial Processes (EIP)** dealt with energy efficiency and CO_2 emissions in industrial applications from two different perspectives, combining methodological work on the potential for economic industrial efficiency with analyses and implementation procedures for energy efficiency and direct solar heat integration. Technological progress was made in increasing energy efficiency in cross-sectoral heat applications and in decreasing CO_2 emissions through advanced adsorption processes. SCCER EIP's research also examined the use of wastewater to reduce energy consumption, e.g. for cooling purposes.

The **SCCER Supply of Electricity (SoE)** analysed possible contributions to the power supply from deep geothermal energy (DGE) and hydropower (HP). Backed up by results from excellent scientific findings, the focus of research on DGE shifted from electricity generation to thermal applications, and important demonstrators were built. A re-assessment of CO_2 sequestration in geological layers revealed a much lower storage potential than anticipated. In the field of HP research, the possibility of a 10% increase in annual production was examined and delivered a number of scientifically sound arguments on which specific efforts are needed to reach this target. Analysis also focused on the flexibility of hydropower use and on concepts with high practical value.

Overall, a total of CHF 724.6m was available for Swiss energy research under the Energy Funding Programme from 2014 to 2020[4].

The **SCCER Biomass for Swiss Energy Future (BIOSWEET)** aimed to contribute to greater use of low-value biomass in the Swiss energy system given the technological, economic, environmental, systemic and societal challenges involved.
Its successful work tackled aspects related to

[4] This figure also includes the CHF 3m received by the SCCERs FURIES and Mobility in the context of the Digitalisation action plan (For more information see the webpage of the State Secretariat for Education, Research and Innovation)

biochemical and thermochemical conversion options for organic material, bringing them to higher technology readiness levels (TRLs).
The scientific results achieved included various methods for providing biomethane, innovative combustion plants for heat provision, new approaches for the production of liquids (chemicals and fuels) and exciting insights into the future role of biomass within the Swiss energy system.

The **SCCER Future Swiss Electrical Infrastructure (FURIES)** worked on future power grid technologies enabling the seamless and sustainable powering of Swiss homes, businesses and communities, based on traditional and new renewable energy resources. The SCCER-FURIES delivered substantial and relevant scientific and technological results regarding new concepts, components and system solutions for the future power infrastructure. Its large-scale demonstrators and laboratories proved attractive to collaborators from industry and the public sector and will continue to serve as research platforms.

In the future energy system, storage options for both short-term and seasonal storage will become very important. **The SCCER Heat and Electricity Storage (HaE)** focused on five topics that may become crucial for the future energy system, namely Thermal Energy Storage, Advanced Batteries and Battery Materials, Hydrogen Production and Storage, Catalytic and Electrocatalytic CO_2 Reduction, and Assessment of Energy Storage. Significant progress was achieved in all topics, ranging from scientifically outstanding results to patents, demonstrators and prototypes. Many of the results were achieved in close cooperation with industry partners, in some cases leading to the creation of startup companies.

The **SCCER Efficient Technologies and Systems for Mobility (Mobility)** applied an interdisciplinary approach that addressed and integrated technical, economic and user-related topics. Particular achievements included the establishment of a new research platform for battery systems, cooling concepts for fuel cell research, lightweight thermoplastic composite technologies, spatial planning and energy infrastructures, and research into the social and economic dynamics of mobility systems. The SCCER Mobility also developed the Smart Mobility Data Platform and identified important elements for cutting CO_2 emissions in the mobility system.

The **SCCER Competence Center for Research in Energy, Society and Transition (CREST)** was set up to cover the key non-technical aspects of the energy transition. Its goal was to deliver recommendations for policies and business strategies that will induce the transformation of the energy system and steer energy supply and demand. Specifically, research activities focused on policies, institutions and firm strategies for facilitating the integration of a larger share of “new” renewables, options for reducing household energy consumption, regional and company-level strategies to support the diffusion of novel solutions, and transition pathways for the Swiss energy system.

Turning to the JAs, **JA Scenarios & Modelling (JASM)** combined the modelling capabilities of all eight SCCERs to develop a set of scenarios for the transition of the Swiss energy system towards a net-zero emissions system over the next few decades. These simulations provided guidance on what can be achieved with current and planned policies and the additional measures that would be needed to achieve the ambitious goals of Swiss energy and climate policy. The results are clear recommendations for the further use of certain technologies, the forced use of systems still under development and systemic recommendations for future energy supply strategies. In particular, they show the need for accelerated electrification, carbon capture and negative emissions, and the promotion of hydrogen.

The objective of **JA Integrated development processes for hydropower and deep geothermal projects: regulatory, political and participatory perspectives (JA IDEA-HDG)** was to provide recommendations on how project development processes (public engagement), the legislative framework and governance structures could be enhanced to resolve conflicts between stakeholders and thus increase investment in HP and DGE projects. JA IDEA-HDG also developed policy recommendations on how to address citizens using appropriate information and steer the policy debate.

JA Socio-economic and technical planning of multi-energy systems (JA RED) created methods and guidelines for the planning of future multi-energy systems, including an analysis of the energy demand at building level and integration into district models taking grid restrictions into account. JA RED also demonstrated how stakeholders can evaluate their potential business models for these multi-energy systems and provided corresponding tools.

JA Coherent Energy Demonstrator Assessment (JA CEDA) brought together the most important results from a number of recent (multi-)energy demonstrator projects and fostered closer links between their research teams by building a common, easy-to-use and well-organised platform to support data exchange, communication and coordination. The concrete deliverable was the CEDA database, comprising archetypes of 27 different energy technologies and associated data provided by the various demonstrators and processed to make them more generic. Initial case studies were carried out to demonstrate the benefits of this approach.

JA White Paper on the Perspectives of Power-to-Product (P2X) Technology in Switzerland (JA P2X) produced a White Paper that assesses both the technical potential and the economic and legal conditions for technologies that convert (green) electricity into gases, liquids or heat that can be stored on a long-term basis and used as feedstock for many kinds of energy use or for the production of chemicals. "X" often stands for hydrogen, synthetic gases such as methane, synthetic fuels such as diesel, gasoline or kerosene, or heat. The White Paper shows that several processes need to become more mature (higher efficiency, greater stability, lower costs) before they can be implemented in the energy system. It also shows that significant changes are required to the legal framework before these technologies can become competitive. A long-term perspective will stimulate development but requires immediate action.

Finally, **JA The evolution of mobility: A socio-economic analysis (JA Mobility)** focused on the role of behavioural aspects in the mobility sector with the aim of better understanding the mobility behaviour of the Swiss population and identifying measures – both incentivising and regulating – for reducing the mobility-related consumption of fossil energy. This included aspects such as home working, car ownership, ride-sharing or online shopping. The highly interconnected workstreams created a comprehensive and coherent picture of mobility behaviour, its importance for energy consumption and how it can be controlled, thereby providing direct starting points for political action and the concrete design of behaviour-influencing measures.

Over the period since the SCCERs were first created in 2014, an average of 1,300 researchers worked on solutions and concepts for Switzerland's future energy system. These included some 70 innovative products, services and processes that are now already used in practice. Researchers also built and operated more than 340 prototypes, pilot plants and demonstrators. These helped showcase research results and acquire 973 additional projec significantly increased its involving non-academic public or private partners. The SCCERs also supported the transformation of the energy system by providing courses for both students (831) and practitioners (361).

Over the duration of the Energy Funding Programme, the SCCERs became well-established competence centers encompassing academia and partners from industry, the public sector and international partners. The SCCERs significantly increased the level of cooperation between the different types of research institutions involved in the programme, i.e. between the ETH Domain, universities of applied sciences and other universities. This cooperation brought about two important outcomes, namely the coalescence and improved coherence of Swiss energy research activities and very successful networking both among the participating research institutions and with implementation partners, public institutions and policymakers. This in turn greatly increased the visibility and awareness of Swiss energy research activities and its manifold infrastructures, both in Switzerland and to an increasing extent abroad. As a result of these efforts, international collaboration clearly progressed throughout the Energy Funding Programme, particularly in the second funding period. This international collaboration is a key contributor – for example through increased resources, cross-fertilisation and benchmarking – to the excellence of research and the speed at which new solutions can be developed and implemented.

The research infrastructure was extended considerably in the second SCCER funding period thanks to new energy technology demonstrators and more research activities with higher TRLs. These developments contributed to an increasing number of cooperations with trade and industry and provided further excellent opportunities for new partnerships with public and private enterprises. World-class basic research was also conducted in a large number of scientific and technological fields, helping fill the research pipeline with new, longer-term activities that offer a high level of potential.

Economic, societal and political aspects were tackled in a systematic way, but there is still potential for further development in these areas given their crucial contribution to the energy transition.

A stronger and much-needed systemic approach was observed over the seven-year lifespan of the SCCERs, particularly with regard to technical issues and interactions between different forms of energy generation, transformation, transport and storage. Economic, societal and political aspects were tackled in a systematic way, but there is still potential for further development in these areas given their crucial contribution to the energy transition. The impact of digitalisation was also addressed in increasing depth, particularly in the SCCER-FURIES and the SCCER Mobility, with additional funds made available in 2019 through the Digitalisation action plan.

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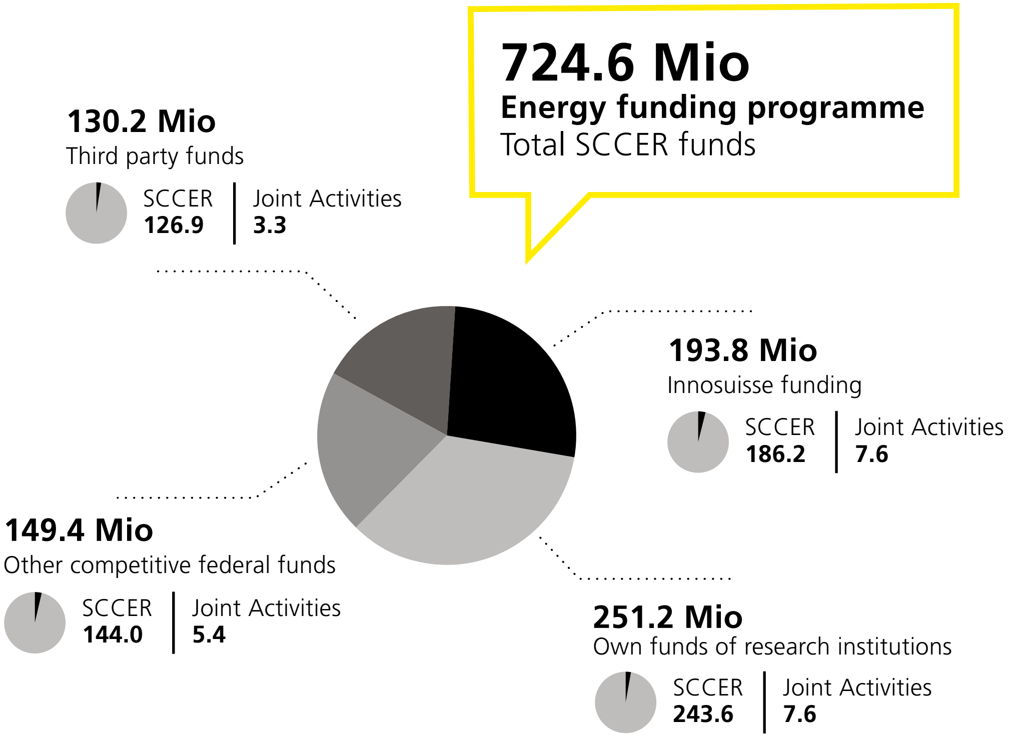
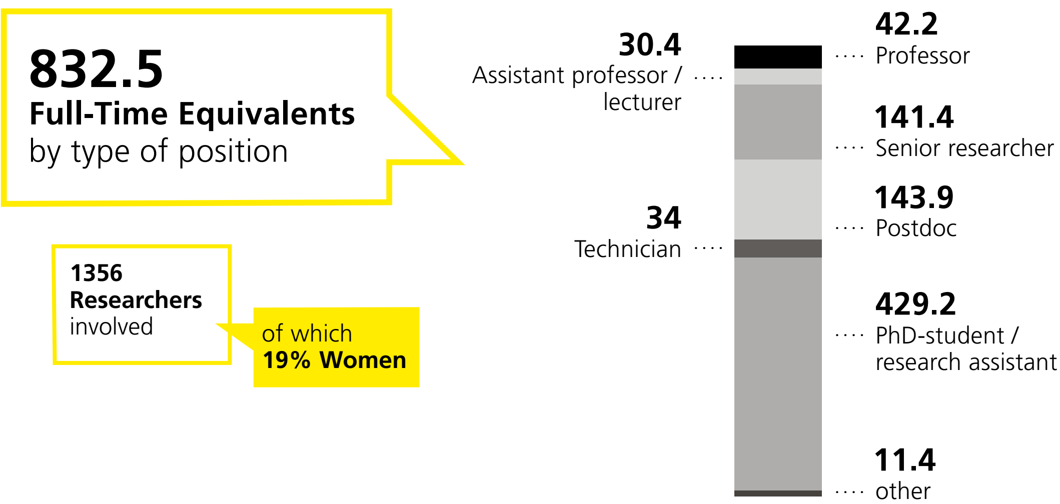
Key Figures

Energy Funding Programme

Finances (2014–2020) in CHF

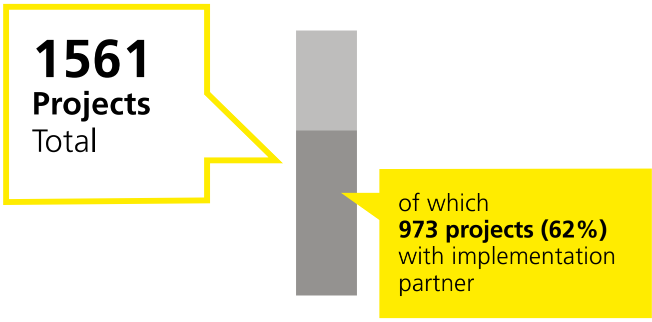


Capacities (2020)

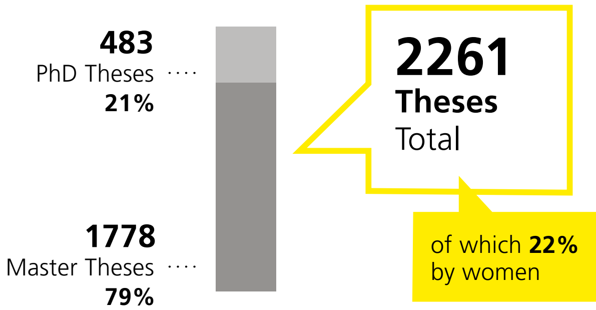


Key Figures
Energy Funding Programme 2013–2020

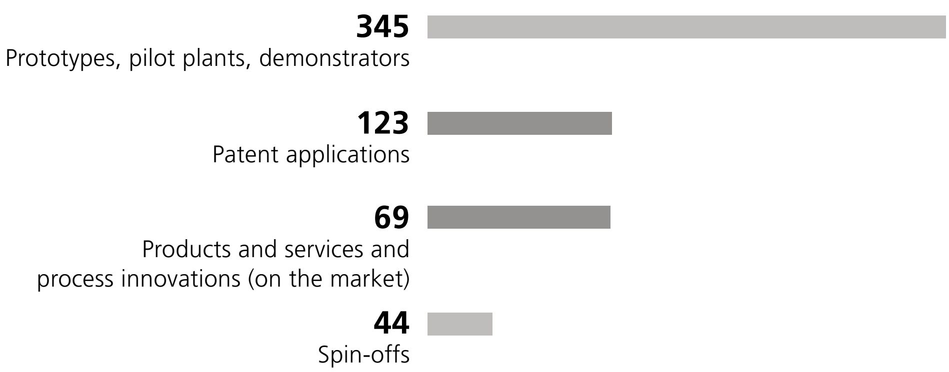
Projects (2014–2020)



Theses (2014–2020)



Output (2014–2020)



The Energy Funding Programme
2013–2020

In the wake of the reactor disaster at the Fukushima Daiichi nuclear power plant on 11 March 2011, the Swiss Federal Council and Parliament decided to gradually phase out nuclear energy and implement the Energy Strategy 2050. This requires a fundamental transformation of the energy system that rests on two pillars: the reduction of energy consumption by increased efficiency and the broadening of electricity supply, in particular from renewable sources.

To support the realisation of the energy systems' transformation, the Federal Council also defined the strengthening of energy research as one of the priorities of the Energy Strategy 2050. It therefore commissioned the drafting of an action plan on coordinated energy research. On 22 March 2013, Parliament approved the corresponding Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016[5].

The overarching goal defined in the dispatch was to make significant contributions through research and innovation to increasing the efficiency of the Swiss energy system and to meeting the demand for electricity after the phase-out of nuclear power generation. This encompassed the entire knowledge chain in relation to production and implementation – from basic research to prototypes and demonstrators. The action plan also identified seven action areas in which energy research should be strengthened: Efficiency; Grids and their components/energy systems; Storage; Power supply (supply of electrical energy); Economy, environment, law, behaviour; Efficient concepts, processes and components in mobility; and Biomass.

To strengthen energy research in Switzerland, the action plan recommended building up research capacity in the ETH Domain[6], the universities of applied sciences and universities, while also establishing and operating energy research competence centers in the above-mentioned action areas. These centers were to include researchers from different types of HEI and give particular importance to applied and interdisciplinary research.

With the approval of the dispatch, the Commission for Technology – the predecessor organisation of Innosuisse – received CHF 72m to coordinate the Energy Funding Programme. Specifically, this involved establishing and operating the SCCERs from 2013 to 2016. In 2014[7], eight SCCERs (see overview on page 17) embarked on this new type of collaboration. By the end of the first funding period (2016), more than 1,000 researchers at the SCCERs were developing solutions for Switzerland's energy future.

On 30 September 2016, Parliament decided to extend the Energy Funding Programme to 2020 and granted funding of CHF 119.6m. In addition to the renewal of all SCCERs, Innosuisse approved seven joint projects between two or more SCCERs – the JAs (see overview on page 247).

The following chapters provide an overview of the most important activities and results of the SCCERs and JAs. In about eight years of work, a great number of noteworthy results have been achieved, although this report cannot cover them all. The report has been written by the experts who oversaw the Energy Funding Programme and is based on texts provided by the SCCERs and JAs.

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5 Federal Council (2012): Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

6 The ETH Domain comprises the two Federal Institutes of Technology in Zurich (ETHZ) and Lausanne (EPFL) and the four research institutes: the Paul Scherrer Institute (PSI), the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Swiss Federal Laboratories for Materials Science and Technology (Empa) and the Swiss Federal Institute of Aquatic Science and Technology (Eawag) (see the ETH Board's webpage).

7 Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

8 Swiss Competence Centers for Energy Research

FEEB&D
Future Energy Efficient Buildings & Districts

Action Area **Efficiency**

▶ p. 18–46

CREST
Competence Center for Research in Energy, Society and Transition

Action Area **Economy, environment, law, behaviour**

▶ p. 218–244

EIP
Efficiency of Industrial Processes

Action Area **Efficiency**

▶ p. 47–71

Mobility
Efficient Technologies and Systems for Mobility

Action Area **Efficient concepts, processes and components in mobility**

▶ p. 185–217

Joint Activities
▶ p. 245–286

SoE
Supply of Electricity

Action Area **Power Supply**

▶ p. 72–93

HaE
Heat & Electricity Storage

Action Area **Storage**

▶ p. 152–184

BIOSWEET
Biomass for Swiss Energy Future

Action Area **Biomass**

▶ p. 94–124

FURIES
Future Swiss Electrical Infrastructure

Action Area **Grids and their components, energy systems**

▶ p. 125–151

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FEEB&D

Future Energy Efficient Buildings & Districts

Action Area
Efficiency

Leading House

Swiss Federal Laboratories for Materials Science and Technology (Empa)

Participating Institutions

Lucerne University of Applied Sciences and Arts (HSLU)
Swiss Federal Institute of Technology Lausanne (EPFL)
Swiss Federal Institute of Technology Zurich (ETHZ)
University of Applied Sciences and Arts Northwestern Switzerland (FHNW)
University of Geneva (UNIGE)

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Prof. Dr. Martin Patel, UNIGE (2017–2020)
Prof. Matthias Sulzer, Empa (2014–2017)

Managing Director

Dr. Stephan Fahlbusch, Empa (2014–2020)

sccer | future energy efficient buildings & districts

Synthesis

The SCCER FEEB&D targeted a substantial reduction in energy consumption and CO_2 emissions of existing and future building stock. The focus was on measures to be realised in single buildings, at district, regional and national level.

Challenges in the "Efficiency" action area

Based on the "Coordinated Energy Research in Switzerland" action plan, the Federal Council specified the following topics in the "Efficiency" action area[8] in its dispatch: more efficient building technologies for existing and new buildings, energy-efficient information and communication technologies, and energy-efficient processes in the industrial environment[9] (page 16 of the action plan). Since more than 40% of Swiss energy consumption can be attributed to the building sector[10], there is great reduction potential. For this reason, a specific SCCER was dedicated to this important topic. The SCCER FEEB&D proposal, covering a wide range of questions arising from this action area, was approved in 2014.

Even more crucial than the 40% of total final energy consumption in Switzerland is the approx. 30% of Swiss domestic CO_2 emissions caused by buildings. It was obvious from the start of the Energy Funding Programme that drastically reducing energy demand and CO_2 emissions at the same time would be a unique challenge for Swiss society and business. The most challenging issues were the economic efficiency of long-term investments in alternative energy technologies, in particular by private building owners, the transformation of the existing building stock towards the requirements of the Energy Strategy 2050, and the extremely low energy prices on today's European spot markets.

Vision and objectives of the SCCER FEEB&D

In 2014, when the SCCER FEEB&D started its activities, Switzerland's building stock had an average specific final energy consumption (energy intensity) of around 180 kWh/m^2 per year for building services, including heating, cooling, domestic hot water and general electricity consumption. The buildings' energy was supplied via a mix of fuels from fossil and renewable sources – electricity, district heat/cooling, gas, oil and biomass. At that time, the energy mix caused average CO_2 emissions of around 140 g

[8] Federal Council (2012): Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

[9] Kaiser T., Hotz-Hart B. and Wokaun A. (2012): Aktionsplan Koordinierte Energieforschung Schweiz. Report commissioned by the Interdepartmental Working Group on Energy (EDI – EVD – UVEK).

[10] Kemmler A., Spillmann T., Piégsa A., Notter B., Cox B., Jakob M. and Catenazzi G. (2019): Analyse des schweizerischen Energieverbrauchs 2000 – 2018 nach Verwendungszwecken. Prognos AG, Infras AG and TEP Energy GmbH, commissioned by the Federal Office for Energy, Bern.

CO_2/kWh (CO_2 intensity). Overall, buildings accounted for approximately 40% of total final energy consumption in Switzerland and around 30% of Swiss domestic CO_2 emissions.

The overarching goal of the SCCER FEEB&D can be summarised as follows: The environmental footprint of the building stock was to be reduced by a factor of three by 2035. To achieve this first milestone of the Energy Strategy 2050 by 2035, the energy intensity would need to be slashed by 50% and the CO_2 intensity by 40%. This was to result in a threefold reduction in specific CO_2 emissions by 2035, i.e. from 25 kg CO_2/(m^2*a) to 7.7 kg CO_2/(m^2*a).

With regard to the structural aspects of energy research, the SCCER FEEB&D aimed to substantially build up the research capacity in the field of energy-efficient buildings and districts and to bring these competences together in a national research competence center encompassing research units from the ETH Domain, the cantonal universities and the universities of applied sciences already operating in this field. This competence center was to collaborate intensively with private and public entities over the whole duration of the programme and continue to operate after 2020.

What was achieved

The building-related scientific achievements were all showcased in the SolAce unit at Empa's NEST building. The unit reached the highest standards in indoor comfort while achieving an energy-positive balance and carbon-neutral working/living space through the combined application of coloured solar panels, window-integrated micro-structured glazing, High Dynamic Range vision-sensing technology for blinds and electric lighting control, and predictive control of multiple energy subsystems, which provided a user-centric approach.

One remarkable contribution was the extensive analysis of energy retrofitting for the residential building stock. The results show that early retrofitting is cost-effective and produces a major reduction in CO_2 emissions.

At district level, the activities led to a spin-off, Urban Sympheny AG, which is now providing energy system planners with appropriate software as a service. The software employs models and optimisation routines developed during phases 1 and 2 of the SCCER to quantify and compare different solutions for renewable decentralised energy systems at district and community level. Significant efforts were also directed at the evaluation of the potential and advantages of local low-temperature heat distribution networks, especially in densely built areas. With regard to whole cities, a multi-scale model was developed to analyse urban heat island effects and the local microclimate.

At national level, the SCCER FEEB&D developed a comprehensive spatiotemporal database, reporting energy demand and renewable energy potential for Switzerland at high resolution.

Contribution to Energy Research and to the Energy Strategy 2050

The SCCER FEEB&D claims that the net-zero target for the building sector can be achieved by 2050. The transformation can be implemented, assuming CO_2 abatement costs of 200–400 CHF/t CO_2, eq., and considering both main measures, i.e. increasing building energy efficiency and transformation of the current energy system into a fossil free system.

For the different technologies and systems developed within the SCCER FEEB&D, some pilot applications gave a reliable indication of the possible contributions to the Energy Strategy 2050: for instance the High Dynamic Range vision-sensing technology for blinds and lighting control, in combination with predictive control of multiple energy systems, could produce energy savings of up to 20% compared with a best-practice controller.

In essence, the SCCER FEEB&D research identified six paradigm shifts that relate to the building stock and will support the transformation of the current energy system into the net-zero CO_2 emission system of the future. These condensed and overarching findings are documented in a White Paper.

With regard to energy research in Switzerland, the SCCER FEEB&D has substantially strengthened scientific collaboration between the ETH Domain, the cantonal universities and the universities of applied sciences in the field of energy efficiency of buildings and districts. The cooperation between academia, industry and public authorities was also widely extended and led to some very intensive networking and joint follow-up research and development (R&D) projects.

Recommendations

based on the SCCER FEEB&D's research findings

- **Adopt regulations**
  Establish the legal basis and regulations for the public, cross-sectoral use of individual energy data and for energy sharing/trading on a local scale.

- **Enable renewable decentralised energy systems**
  Develop masterplans at district and municipal level that consider the local renewable energy sources and the public energy infrastructure for supply, storage and distribution.

- **Re-engineer the energy business**
  Promote innovative business models for sharing energy and data, the pricing of flexibility and the economically attractive integration of distributed privately owned renewable energy (electricity and heat).

Results

WP 1 – Efficiency at Building Scale

Leader WP 1
Prof. Dr. Jean-Louis Scartezzini, EPFL

Work Package (WP) 1 aimed to substantially increase energy efficiency and simultaneously eliminate CO_2 emissions over the whole lifespan of the building stock. To reach this twofold goal, the research activities focused not only on technical components and systems, but also on human behaviour, regulations and incentives.

Objectives

WP 1 dealt with products and technologies to increase energy performance, reduce CO_2 emissions and improve the indoor environment quality of residential and commercial buildings.

The focus was on reducing the energy performance gap, on optimising the energy performance of building envelopes, on human/building interaction, and on building services and control.

The overall goal of this WP was to make a major contribution via the products, technologies and systems developed to reducing the environmental footprint of the building sector by a factor of three by 2035.

What was achieved

The main achievements of WP 1 are described according to its three main research topics: (1) performance gap and building envelopes, (2) human/building interaction and (3) building services and control.

The causes and scale of the energy performance gap (EPG), i.e. the difference between the calculated and measured energy use in building retrofits, was investigated by analysing the Swiss Cantonal Energy Certificate for Buildings (CECB) database, containing details of approximately 50,000 residential buildings. The study confirmed that buildings in low energy performance classes use less energy than calculated, while those in average and high energy performance classes have a considerably higher EPG. An analysis of several very high-performing buildings (class A or Minergie labels) demonstrated that the EPG could be much smaller if sufficient attention were given to quality during design and construction and to post-construction monitoring.

HIGHLIGHT

ENERGY-POSITIVE BUILDINGS

The SolAce unit, the combined living and working space realised within the NEST at Empa in Dübendorf, is definitely one of the highlights of WP 1. With its glazing, the blue-coloured building-integrated photovoltaics, solar thermal collectors, micro-structured glazing and optimal energy management, the NEST SolAce unit is energy-positive after the space heating, domestic hot water and electric appliances demand is taken into account. Embodied energy was also minimised. The SolAce unit fulfils the highest expectations in terms of indoor environmental quality.

Also supported by the Swiss Federal Office of Energy (SFOE), BASF, SwissINSO, Solstis, CSEM, Griesser, Regent, AGC, Geberit, V-Zug, ABB and Duscholux

Much of the EPG on CO_2 emissions was attributed to the difference in heating systems between energy labels (only the top labels require a low-carbon heat supply such as heat pumps). This highlights the importance of first decarbonising the heat supply and then implementing energy-efficiency measures on the building envelope in a second step. Scenarios for different transition pathways between energy-efficiency labels, along with their potential impact on the Energy Strategy 2050, were investigated: they showed that it is impossible to achieve the Energy Strategy 2050 objectives by maintaining current renovation rates for existing buildings.

At the SolAce unit at Empa's NEST, multifunctional façade technologies were successfully implemented and tested in a real-scale application. Coloured nanotechnology-based glazing for photovoltaic (PV) solar modules and solar thermal collectors were also tested. Electricity needs were almost entirely met by the annual PV solar production on façades alone. Overall, the NEST SolAce unit is energy-positive, when taking space heating, domestic hot water and electric appliances into account, on the way to attaining the Minergie-A ECO standard.

The SCCER FEEB&D research results show that window-integrated micro-structured glazing provides optimal management of daylight and solar gains, with a 38% electricity-saving potential for electric lighting. High Dynamic Range vision-sensing technology for blinds and electric lighting control, together with predictive control of multiple energy subsystems, provided a user-centric approach that produced impressive energy savings compared with a best-practice controller, as well as providing users with thermal and visual comfort.

HIGHLIGHT

INNOVATIVE GLAZING

On the level of the single technologies, the invention of the micro-structured glazing can be rated as a true highlight. This novel glazing reflects glaring sunlight to the ceiling of the internal room, while being nearly transparent on a horizontal line, so that residents can see the landscape along direct eyesight. The solution is in early transfer to a strong industry partner. In parallel, it has been successfully tested on the SolAce unit at the NEST.

Also supported by BASF Schweiz AG

At the HiLo unit of Empa's NEST, novel structural solutions were applied for the building envelope, based on traditional building principles and digital technologies and incorporating a reusable steel framework concept for double-curved structures (consisting of a cable net covered with a membrane). Flexible solar cells were placed on this innovative roof. Genetic algorithms were used to optimise the electrical layout and the design of the PV solar modules. A direct current (DC) network was realised with the aim of avoiding inefficient DC/AC (alternating current) and AC/DC conversions. An adaptive solar façade (ASF) of thin-film PV modules with soft, pneumatic actuators for solar tracking and daylight control was designed.

One remarkable research result achieved in phase 1 was the development of a new raw material combined with an energy-efficient production process, enabling the manufacture of silica aerogels at a much lower price and with physical properties similar to competitor products.

Contribution to the SCCER's objectives

The potential contributions of most of the research results achieved in WP 1 are relevant for the implementation of Energy Strategy 2050. The SCCER FEEB&D sought to quantify these contributions for each individual product or measurement; it documented its findings in the "Impact Mapping 2018" report. For WP 1, the SCCER FEEB&D estimates energy savings of between 17% and 33%, from the combined application of controlled electrochromic glazing, High Dynamic Range vision sensors and automated "Eyesight" venetian blinds in residential and non-residential buildings, plus a further energy saving of 10% to 30% from the implementation of predictive control in new and retrofitted buildings. Although their effectiveness is impressive, the economic efficiency of these measures is still in question. The impact of the research results of WP 1 on the Energy Strategy 2050 will therefore depend to a large extent on the penetration of these new technologies into the Swiss market.

The SCCER FEEB&D has already initiated transfer to market, by creating three spin-offs and through close collaboration with strong industry partners. Under these partnerships, the SCCER FEEB&D has generated a huge number of patents (10), licences (5) and R&D projects (18), a convincing proof of the close and successful collaboration with industry.

Within the research community, the coordinated energy research unlocked many important synergies. For the academic institutions, i.e. the ETH Domain and the cantonal universities, this collaboration with the universities of applied sciences opened many doors to the practical world. Conversely, the universities of applied sciences benefited greatly from cooperating with the academic institutions with regard to the scientific quality of their research and opportunities to publish in peer-reviewed papers. The integration of different products, systems and processes into the SolAce and HiLo units at NEST for experimental investigations also intensified the collaboration between the various research groups in WP 1.

Assessment of the achievements

Overall, the targets of WP 1, i.e. the milestones and deliverables, were achieved. WP 1 met the highest international standards with regard to the quality of the research and the results achieved. There were naturally differences between the various tasks: some were close to basic research, e.g. the glazing research and the development of the new silica aerogels, whereas others are clearly applied science, e.g. the automated venetian blinds. However, most results created novel and innovative scientific knowledge compared with the existing state of the art.

The conclusions regarding the EPG were rather disappointing: asking for more quality in the planning, execution and operation of a building is not a valuable strategy for exploring the huge energy and CO_2-saving potential linked to the EPG. Furthermore, increasing the average renovation rate to above 2.0 will not have any influence on reducing the EPG. Instead, WP 1 could at least have outlined a strategy and operational concept for effectively tackling the EPG, despite the increasing implementation of building information modelling and building management systems. In this respect, the SCCER FEEB&D missed a tremendous chance to effectively support the implementation of the Energy Strategy 2050.

WP 2 – Renewable Energy Systems from Building to District Scale

Leader WP 2
Dr. Kristina Orehounig, Empa

WP 2 shifted attention from building scale to district scale. Economies of scale and additional operational degrees of freedom were to be used for the benefit of energy efficiency, thus reducing energy consumed and the carbon footprint.

Objectives

The main objective of WP 2 was to develop tools to enable optimal combinations of building, district and centralised solutions to be identified in specific cases, based on a broad analysis with multi-criteria, transformation and operational analysis. Such solutions should include novel renewable energy technologies, but also traditional retrofitting of the building envelope.

The main scientific claim of the whole SCCER FEEB&D is contained in WP 2, i.e. that opting for distributed renewable energy systems, while clustering operation at district level, will most significantly improve overall energy efficiency and thus reduce consumption per m^2 of living space.

What was achieved

WP 2 looked at planning, implementation and operation of district-level energy systems. There was an expectation that good tools are paramount in strongly pushing the integration of renewables.

A first tool was developed to support the selection of the most cost-effective retrofit solution. Finding a solution was based on a comparison with building archetypes, building simulation and optimisation routines. Simulation results showed that by scaling the technically and economically optimal solutions to the entire building stock, CO_2-equivalent emissions could be reduced by up to 80%. This showed that it is technically feasible to achieve the Energy Strategy 2050 targets for Switzerland's building stock; however, CO_2-optimal solutions are usually significantly more expensive than the cost-optimal solution.

The second tool, named the Ehub Tool, targeted the optimal design of multi-energy systems on a district scale. This tool was used in practice in nine case studies with commercial and municipal partners, so as to actively support the planning of local energy systems for sites from the size of a neighbourhood to a city district. These case studies showed the potential benefits of an integrated approach combining multiple energy carriers and technologies in terms of enhancing sustainability and reducing energy supply costs.

HIGHLIGHT

EHUB TOOL – FROM SCIENCE TO MARKET

The Ehub Tool software is an important driver on the way towards the broad realisation of renewable decentralised energy systems (RDESs) at the district scale for specific cases. It is a powerful tool that will substantially facilitate the implementation of RDESs and sector coupling at the local level. The recently founded Urban Sympheny AG spin-off will commercialise software as a service based on the Ehub Tool. The software will help energy planners to quickly sift through a large range of energy supply solutions for that site – considering possibilities for energy production, conversion, storage and distribution in different forms, and including both conventional and novel technological solutions – ultimately aiding the identification of the optimal RDESs.

Also supported by the City of Zurich, St. Galler Stadtwerke, Regionalwerke Baden, Energie Wasser Bern, Eicher+Pauli, Roche Diagnostics, Helbling and IBC Energie Wasser Chur

Aside from planning, WP 2 also dealt with the operation of distributed energy systems. Data-driven control (DDC) was successfully implemented in two projects: in the first to efficiently control the temperature in apartments and in the second to control a multi-energy system in which a heat pump is used to stabilise the electricity grid.

Various heating and cooling experiments with the Urban Mining and Recycling (UMAR) experimental unit at the NEST demonstrator building at Empa showed that predictive methods for the demand side and for storage units combined with weather forecasting allowed temperatures in residential apartments to be controlled with energy consumption reduced by 20–30%. The achievements demonstrated that both applications – room temperature control and electrical reserves with heat pumps – are feasible with data-driven methods.

HIGHLIGHT

LOW-TEMPERATURE NETWORKS

In reaction to the challenges experienced in the recent past with low-temperature networks, a completely new network topology was developed: the reservoir low-temperature network. This topology allows complete hydraulic decoupling of circulation pumps and therefore a meshing of networks by temperature cascading. Input energy is expected to come from excess heat from industry and from geothermal sources. This innovation will facilitate the optimal design of thermal networks and reduce the initial investment cost. This makes low-temperature networks the real drivers of CO_2 reduction in densely built areas. The basic principles of thermal low-temperature networks are described in a publication by EnFK to further help politicians, policy-makers and the public to understand thermal networks and their role in meeting the goals of the Energy Strategy 2050.

Also supported by the SFOE, Belimo, Baugenossenschaft Zurlinden, Roche Diagnostics International, Verenum, St. Galler Stadtwerke, Migros, the Conference of Energy Specialists (EnFK) and the International Renewable Energy Agency (IRENA)

In the context of low-energy concepts, experimental research was performed in low-temperature district networks. A methodology on the energy efficiency of centralised vs. decentralised circulation pumps was developed, and the findings were shared to help practitioners design the best topology in an early planning stage. Methods to reliably operate decentralised circulation pumps in thermal networks were developed. In particular, a valve was developed to switch the connection point of the expansion vessel in reaction to varying system pressures. A patent has been granted, and a real-size prototype was recently installed at the network of ETHZ, Campus Hönggerberg. In reaction to the challenges experienced in the previous studies, a completely new network topology was developed: the reservoir low-temperature network. This topology allows complete hydraulic decoupling of circulation pumps and therefore a meshing of networks by cascading.

Contribution to the SCCER's objectives

Retrofitting the building stock is key to considerable energy and CO_2 savings and is therefore fully in line with the Energy Strategy 2050. For housing alone, the SCCER FEEB&D's best-case scenario estimate is for average savings per year for heating of approx. 1.0% p.a. of total heating demand or approx. 0.21% p.a. of total Swiss end-energy consumption, assuming a renovation rate of 1.8% and a reduction of 80% from retrofitting. At first glance, these figures do not look very promising, but by 2050 this would result in a reduction of approx. 7% of Switzerland's total annual energy demand, or one-third of the total heating energy consumption in buildings. To substantially increase the renovation rate, retrofitting costs should be reduced drastically, e.g. through new materials and technologies, and financial incentives need to be increased.

The impact of RDESs or of low-temperature networks (LTNs) is harder to forecast, because it depends very much on each specific case. Rough estimates by the SCCER FEEB&D based on real cases have shown potential autonomy due to local renewable energy installations of between 17% (without building retrofit) and 77% (combined with an overall Minergie-P renovation), and a potential reduction in CO_2 emissions by about 10% (with no renovation scenario). The SCCER FEEB&D has also estimated that roughly 40% of heat demand from buildings (space heating and domestic hot water demand) could be covered by LTNs, which would result in an annual reduction of approx. 5 million t of $CO_{2\ eq}$.

All WP 2 tasks are the result of very fruitful joint research activities by the ETH Domain, in particular the Empa in Dübendorf, and Lucerne University of Applied Sciences and Arts. In addition, many industry partners and public institutions worked closely with the researchers on a bilateral basis. Overall, there was abundant collaboration within WP 2, whereas contact with other WPs of the SCCER FEEB&D or with other SCCERs was fairly rare.

Assessment of the achievements

Overall, the targets of WP 2 were fulfilled to a large extent. With respect to the research plan and the implementation plan for phase 1 and phase 2, most of the milestones were achieved on time, and the deliverables were submitted as planned.

WP 2 met the highest international standards with regard to the quality of the research and the results achieved. There are naturally some differences between the tasks, depending on the technology readiness level (TRL) achieved by the end of the programme. However, most results created novel and innovative scientific knowledge compared with the existing state of the art.

WP 3 – Energy Performance at Regional and National Scale

Leader WP 3
Dr. Jonathan Chambers, UNIGE

WP 3 examined the overall heat and electricity demand of the building stock and the renewable energy potential of Switzerland. The work focused on how the energy use of the built environment can be drastically reduced, while making the best possible use of local energy resource options and matching demand and supply strategies geographically and over time.

Objectives

- WP 3 aimed to study how the energy use of the Swiss building stock could be drastically reduced, while making the best possible use of local (decentralised) energy resource options and matching strategies demand and supply geographically and over time.

- One main target of WP 3 was to develop a novel assessment of the Swiss energy system at national scale with high resolution, addressing a gap in existing research: research has generally either focused on macroeconomic analysis (large spatial coverage but low spatial resolution) or case studies in cities and districts (high spatial resolution but low spatial coverage). This was to use different modelling approaches (bottom-up modelling, systems analysis, statistical methods, energy hub simulations, geographic information system (GIS) analysis, etc.) to achieve integration of renewable energy resources at local scale as a hybrid system (wind, solar PV, solar thermal and geothermal).

- Finally, these findings were to be assembled in a renewable energy database so as to develop a long-term forecasting tool for the potential evolution in 2035 and 2050, depending on climate change effects and demographic and urban changes.

What was achieved

WP 3 established a database reporting energy demand and renewable energy potential for Switzerland with high resolution, i.e. at the level of individual buildings, using geospatial data, spatiotemporal modelling and machine learning. In this database, energy demand encompasses space heating and cooling, domestic hot water and electricity, whereas the supply side considers renewable energy sources such as PV, wind and shallow geothermal. The methods developed are also useful in performing a long-term forecast of the potential evolution in 2035 and 2050, depending on climate change effects and demographic and urban developments, and for different levels of legal interventions. The database was validated and improved with a series of real case studies and is currently available to policymakers and urban planners, giving them a comprehensive basis for both strategy and implementation of the energy transformation.

Co-simulation and optimisation platforms were developed on top of the database, which combines various disciplines in building engineering. This allows different scenarios to be assessed on a national scale (different microclimates and energy demands, different retrofit rates, different levels of local energy storage, etc.).

HIGHLIGHT

ENERGY DEMAND AND RENEWABLE ENERGY POTENTIAL DATABASE FOR SWITZERLAND

Geospatial datasets for energy consumption were generated that also include time series aspects (load curves). They are valuable as inputs into macro energy system models. The calculation of the renewable energy potential for Switzerland allowed a national hybrid energy database to be created. By combining energy resources, this can yield greater economic and environmental returns than standalone systems. The interactive online platform allows the potential at different levels of aggregation to be visualised, providing inputs for municipalities, building owners and energy suppliers as regards potential energy generation and savings. The platform also includes a spatial mapping of uncertainty at single-rooftop resolution and enables a distinction to be drawn between the uncertainty arising from the modelling process and the uncertainty related to the data.

Also supported by the SNSF

In contrast to other works on building and district energy modelling, this work adopts a multi-scale approach that is computationally efficient and allows large geographical areas – such as the whole of Switzerland – to be analysed. This is particularly important in the context of the analysis of thermal energy supply and demand, as thermal energy cannot be transported over long distances and so analysis must consider spatial constraints and have relatively high resolution.

The database was used for various studies aimed at policymakers and planners. One study identified the solar rooftop potential, while another estimated the potential for thermal networks (both on a national scale). The work showed that solar PV could contribute up to 40% of Switzerland's electricity consumption (2018) and geothermal up to 42% of its heating consumption – remarkable results. With regard to industrial excess heat, a spatiotemporal analysis showed only a small contribution, given to the fairly long distance between heat supply and consumption. Multidimensional studies revealed interesting relationships, for example that when setting ambitious carbon targets, buildings need to be more spaciously arranged, whereas less strict carbon targets allow for higher densities.

HIGHLIGHT

FEASIBILITY OF HYBRID RENEWABLE ENERGY SYSTEMS

WP 3 developed a building archetype-based model of residential building energy demand and retrofit. Using this model, it was possible to explore different cost-optimal pathways for retrofitting of the building stock considering different investor perspectives. Change in demand is an important factor in determining the renewable energy supply. National mapping of district heating system potential for high and low-temperature network technologies was performed for today and under different energy-saving scenarios. In addition, general methods for mapping district heating under different conditions were produced. They highlighted the large potential for district heating systems, but also the tensions between investments in energy efficiency (building refurbishment) and heat decarbonisation (thermal networks and heat pumps), as investments in efficiency can reduce the cost-effectiveness of decarbonisation, and vice-versa. In a series of case studies, different scenarios and strategies were evaluated to determine the impact of developing hybrid energy systems. An analysis of different levels of penetration of renewable energy in the energy mix and of the implementation of a more stringent carbon tax was carried out. The impact of future climate change on demand and on the reliability of the energy system was also investigated.

Contribution to the SCCER's objectives

The Energy Demand and Renewable Energy Potential Database developed by WP 3 clearly does not contribute directly to energy savings or to reducing CO_2 emissions. There is no doubt, however, that comprehensive and reliable statistical and geospatial energy data are central to designing, building and operating holistic decentralised energy systems. The database's impact on successful implementation of the Energy Strategy 2050 should therefore not be underestimated, even though it cannot be quantified or measured.

It was reported under WP 2 above (see page 29) that the SCCER FEEB&D estimated that roughly 40% of buildings' heat demand (space heating and domestic hot water demand) could be covered by LTNs, which would save an annual approx. 5 million t of $CO_{2\ eq}$.

Real and active research collaboration between WP 3 and other WPs (e.g. with WP 2 on use of the Ehub Tool, and with WP 5 on cooling demand), as well as with certain public authorities (e.g. Meteoswiss and SwissTopo) was essential. Academic exchange took place with various Swiss universities (e.g. Universities of Geneva and Lausanne) and the University of Oxford, whereas cooperation with industry was low because there was no immediate need.

Assessment of the achievements

WP 3 fulfilled the targets set in the proposal. With respect to the research plan and the implementation plan for phase 1 and phase 2, all milestones were achieved on time, and the deliverables were submitted as planned.

WP 3 met the highest international standards, particularly in respect of the database and the data quality. As such, all of the research results created novel and innovative scientific knowledge compared with the existing state of the art.

WP 4 – Diffusion of FEEB&D Technologies

Leader WP 4
Dr. Christof Knoeri, ETHZ

WP 4 investigated the drivers and barriers behind the adoption of new energy technologies in the building sector. The key findings are in three major areas: policies, RDESs, and guidelines and business models.

Objectives

WP 4 aimed to increase the speed of diffusion of energy efficient buildings and districts (EEB&D) technologies developed within the SCCER FEEB&D, in particular in WP 1 and WP 2, by eliminating the most important barriers.

In phase 1, the focus was on better understanding these barriers; in phase 2, WP 4 concentrated on how to overcome these barriers.

To achieve this, the analysis focused on three areas: (1) accelerating the diffusion of EEB&D technologies; (2) facilitating the diffusion of RDESs; and (3) supporting business model innovation for FEEB&D.

What was achieved

A cross-country comparison of a broad range of responsive policy designs has demonstrated that responsive policy adjustments over time can better account for rapidly decreasing technology costs and might produce policies that are geared more closely to their targets, at lower cost and with less uncertainty. However, such temporal evolution of policy instruments only works if cross-technology effects are considered.Feed-in remuneration for solar PV might, for instance, disincentivise battery diffusion. Careful orchestration of different policy instruments is therefore pivotal to achieving the best system outputs. Furthermore, the ideal mix and path of such instruments (e.g. subsidies, regulations, labels, etc.) also depends on maturity, modularity and cross-technology interaction, as the analysis of heat pumps, comfort ventilation and low-e glazing showed. Policy recommendations for emerging energy-efficient building technologies were also published.

WP 4 concluded that some RDES configurations are already cost-competitive for grid-connected settings, especially for newly built districts. For existing districts, increased retrofitting will be necessary to achieve the Energy Strategy 2050 energy-efficiency targets in combination with RDESs. Furthermore, the development of RDESs is very different from the standard construction process, as they are much more technologically complex. According to WP 4, this requires architects, engineers and contractors to adapt their traditional roles in the construction process.

WP 4's investigations demonstrated that business ecosystems – combined ventures between multiple companies to jointly create an offering – seem to be a promising approach for new energy-efficient building technologies. Such business ecosystems should be based on digitalisation, the exchange of data on the local technology setup, demand profiles and customer characteristics. The ecosystem should also provide a clear economic return for the connected technology providers and an attractive business model for the ecosystem lead.

Current business models within the broadly fragmented electricity domain do not differentiate sufficiently between different end-user markets. More customer-oriented business models, mainly applied in foreign markets, tend to be successful in accelerating the energy transition. WP 4 developed a reliable taxonomy of business model elements and a database of analysed business models, which could substantially speed up the adoption of these successful business models in the Swiss market. The theoretical taxonomy provides only few substantially new insights, but it is a prerequisite for systematic evaluation of different business models.

Contribution to the SCCER's objectives

The recommendations and guidelines produced by WP 4 addressing EEB&D technology providers will clearly not contribute directly to energy savings or to reducing CO_2 emissions. Nevertheless, these instruments will definitely facilitate and speed up the dissemination of the SCCER FEEB&D's research findings. Its impact on successful implementation of the Energy Strategy 2050 should therefore not be underestimated, even though it cannot be quantified or measured.

Assessment of the achievements

WP 4 fulfilled most of the targets set out in the proposal, and the research questions as originally formulated were answered. There were some minor changes due to the long duration of the Energy Funding Programme and the nature of the research work. In any event, WP 4 reached its milestones and submitted the planned deliverables on time. Given that WP 4 produced a lot of fairly isolated findings that need to be bundled together to arrive at the expected impact on the diffusion of FEEB&D technologies and concepts, it is not possible to identify highlights.

WP 4 met the highest international standards in respect of the quality of the research and of the results. This was assured through intensive scientific exchanges with internationally renowned universities in other countries, such as UC Berkeley, Stanford University, Harvard University, the University of Cambridge and the University of Oxford. As such, most of the research results created novel and innovative scientific knowledge compared with the existing state of the art.

WP 5 – Urban Planning for Smart and Resilient Cities and Communities

Leader WP 5
Dr. Luca Baldini, Empa

WP 5 focused on the planning of smart and resilient cities and communities. It considered resilience under climate change action with a particular focus on urban planning scenarios, urban form, urban microclimate and cooling demand, along with exploitation of renewables and passive design concepts.

Objectives

- The overall objective of WP 5 was to protect the population against negative effects on health and comfort from local urban overheating, e.g. during heat waves, amid a changing climate, while at the same time reducing CO_2 emissions from buildings by increasing their energy efficiency and integrating renewables.

- As such, WP 5 aimed to reduce greenhouse gases, therefore contributing directly to the top goal of SCCER FEEB&D. The research focused on the heat island effect in dense cities and communities, its characteristics and causes, and on mitigation options through spatial planning or adapted forms and materials.

- It also analysed the use of passive and renewable cooling measures instead of inefficient cooling equipment, in order to cut peak electricity demand and the heating up of inner cities by breaking the vicious circle whereby waste heat rejection creates further demand for cooling.

What was achieved

WP 5, which only began its work in 2019, used multi-scale modelling to improve the representation of urban areas in regional climate models. This enabled the impact of the local climate and of future climate change on energy demand to be evaluated. The impacts of future urban planning scenarios and of extreme conditions on future energy systems were also analysed, and it was demonstrated that the reliability and resilience of decentralised energy systems are tightly coupled with the urban planning scenarios. Finally, multi-scale modelling enabled the impact of urban planning scenarios on outdoor comfort to be evaluated.

At the city scale, simulations were performed using the COSMO meteorological model, applying statistical urban parametrisation models. At lower scales, i.e. neighbourhood and street canyon, a new coupled urban microclimate model was developed, extending the OpenFOAM open-source computational fluid dynamics (CFD) library with a coupled heat and moisture transport model for urban materials, a vegetation model, a solar radiation model and a wind-driven rain model. The reduction in ambient air temperature and an increase in relative humidity in green areas during the daytime was shown for the district of Basel. Coupling urban climate CFD simulations of various urban configurations at neighbourhood scale with a building energy model showed that local air temperatures may be more than 2 K above the ambient temperature in the suburban area, which can lead to a 20% increase in space cooling demand.

With regard to mitigation measures, multi-layered porous urban materials combined with artificial watering (spraying) were analysed and showed that daily artificial wetting of 6 mm spread on porous street pavements produces an improvement of more than 2 K in local thermal comfort. This result is promising, but the water consumption is prohibitive, especially in the megacities of developing countries.

A building stock model combined with Monte Carlo simulations was implemented and extended to estimate the current and future cooling demand in the Swiss service sector; a bottom-up, physics-based simulation approach was used for the same purpose for residential buildings. The simulations showed that under all climate change scenarios, cooling demand will increase substantially in the period to 2050. For the service sector, this means that the cooling demand will be equivalent to more than 50% of today's heating demand, which will necessitate mechanical cooling systems. The simulations also showed that in residential buildings, passive cooling measures, e.g. night ventilation, window shading and activation of the thermal mass, have the potential to reduce the future cooling demand intensity by approx. 80%. Mechanical cooling systems will therefore not be required for housing.

The third topic of WP 5 concerns the digitalisation of building technologies and smart city platforms. A survey of the diffusion of novel ICT technologies in the building industry was carried out through interviews with the management of building enterprises. The main conclusion is that digitalisation will strongly affect the building industry and offer potential for new energy efficiency-related services. In particular, WP 5 assumes that digitalisation has the potential to substantially increase energy efficiency and reduce CO_2 emissions by buildings. Unfortunately, neither of these assumptions has been verified through comprehensive research.

Contribution to the SCCER's objectives

After just two years of research, it is too early to assess the potential contributions of the research results to the implementation of the Energy Strategy 2050. There is no doubt that reducing the urban heat island effects and their impact on indoor and outdoor environmental quality will substantially contribute to reducing energy demand in dense cities and communities. However, it must also be considered that heat island effects and heat waves are not as significant in Switzerland as in hot regions, even considering climate change.

Assessment of the achievements

WP 5 began in early 2019, with the aim of continuing its activities after the end of the Energy Funding Programme (in 2022). All the milestones due by the end of 2020 were achieved on time, as were as the deliverables. Given that WP 5 has only been in existence for two years it would be premature to report on its highlights.

WP 5 met the highest international standards in respect of the quality of its research and results. This was assured through intensive scientific exchanges with internationally renowned universities, such as EPF Lausanne, University of Geneva, KADK Copenhagen, University of Lund, various universities of applied sciences and the Future Cities Lab of ETHZ in Singapore, and with other research projects, e.g. EO COST RESTORE. There was also intensive cooperation with industry (e.g. Consolar GmbH in Lörrach, Energie Solaire SA in Sierre and ENEL X in Boston). As such, most of the research results achieved within these two years created novel and innovative scientific knowledge compared with the existing state of the art.

WP 6 – Leveraging Ubiquitous Energy Data

Leader WP 6
Prof. Dr. Roy Smith, ETHZ

WP 6 had a cross-sectional task, as it supported the other SCCER FEEB&D WPs with knowledge and solutions for the management of ubiquitous energy data in specific cases, in particular regarding information handling and machine learning. WP 6's six tasks were therefore largely independent.

Objectives

- The overall objective of WP 6 was to make effective and efficient use of geospatial, building and energy data in order to support technology advancement and the assessment of potential by applying innovative information and communication technologies and artificial intelligence (AI), in particular machine learning.

- The research focused on the following six tasks: (1) potential of low-cost sensors and mobile data devices in learning energy consumer patterns and preferences; (2) modelling an information layer to facilitate effective large-scale data collection and exploitation in RDESs; (3) mapping the hourly variations in solar and wind power potential; (4) leveraging new business models; (5) identifying cost-optimal retrofitting strategies; and (6) identifying opportunities for demand-side management at district and city level.

What was achieved

It must be clarified that some of the results reported under WP 6 have already been mentioned in other WPs of the SCCER FEEB&D, because they were the output of a joint research effort. Furthermore, this WP also only began its work in 2019.

In the first task, human thermal comfort models were developed and evaluated. Experimental experience at the NEST building showed that occupant behaviour effects are captured in both historical and adaptive data-based methods. The experimental comparison of direct data-based control methods (using machine learning/neural networks) with model-based methods showed a remarkable result: model-based methods achieve higher efficiency in operation.

In WP 6's second task, minimum requirements for creating digital twin prototypes and instances of building energy systems were defined, including details of the end-use, geometry, envelope, heating, ventilation and air conditioning (HVAC) systems, boundary conditions, metered heating and electricity consumptions. Two layers were defined based on the availability of information and their update cycles: (1) the semi-static layer, which contains information on end-use, geometry, envelope and HVAC systems, and (2) the dynamic layer, comprising metered consumption and boundary conditions. Fine-tuning of a digital twin building was tested in various case studies. Although the calibration can be performed at the same temporal resolution as the update cycle (6 hours), the results show great information loss when calibrating models with coarse granularities.

In task 3, the data-driven estimate of solar and wind energy potential at the hourly scale for the whole of Switzerland was accomplished and will be made available through a digital platform. This online portal allows users to navigate and retrieve data at the desired resolution, along with the uncertainty information. The results do not include real-time predictions.

Due to the availability of data, the research in task 4 focused on energy time series from supermarkets (such as Migros) to test machine learning algorithms. Such electricity consumption patterns turned out to be more periodical, meaning that a feature transformation (Fourier) and reduction (principal component analysis, PCA) could have been applied to extract the inputs for the algorithm. The unsupervised machine learning algorithm for clustering (DBSCAN) applied to these features provided a two-fold result: (1) a separation of buildings by type (e.g. supermarkets vs gyms) and (2) a weekly classification of energy consumption patterns. Weeks falling in the outliers class exhibit anomalous behaviour and thus trigger an investigation by the building energy managers.

As part of WP 2, two modelling streams – (1) lumped resistance-capacitance (RC) thermal models and (2) machine learning prediction models – were successfully applied to derive cost-optimal retrofit solutions. Both these streams rely on in-situ measurements obtained using a wireless sensor network (developed by ETHZ as part of WP 1).

In another task, a dataset of hourly electricity readings from 1,000 sites, including residential (apartments in multi-family homes and single-family homes) and commercial buildings (schools, hospitals, offices, restaurants, hotels) were used in a cluster analysis of three demand-side management strategies, i.e. flexibility, peak demand reduction and ramp rates. Significant differences in electricity use patterns among and within the building types were found, as well as between seasons and days of the week. A key finding of the research is that households have higher peak intensities and offer more demand-side management potential than the non-domestic sector. Power suppliers should therefore be motivated to develop dynamic electricity tariffs, and households should be incentivised to apply them.

Contribution to the SCCER's objectives

The research results produced by WP 6 will clearly not by themselves contribute directly to increasing the energy efficiency of and reducing CO_2 emissions from the Swiss building stock. However, they are of the utmost relevance for the accuracy and reliability of any numerical analysis or simulation based on energy data. As such, they will have a substantial impact on the identification and evaluation of different strategies and measures that will contribute to the successful implementation of the Energy Strategy 2050.

Assessment of the achievements

WP 6 began its work in January 2019. All milestones due by the end of 2020 were achieved on time, as were the deliverables. It must be pointed out that – in line with the research proposal – some of WP 6's tasks will be performed after the end of phase 2, i.e. by the end of 2022. Given that WP 6 has only been in existence for two years, it would be premature to report on its highlights.

WP 6 met the highest international standards with regard to the quality of its research and results. This was assured through intensive scientific exchanges with internationally renowned universities and institutions, such as Empa and the NEST facility, the Universities of Lausanne and Geneva and the University of Oxford. There was also intensive cooperation with industry (e.g. Swisscom, OPIT Solutions AG, Migros, Swisspor, Flumroc, BASF and Eberhard Recycling AG). As such, most of the research results achieved within these two years created novel and innovative scientific knowledge compared with the existing state of the art.

Finances and capacity of the SCCER

The SCCER FEEB&D's activities, and in particular the development of research capacity, had total financing of CHF 61.9m between 2014[11] and 2020. Innosuisse support was CHF 18.3m, while the participating HEIs contributed CHF 22.2m and the remaining CHF 21.4m came from competitive federal funds (CHF 10.5m) and from contributions by industry partners and international projects (CHF 10.9m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period. Funding from own sources clearly exceeded that requirement.

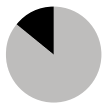
Research Capacity + Operating Expenses + Other direct costs

Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**18'335'196**	**22'200'780**	**10'484'423**	**10'886'940**	**61'907'339**
Share in percentage	30%	36%	17%	17%	**100%**
Ratio (Innosuisse = 100%)	100%	121%	57%	59%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	2.4	12	20%
Assistant Professor / Lecturer	1.3	2	65%
Senior Researcher	19.8	39	51%
Post Doc	10.3	14	73%
Technician	1.1	5	22%
PhD student / Research Assistant	21.1	42	50%
Other	3.3	5	66%
Total	**59.3**	**119**	**50%**

Gender ratio



As at the end of 2020, 119 researchers were involved in the SCCER FEEB&D. This corresponds to 59.3 full-time equivalents (FTEs). 36% of the active researchers within this SCCER were PhD students or research assistants. 14% of the researchers were female.

Conclusion and outlook

Overall, the SCCER FEEB&D's performance over the last seven years was good. The envisaged capacity build-up and intensive cooperation between the most renowned researchers from research institutions in Switzerland in the field of energy efficiency and CO_2 reduction for buildings and districts were implemented successfully. In addition, a comprehensive network incorporating important industrial companies and the relevant public authorities in Switzerland was realised. Most of the research results achieved by the SCCER FEEB&D are of top quality and can compete with the scientific output of any renowned international university.

The innovative technologies and systems and many modelling and simulation tools developed by the SCCER FEEB&D have the potential to substantially contribute to the transformation of the Swiss energy system and the successful implementation of the Energy Strategy 2050. Obviously, some relevant issues have not yet been investigated, such as grey energy and embodied CO_2, and the full potential of digitalisation. Nonetheless, applying all these mature technologies and measures could lead to a Swiss building stock that is free from fossil and nuclear energy and without CO_2 emissions by 2050. However, politicians, business and the population must expressly want this transformation and must finance it.

Within the SCCER FEEB&D's field of action, the following future research is needed. In order to exploit the full potential of the manifold technologies and systems developed in WP 1, sound and specific building retrofit strategies are paramount in order to:

- reduce the energy intensity of buildings by improving the performance of their envelopes and energy management systems at a reasonable cost;
- mitigate the carbon intensity of buildings by promoting the integration and optimisation of renewable energy systems;
- reduce the amount of grey energy and embodied CO_2 in existing and new buildings.

Surrogate models for building retrofitting will be further developed to upscale this throughout the whole of Switzerland. The target is to develop a retrofitting advisor for the Swiss building stock which allows the optimal retrofitting solution for individual buildings to be identified. In this context, a multidimensional model of the Swiss building stock including materials will be further developed based on semantic data assembled from different sources.

Energy hub modelling methods are to be advanced, including non-linearities, interactions with mobility and other larger energy systems, larger districts/entire urban areas and emerging technologies (e.g. fifth-generation district heating, micro data centres). In addition, automation and control of thermal grids will be further researched and the NODES-Lab (new opportunities for decentralised energy systems) will be expanded to better understand the interaction between components (such as heat pumps) and thermal grids. Semi-automated modelling methods also require further investigations regarding their scalability, their data property requirements and their sample efficiency.

With regard to energy performance at regional and national scale, there are a large number of open research challenges. These include:

- Mechanical engineering questions, notably the development of low-exergy district thermal network systems and more flexible systems that allow buildings to be both producers and consumers of thermal energy.

- Energy systems research, such as system planning and urban planning around thermal networks.

- Legal and policy aspects, such as how to encourage system deployment and manage ownership and contractual relations between energy consumers and producers.

In order to advance the diffusion of FEEB&D solutions, technologies and energy solutions need to focus on building retrofitting, and policies and business models should specifically target this issue. Several follow-up projects of this SCCER are already taking first steps in this direction. Future research should therefore focus on data, algorithms and platforms towards this goal, and also on how the regulatory and market environment needs to change to enable such systems.

In the area of urban planning for smart and resilient cities and communities, further research on specific technical solutions and overheating protection measures needs to be carried out and tested in real cases.

Algorithms that exploit both databases and real-time measurements would help to handle the complexity of controlling multi-energy systems efficiently and effectively. In addition, the full potential of digitalisation in relation to the design and operation of buildings needs to be investigated and broken down into user-friendly tools.

Further Information

LITERATURE

Geisler-Moroder D., Lee E.S., Ward G., Bueno B., Grobe L.O., Wang T., Deroisy B. and Wilson H.R. (2021): BSDF generation procedures for daylighting systems – White Paper, BSDF generation procedures for daylighting systems IEA SHC Task 61/EBC Annex 77.

Hochparterre and SCCER FEEB&D (eds.) (2019): Im Untergrund.

Mennel S., Ködel J. and Hangartner D. (2019): Fernwärme in Kürze, Conference of Cantonal Energy Directors.

Sulzer M., Orehounig K. and Bollinger A. (2021): Wegweiser aus dem Energie-Trilemma, bulletin.ch.

Scartezzini J.-L. (2020): Une autre consequence du changement climatique, bulletin.ch.

Steinmann W. (2021): Wie schaffen Städte den Umstieg in die neue Energiewelt?

Sulzer M. (2021): Energieinnovationen brauchen Investitionen – 7 Jahre Energieforschung für die Schweiz. Energiaplus.com, Swiss Federal Office of Energy.

VIDEO

"Circular Economy", CISBAT 2019.

"Energy Hub System Control", CISBAT 2019.

"Energy Hub System Control", CISBAT 2019.

"Full Renewable Energy Potential Switzerland", CISBAT 2019.

WHITE PAPER

Sulzer M. (2020): Paradigm shifts for the Swiss building sector to shape the future energy system.

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EIP

Efficiency of Industrial Processes

Action Area
Efficiency

Leading House

Swiss Federal Institute of Technology Zurich (ETHZ)

Participating Institutions

Eastern Switzerland University of Applied Sciences (OST)
Lucerne University of Applied Sciences and Arts (HSLU)
Swiss Federal Institute of Aquatic Science and Technology (Eawag)
Swiss Federal Institute of Technology Lausanne (EPFL)
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SCCER
EFFICIENCY OF
INDUSTRIAL PROCESSES

Synthesis

The SCCER EIP linked research institutions from all types of HEIs with a multitude of industry partners to push forward industrially relevant methodologies and technological innovations in the field of energy efficiency and to improve transparency over energy-efficiency potential within Swiss industry as a whole.

Challenges in the "Efficiency" action area

The "Efficiency" action area as defined in the Federal Council's Dispatch[12] also covered the issues related to energy-efficient processes in the industrial environment. Industrial processes are responsible for more than 20% of Switzerland's energy demand[13]. According to the action plan, research therefore needed to be strengthened in new analysis methods, heat recovery, solar heat for industry (100–500°C), CO_2 capture from power and cement plants, heat pumps and refrigeration systems in industrial processes.

The "political measures" (POM) scenario of the Energy Strategy 2050 targeted a 20% energy reduction for industry in 2035 and 33% in 2050, which corresponds to absolute energy reductions of 9 TWh and 14 TWh respectively.

With this in mind, it is not sufficient to proceed at the same pace of energy-efficiency increases as in former years. Methodologies need to be developed that enable companies to identify energy-efficiency potential easily, evaluate them comprehensively and derive corresponding measures. Policymaking requires advice on which existing and economically feasible technologies and energy-efficiency measures are to be implemented in industry. However, existing efficiency technologies are not sufficient to reach the intended goal. New technologies that significantly reduce primary energy demand on the part of industrial companies need to be developed for both core processes and supporting processes.

Vision and objectives of the SCCER EIP

The SCCER EIP's vision was to develop the science and technology to enable Swiss industry to transition to sustainable use of energy in its processes, to reduce greenhouse gas emissions and to ensure that the target of 14 TWh energy consumption

[12] Federal Council (2012): Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

[13] Kemmler A., Spillmann T., Piégsa A., Notter B., Cox B., Jakob M. and Catenazzi G. (2019): Analyse des schweizerischen Energieverbrauchs 2000 – 2018 nach Verwendungszwecken. Prognos AG, Infras AG and TEP Energy GmbH, commissioned by the Federal Office for Energy, Bern.

reduction is achieved by 2050, while at the same time keeping the economic impact of these processes to a minimum.

The goals for phase 2 of the SCCER EIP were twofold. The first focused on developing new methods to increase the implementation of energy-efficiency measures and technologies in industry and improve transparency concerning the relative merits of economically feasible energy-efficiency measures in different sectors of industry. This first workstream aimed for an indirect impact on the Energy Strategy 2050, with both, policymakers and industry getting advice on how and where to apply energy-efficiency measures.

The second workstream addressed the development of novel technologies to increase the energy and material efficiency of existing and new processes. Three specific research fields were identified. The first was the development of technologies enabling increased energy efficiency, such as high-temperature heat pumps, advanced heat exchange via dropwise condensation and vapour recompression. The second was research into technologies that reduce CO_2 emissions, such as enhanced absorption processes for hydrogenation and direct air capture processes, cement recycling and industrial solar heat utilisation. The third workstream dealt with the utilisation of wastewater within households and at wastewater treatment plants for efficient pre-heating and evaporative cooling purposes.

An important additional objective was to feed the latest insights on efficiency potential and costs into JA Scenarios & Modelling (JASM) (see page 248), which started with the second phase of the Energy Funding Programme.

With regard to the structural aspects of energy research, the SCCER EIP aimed to substantially build up research capacity in the field of energy-efficient industrial processes and to bring these competences together in a national research competence center encompassing research units from the ETH Domain, the cantonal universities and the universities of applied sciences that were already active in this field. This competence center was to collaborate intensively with private and public entities over the whole programme duration and then continue to do so beyond 2020.

What was achieved

The SCCER EIP effectively promoted and raised awareness of the importance of industry in the entire Swiss energy system as a key component in achieving the goals of the Energy Strategy 2050, and reduced barriers by supporting decision-makers with methods and tools.

Several valuable studies and analysis tools were developed. They support the development of macroeconomic policy strategies, give overviews of the technological state of the art and support the technical implementation of energy-efficiency measures and solar heat within companies; they include the pinch analysis and multiple benefit evaluation and the “Gain Buddy” and “SolindTool” tools.

In terms of technological advances, a high-temperature heat pump with environmentally friendly refrigerants and an oil-free compressor were developed, and the first prototypes were tested successfully. Further, prototypes featuring gas-lubricated bearings were tested successfully for oil-free turbomachinery-driven refrigeration and heat pumps, as were a novel surface made of a nanocomposite of PTFE and carbon nanofibres and a novel material offering high performance in single-cycle hydrogen purification and CO_2 separation.

In collaboration with neustark (a SCCER EIP-driven startup), Kästli and wastewater treatment plant (WWTP) Region Bern, a mineral carbonation plant was designed, constructed and successfully put into operation, representing a clear highlight of this SCCER.

In the field of wastewater utilisation, a test rig for on-site grey water treatment and usage for evaporative cooling spraying on absorbers was installed at the OST and the WWTP Birsfelden and operated by the FHNW.

Contribution to Energy Research and to the Energy Strategy 2050

The SCCER EIP showed that the activities in the industrial sector to date are insufficient to reach the 2035 milestone targets and even less likely to achieve net-zero carbon objectives, and provided technological solutions to address this.

High-temperature heat pumps seem to be among the most important technology paths to be pursued in order to reach the climate targets, leading to a saving potential of 5,000 TJ/a. The utilisation of vapour recompression using waste heat of just 60°C leads to a 30% reduction in primary energy consumption compared with conventional gas burners and a 70% reduction compared with electrically heated steam generators. The intention is for the application of dropwise condensation to achieve a 15% decrease in energy utilisation in the chemical and pharmaceutical industry by 2035. The work on wastewater heat recovery aims for a decrease of 1.8 TWh_{th}/a by 2035 and 3.2 TWh_{th}/a by 2050 for the production of hot water in households and a reduction in the net energy demand of wastewater treatment plants of 0.070 and 0.12 TWh_{el}/a respectively.

A very good level of collaboration and trust was achieved among the SCCER EIP partners, creating a basis for further fruitful collaboration. Several spin-off projects were launched, which would not have been possible without the SCCER EIP. The combination of the ETH, the universities and the universities of applied sciences produced favourable results, playing to the strengths of each of these institutions.

Recommendations

based on the SCCER EIP's research findings

- **Breakthrough for pinch analysis in industry**
  A streamlined user workflow for pinch analysis in combination with process simulation and lifecycle assessment allows energy-efficiency potential and measures to be identified and evaluated at a multitude of Swiss companies including small and medium-sized enterprises (SMEs). Efforts must be redoubled if a breakthrough in the application of this approach is to be achieved rapidly. This new workflow supports process engineers by making transparent the trade-offs between economics, energy and carbon savings. Mass and energy balances can be conducted quickly and accurately for a wide array of systems. It therefore acts as a natural complement to enabling process understanding. Conceptualised energy-efficiency measures based on pinch analysis of system changes can also be validated.

- **Market penetration of high-temperature heat pumps and vapour recompression systems**
  High-temperature heat pumps (HTHPs) and vapour recompression systems enable significant energy savings and reductions in CO_2 emissions in industry. Up to now, most of the practical applications of HTHPs in Switzerland have been in the food sector or for district heating, using industrial waste heat, wastewater and lake water as heat sources. There are still too many barriers hindering widespread implementation, such as relatively high investment cost, a small pool of manufacturers and inexperience. In order to overcome these hurdles, it is recommended that the applicability and long-term benefits of these new technologies be demonstrated in several industrial scenarios and in piloting facilities.

- **Towards climate-neutral concrete**
  Concrete has the potential to reabsorb all emissions relating to the decomposition of calcium carbonate in the clinker burning process. In order to industrialise this natural process, a pilot plant for the carbonisation of demolition concrete using CO_2 captured from the air was built and operated, showing very promising results: the plant operation was very stable, the CO_2 uptake was robust, and the carbonation process was managed successfully by the normal cement plant staff. The next step is to transform the concrete fines into calcium carbonate and sand. Both materials will subsequently be used in concrete, meaning that the concrete mixture embodies all CO_2 emitted along the cement and concrete manufacturing value chain. This will bring about climate-neutral concrete. Achieving this challenging goal, however, will still require tremendous efforts on the part of the construction industry to upscale these methods and implement the new construction material.

Results

WP 1 – Implementation of Industrial Energy Efficiency

Leader WP 1
Prof. Dr. Beat Wellig, HSLU

WP 1 dealt with the development of comprehensive strategies at technological, company and national level to facilitate the implementation of existing and future energy-efficiency measures and technologies to mitigate CO_2 emissions and optimise the electricity usage of industrial sectors.

Objectives

WP 1's objective of facilitating the implementation of energy-efficiency measures and technologies was pursued through four sub-goals:

- First, the identification and assessment of the impact of existing and promising technologies and processes on the Energy Strategy 2050.
- Second, the application of pinch analysis and process integration techniques at companies at site level via model-based decision-support methods for the identification and the implementation of energy-efficiency measures and technologies.
- Third, the identification and quantification of multiple benefits of implementing energy-efficiency measures and advanced energy conversion technologies in production and non-production areas.
- Fourth, the aggregation of the insights to national level in order to assess the impact of the implementation of energy-efficiency measures and technologies on electricity demand and CO_2 emissions, so as to recommend implementation strategies that are in line with the Energy Strategy 2050 targets.

What was achieved

WP 1 made a strong contribution to support decision-makers in companies in identifying and evaluating energy-efficiency measures. It developed two methodologies.

First, the pinch analysis tool was embedded into a holistic methodological and iterative approach to support engineers in the evaluation and implementation of comprehensive energy-efficiency measures. It was applied in and integrated into industrial process simulation and in the design of heat exchange networks with a lifecycle assessment. Besides continuously focusing on energy-efficiency measures and the reduction of CO_2 emissions while applying the methodology, great importance was attached to reducing its application efforts, especially in terms of data extraction, as this typically accounts for 60% to 70% of the pinch analysis costs. The case studies performed showed an average increase in energy efficiency of up to around 40%. The work on pinch analysis turned out to be very valuable for the identification and implementation of energy-efficiency measures, was validated in multiple use cases and supports future energy savings in industry.

HIGHLIGHT

PINCH ANALYSIS

Within the scope of WP 1, the iterative methodology and workflow that were developed combine process simulation tools, pinch analysis, capital cost, environmental optimisation and heat exchange network design, to aid engineers in rapid process understanding and to produce feasible and practical energy-efficiency solutions. It addresses the broader challenge of ensuring engineers converge on energy-efficiency solutions likely to be adopted by the company conducting the analysis. The system is therefore envisioned, designed, validated, redesigned and revalidated within the conceptual design space. By keeping the engineer central to decision-making at all stages, while providing them with the best available guidelines and tools in the form of the workflow and associated elements, a practical solution can rapidly be found.

also supported by Chemstations Europe

The second methodological approach to support industrial decision-makers is based on the multiple benefits analysis of energy-efficiency measures. The ex-ante monetarisation of these multiple benefits increases the attractiveness of energy-efficiency measures by decreasing payback periods, which helps to boost the number of economic energy-efficiency measures. Such multiple benefits could include improvements in production and quality, more efficient operation and maintenance, reductions in waste and emissions, or improvements to the working environment.

While the multiple benefit and pinch analysis approaches are bottom-up approaches, WP 1 also worked on a top-down approach to analyse the industrial energy-saving potential in the whole of Switzerland. Sector-specific energy-efficiency cost curves which show the specific costs of the saved energy relative to the cumulative annual potential of the final energy savings and associated CO_2 emissions were developed for different measures in the cement, chemicals, metal, and food and beverage sectors, and for two key cross-cutting technologies: electric motor systems and excess heat recovery. A total saving potential of between 16.5% and 19% of total Swiss industrial energy consumption was identified as realisable with economic energy-efficiency measures. This would mean annual CO_2 savings of 1.3 to 1.5 million tonnes per year. The required investment costs of about CHF 2bn and net cost savings due to avoided energy consumption and CO_2 taxes in combination with a discount rate of 12% would lead to net cost savings of CHF 314 to CHF 343 per unit of CO_2 abatement.

HIGHLIGHT

REALISTIC SAVINGS POTENTIAL IN SWISS INDUSTRY

The potential energy savings in Switzerland from implementing economically valid energy-efficiency measures in the short to medium term are a second highlight of WP 1. The figures were derived from detailed analyses of the cement, chemicals and pharmaceuticals, basic metals and metal products, food and beverage subsectors, along with electric motors and drives. The total economically viable energy-efficiency potential of Swiss industry across all analysed sectors is calculated to be 6% to 7% excluding heat recovery. Another 9% is estimated to be economically feasible from process integration and heat recovery, including the potential of SMEs.

WP 1 firstly broke down industrial energy use by sector into components related to growth, energy savings and structural changes. It concluded that in the food sector, for example, the energy perspectives imply very significant energy-efficiency improvements which are close to or even partly beyond the level of today’s best available technologies and anticipated that failure to reach the goals of the Energy Strategy 2050 would be likely without further technological efforts.

Contribution to the SCCER's objectives

WP 1 effectively promoted and raised awareness of the importance of industry within the entire Swiss energy system as a key component in achieving the goals of the Energy Strategy 2050, and reduced barriers by supporting decision-makers with methods and tools. Swiss industry consumes about 30% of final energy (60% heat, 40% electricity). Politicians are placing high expectations on Swiss industry to contribute to significantly reducing CO_2 emissions. However, WP 1 shows that the activities in the industrial sector to date are insufficient to reach the 2035 milestone targets and are even less likely to achieve net-zero carbon objectives.

WP 1 also elaborated tools and methodologies that address pinch analysis and multiple benefits very well and implemented them in the first industrial applications. Broad rollout could begin more or less immediately.

The many industry partners, such as Nestle and the Energy Agency of the Swiss Private Sector (EnAW), that were open to collaboration and to putting effort into the development of the tools were crucial for the user-oriented results. Some partners are also very important for the future development of user-friendly front ends, e.g. Chemstations Europe.

A very good level of collaboration and trust was achieved among the SCCER EIP partners, creating a basis for further fruitful collaboration e.g. in response to the SWEET (Swiss Energy research for Energy Transition) call. WP 1 also incorporated results of the industrial efficiency improvements into the work of JASM and built on the concepts of the "Energyscope" tool.

Assessment of the achievements

All objectives defined in the original work plan were achieved. One major achievement of WP 1 was to establish pinch analysis as a holistic approach. The workflow performs a trade-off between economics, energy and carbon savings. It is increasingly being applied in Swiss industry and even to some extent abroad. The tool and the methodology need to be maintained and disseminated in the future, including some extensions to other industrial thermal processes and a professional user interface.

WP 1 met the highest international standards with regard to the quality of its research and the results achieved. In total, more than 45 peer-reviewed publications describing methods and tools to be applied in industry were produced. The results created novel and innovative scientific knowledge compared with the existing state of the art.

Both the user workflow for streamlined pinch analyses and the determination of the realistic savings potential in Swiss industry have distinct audiences for whom the results are highly important. Nevertheless, both seem to represent important supporting results rather than breakthroughs. The determination of realistic savings potential might gain practical importance if legislators start subsidising specific market segments.

WP 2 – Process Efficiency (direct)

Leader WP 2
Prof. Stefan Bertsch, OST

In Swiss industry, 4 TWh/a of process heat below 130°C accounts for about 9% of the total final energy consumption. In WP 2, activities were performed in three technical areas addressing process heat of up to 130–150°C: HTHPs, steam generation via water vapour recompression, and process integration of solar heat.

Objectives

- A first target of WP 2 was to create scalable high-temperature heat pump technology using oil-free and conventional compressors together with environmentally sound refrigerants; most currently use refrigerants that will eventually be phased out due to their high global warming potential. Estimates indicate that these heat pumps could potentially significantly reduce CO_2 emissions.

- A second objective was to investigate small and mid-power-range steam generators based on water vapour recompression combined with thermal storage. The system would be able to use waste heat to greatly reduce primary energy consumption in steam generation. The use of small-scale turbines, currently used in the small and mid-power range, to create power from steam expansion in industrial processes was also to be explored.

- The third objective of this WP was to analyse in greater detail which processes and system levels are particularly suited to the use of solar energy in Switzerland, as solar heat is intended to cover between 10% and 40% of total heat demand at certain sites.

What was achieved

An investigation of commercially available industrial applications of heat pumps with a heat sink temperature of more than 100°C and several industrial heat pump systems installed in Switzerland was performed. At 120–150°C sink temperatures, a coefficient of performance (COP) in the range of approx. 2.2–2.8 at 70 K temperature lift can be realised; this enables HTHPs to make low-pressure saturated steam used in the food, textile, paper and chemical industry. Against this background, researchers at the OST university of applied sciences working on WP 2 developed a high-temperature heat pump with an oil-free compressor and environmentally friendly refrigerants that reaches heat sink temperatures of between 70°C and 150°C at a COP of 2.1 to 4.5 and a temperature lift of 30 to 70 K. While there are already systems in operation, several impediments tor quick market introduction were identified, such as high specific investment cost, very few manufacturers of the heat pumps systems on the market, little experience on the part of planners and end-users, and preconceptions in respect of lifetime and suitability.

HIGHLIGHT

HIGH-TEMPERATURE HEAT PUMP

The research on HTHPs with eco-friendly refrigerants was certainly a highlight of this SCCER, and most of the R&D results were published in the book entitled "Hochtemperatur-Wärmepumpen". Besides the theoretical analyses, a prototype was developed at the OST university of applied sciences reaching 70°C to 150°C heat sink temperature with a COP of 2.1 to 4.5 and a temperature lift of 30 K to 70 K; this is above the average of the investigated heat pumps, but below two reported lab prototypes. However, as the current availability of HTHPs in the markets was identified being pretty low, the outstanding potential of this technology to reduce CO_2 emissions in several industry sectors needs to be addressed on a huge scale – especially given that WP 2 pointed out that the best compromise for generating steam currently seems to be a heat pump system in combination with waste heat recovery.

also supported by the SFOE and more than
30 companies and organisations

A theoretical case study on steam generation was also performed. Fourteen different processes to produce saturated steam of three bar were analysed and simulations were performed using different waste heat temperatures. Results show that water vapour compression requires about three times less energy than systems with gas-fired boilers or electrical heating elements. Nevertheless, WP 2 concluded that the best compromise to generate steam currently seems to be a heat pump system in combination with waste heat recovery, as they offer good efficiency, low operating cost and low CO_2 emissions while already being available on the market in some cases. Unfortunately, only very few heat pumps featuring a heat sink temperature of 133°C are currently on the market.

The progress that WP 2 achieved in the area of heat pumps and steam generation is certainly very valuable concerning transparency and knowledge generation about the thermodynamics and the technology itself. At the same time, however, only one prototype in combination with a piston compressor was built.

Solar heat integration was studied in WP 2 as a possible complement for industrial processes in need of thermal energy. The food, chemical/pharmaceutical, textiles and paper sectors have high thermal energy demand, at mostly low operating temperatures, and so theoretically would be expected to benefit from solar energy. In fact, the proportion of low-temperature thermal energy in these industries is estimated at 14.6 PJ, which represents a non-negligible 9% of the final energy consumption by Swiss industry in 2016. The SCCER's activities were limited to case studies. Unfortunately, WP 2 did not perform an economic feasibility study of solar thermal process heat and did not identify a final intention beyond the "Gain Buddy" and "SolindTool" analysis tools that were created. In general, it seems that the application of solar heat in industry is perfectly possible with the given technologies, but that there is a lack of productised solutions, ready for straightforward integration design. This naturally makes it less attractive to industrial companies from both a cost and a project duration perspective.

Another key topic was the development of "small-scale turbomachinery". Three prototypes featuring gas-lubricated bearings were tested successfully. The tests highlight the potential of oil-free turbomachinery-driven refrigeration and heat pump cycles while improving the COP by 20% to 30% compared with state-of-the-art systems. The tested heat pump compressor comprised fully 3D-printed foil bearings, which are considered a major breakthrough in the area of gas-lubricated bearings. An 8 kW organic Rankine cycle radial inflow turbine supported on herringbone-grooved journal bearings was tested and achieved a record expander efficiency for its class of 67%. Lastly, one of the smallest anode off-gas recirculation devices was tested, increasing the fuel cell system gross DC efficiency from 61% to 66%.

However, some questions remain, e.g. a comparison with state-of-the-art volume displacement machines, an economic analysis of the increased expander efficiency and the high-temperature (> 800°C) durability of the recirculation device.

Contribution to the SCCER's objectives

It cannot be overemphasised that HTHPs seem to be one of the most important technology paths to be pursued in order to reach the climate targets. It is no surprise at all that a lot of research is conducted internationally in this domain. Raising the condensing temperature from 100°C to 150°C allows approximately 25% more of the process heat needed in industry to be addressed, leading to a saving potential of 5,000 TJ/a in Switzerland. Vapour recompression using waste heat of only 60°C leads to a 30% primary energy reduction compared with conventional gas burners and a

70% decrease compared with electrically heated steam generators. Steam is used in almost all industrial sectors for one or more of the following applications: cleaning and disinfection, humidification, heating, shrinking, propelling, drying, sputtering, etc., and its generating device can be altered without changing core industrial processes, which allows for quick market penetration.

In the case of HTHP, transfer to the market has already started with a few examples as shown in International Energy Agency (IEA) Annex 48. Several more systems are in preparation for the coming years, which will enable more and more customers to experience the advantages.

Knowledge and technology transfer (KTT) within WP 2 was very active. The topic of HTHPs in particular attracted significant interest. Several spin-off projects were started, which would not have been possible without the SCCER EIP. The combination of the ETH, universities and universities of applied sciences produced favourable results, playing to the strengths of each of these institutions. One example of a beneficial collaboration between the different educational institutions was the system-level design and market research carried out by the OST university of applied sciences, complemented by the more basic research at component level by EPFL. The OST university of applied sciences has established itself as a test and qualification center for HTHPs even beyond the end of the SCCER funding period.

Assessment of the achievements

The progress of the research conducted corresponds to the plan for WP 2. There were only a few delays in achieving the milestones, and these were offset by achieving other milestones earlier.

This WP met the highest international standards with regard to the quality of the publications in general. There are naturally some differences between the tasks: some are close to basic research, such as the research into turbo machinery and heat pumps, whereas others are clearly applied science, such as the research into solar thermal systems. However, most results created novel and innovative scientific knowledge compared with the existing state of the art.

Impressive advances were undoubtedly made. While the turbo compressor research still has a relatively low TRL, the test results indicate significant potential for future exploitation in combination with absolutely oil-free operation, which is the basis of many open compression systems (i.e. water vapour compression). High interest from several academic and industry partners showed the relevance of this topic. The research into this topic is very much at the international forefront.

In contrast, solar thermal systems are the subject of widescale national and international research. Although all targets were met, the results feed into a high-quality international research field. The lack of innovative technological progress is due to the work plan, which placed the focus on generating transparency and tools for technology transfer.

WP 3 – Process Efficiency (direct)

Leader WP 3
Prof. Dr. Marco Mazzotti, ETHZ

The overall objective of WP 3 was to enhance energy efficiency by improving process efficiency. The WP dealt with technologies, mainly in relation to materials and processes. A comparison of the key indicators with respect to state-of-the-art technology was carried out, providing guidelines for further use and implementation of the WP results.

Objectives

- Considering that 10% to 15% of the world's energy use is currently in separation processes, one major objective of this WP was to increase their efficiency through enhanced separation materials and their implementation in advanced processes. The results should lead to a significant improvement in various gas separation processes, such as the separation of CO_2 from air and biofuels or the purification of natural gas.
- A second objective of this WP was to identify the best manufacturing process for the realisation of multifunctional integrated microfluidic devices, and to successfully apply them to an existing industrial process.
- The final objective was to produce engineered surfaces for intensified processes via existing and novel manufacturing routes and upscale them to industry-relevant conditions. These research activities were to enable energy utilisation in the chemical and pharmaceutical industry to be reduced by 15% by 2035.

What was achieved

In order to improve condensation heat transfer, various hydrophobic and super-hydrophobic surface coatings were characterised and compared. A novel surface made of a nanocomposite of PTFE and carbon nanofibres showed a ninefold increase in heat transfer compared with standard copper oxide surfaces, as it is a hydrophobic surface on which the vapour condenses in the form of discrete liquid droplets instead of a film. Accelerated lifetime testing at high temperatures produced promising results.

HIGHLIGHT

HYDROPHOBIC AND SUPER-HYDROPHOBIC SURFACE COATINGS

A highlight of this WP was the work on improved condensation for heat transfer. The partners developed thin and scalable robust super-hydrophobic nanocomposites consisting of a mixture of polytetrafluoroethylene (PTFE) and carbon nanofibres (CNF); micro-grooved surfaces consisting of aluminium micro-milled slots coated with a thin PTFE coating; ZnO nano-structured surfaces with additional antibacterial action; and laser-textured surfaces that enhance directional and passive droplet mobility. All these surfaces are designed on metal substrates that are typically used in industrial condensers. The most promising surface to be used in industrial condensers is PTFE/CNF nanocomposite, due to its scalability, robustness and ability to dramatically enhance condensation heat transfer.

The subject of separation has attracted interest lately, as CO_2 capture directly from air is under intensive discussion for the transition phase prior to a carbon-free energy system. Massive volumes of air are required to be treated in that process, because the CO_2 concentration in air is so low that high-volume flow rates need to be processed to capture the desired quantity of CO_2. The energy efficiency of an adsorption-based direct air capture process therefore plays a major role. The work shows that there is an optimum desorption time at which CO_2 uptake is highest while the specific energy consumption is low, but the sorbent cannot fully regenerate in that state. Thermodynamic and kinetic aspects have been studied both experimentally and theoretically to describe the interaction between the air and the materials. The work is still at an early stage. The initial results are promising but not conclusive.

The development of a novel material offering high performance in single-cycle hydrogen purification and CO_2 separation from synthesis gas was another field of action for WP 3 within separation processes. The results obtained show that the methodology developed for strategically improving the performance of vacuum pressure swing adsorption processes is superior to simply comparing one-dimensional key performance indicators such as the uptake of the adsorbent of a target gas at a single temperature and pressure. The approach developed shows that the overall performance of the adsorbent performance in industrially relevant applications depends strongly on the interplay of various factors.

HIGHLIGHT

MINERAL CARBONATION PROCESS FOR RECYCLED CONCRETE AGGREGATE

One outstanding highlight of this WP was the mineral carbonation process for recycled concrete aggregates. The team established the spin-off company neustark, which has already successfully built up and integrated the technology into an industrial plant. The CO_2 uptake potential under this approach very much contributes to the climate strategy. The team has also already planned to proceed with a follow-up project targeting net-zero CO_2 concrete in collaboration with neustark and Jura Zement. The aim of this project is to transform concrete fines into calcium carbonate and sand. It will be supported by Innosuisse. Very high expectations have been raised for this project; it is hoped that this will lead to a significant decrease in embodied CO_2 emissions in the building and infrastructure construction sectors.

also supported by the Federal Office for the Environment (FOEN), Klimastiftung Schweiz, Kästli and WWTP Region Bern

Demolition concrete represents one of the largest global solid waste streams, and this is projected to double every decade. Today's recycling practice basically recovers stone of lower quality, which is incorporated in concrete or used as roadbed material. As concrete can reabsorb CO_2 (which has been emitted during the clinker burning process), the basic idea within this WP was to develop a mineral carbonation process for recycled concrete aggregates resulting in net-negative CO_2 emissions for concrete derived from recycled material, and even to achieve superior quality to conventional concrete in so doing. In collaboration with neustark, Kästli and WWTP Region Bern, a mineral carbonation plant (TRL7) with a capacity of 120–200 t concrete aggregate per day and a storage capacity of about 1,200–2,000 kg of CO_2 per day was designed, constructed and successfully put into operation.

Contribution to the SCCER's objectives

All WP 3's activities have a potential impact on the Energy Strategy 2050. However, that impact is not easy to measure and is indirect in some respects, as some of the activities focus on carbon capture rather than energy saving.

The work on engineered surfaces and mineral carbonation processes for recycled concrete aggregates enables some very specific contributions to be made to the Energy Strategy 2050. WP 3 aimed to cut energy use in the chemical and pharmaceutical industry by 15% by 2035, using dropwise condensation technology. Assuming carbon-neutral energy supply, the work on recycled concrete aggregates aims for carbon neutrality for this sector, which is very ambitious but also well worth pursuing. In both areas, the technology transfer requires a significant push to reach this goal.

By contrast, the work on direct air capture and hydrogen purification remains more theoretical and does not seem as though it will be transferred into practice in the short term. While hydrogen purification from natural gas is not currently intended to play a significant role in the Energy Strategy 2050, direct air capture might one day become relevant to realising worldwide net-negative CO_2 emissions. However, there will be a great deal of competition to achieve the lowest carbon capture costs from among the many different technologies.

The funding period showed the development and relevance of the cooperations within this WP. While direct air capture and hydrogen purification will more or less stay within basic research in academia, the results of dropwise condensation are starting to be transferred. The partners in the work on mineral carbonation processes for recycled concrete aggregates have a very strong intention to directly transfer the results.

The work within WP 3 was dominated by the ETH, without obvious effects in terms of structures, other than a collaboration between ETHZ and EPFL in the field of vacuum swing absorbing processes.

Assessment of the achievements

In general, the work of WP 3 met the plan, and the team reached the goals, milestones and deliverables. It must also be mentioned that direct air capturing and concrete recycling were not originally in the scope of the SCCER EIP, which was originally supposed to be an energy-efficiency programme, not a carbon reduction programme. As the recycling of concrete is the principal highlight of the SCCER, it is remarkable that it was not originally part of its remit. The SCCER EIP's management was courageous in shifting focus during the journey, thanks to its outstanding success in third-party fundraising.

WP 3 met the highest international standards with regard to the quality of the research and the results achieved, and was very much oriented towards basic research. There are naturally some differences between the tasks in terms of the quantity of publications. The team working on dropwise condensation in particular published in internationally ranked journals. By contrast, the work on concrete recycling fell into the field of applied science. Irrespectively, most results created novel and innovative scientific knowledge compared with the existing state of the art.

WP 4 – Process Efficiency (direct)

Leader WP 4
Prof. Dr. François Maréchal, EPFL

WP 4 was set up to find strategies to reduce the wastewater-related impacts on Swiss energy demand. Based on a systemic analysis, it was hypothesised that the best strategies would aim to reduce the net energy demand for warm water production and make use of the wastewater heat and cooling potential.

Objectives

- Swiss energy consumption for domestic hot water production is around 9 TWhth/a, while net energy consumption for wastewater treatment is < 0.35 TWhel/a. In 2012, cooling applications used 8 TWhel/a (14%) of the Swiss electrical energy, of which 14% was used for space cooling purposes.
- Given the need for energy-intensive, large-scale redistribution systems, on-site, decentralised greywater treatment could be an energy-efficient alternative, provided that energy-efficient treatment methods can be applied. In any event, access to recycled greywater opens up opportunities for new on-site cooling or heating strategies.
- From a systemic perspective, the goals of WP 4 were thus to assess energy-saving measures for hot water production in households, including possible synergies and competition between different measures, as well as the potential for cooling and heating technologies using (treated) wastewater at different scales.
- WP 4's objective was to analyse the feasibility of on-site wastewater treatment for on-site cooling and heating strategies and its systemic implications for wastewater-related energy management at different scales, i.e. the impact on WWTP performance and greenhouse gas emissions.

What was achieved

WP 4 began in phase 2 and followed two workstreams: heat recovery from wastewater and wastewater utilisation for cooling purposes.

Within the first workstream, a new modelling framework to evaluate the potential of wastewater heat recovery technologies and to investigate the consequences of their integration into domestic hot water systems was developed and made publicly available. The "WaterHub modelling framework" provides a library of models to simulate energy and water flows in domestic hot water systems and a stochastic generator for (hot) water demand.

Active greywater heat recovery as a retrofitting strategy for buildings with floor heating and air-source heat pumps was also analysed. The basic idea is to harness the potential of using greywater to preheat the ambient airflow to a heat pump, thus decreasing the required temperature lift and increasing the system COP. The evaluation shows an annual average COP increase of roughly 3%, which results in about 60 kWhel/a. A second technology that was analysed with negligible results is a drain water heat exchanger to preheat the cold supply water.

Centralised heat recovery of sewer systems with heat exchangers in the sewer and heat pumps was also investigated, at the recommendation of the evaluation experts. The first results show that nearly 8.5% of heating demand could be covered if the heat exchange is downstream of the water treatment plants. The technology of using sewers in cities as a heat source for heat pumps does not require significant further basic research, as it is practically proven. By contrast, mapping of the potential in certain cities could be helpful for future planning activities.

A second workstream of WP 4 focused on wastewater utilisation for cooling purposes. Free cooling technologies reach high efficiencies, potentially limiting the additional electrical energy demand of increasing space cooling loads. A novel approach is to use activated components of the building envelope, e.g. solar components such as uncovered solar absorbers or PV/T collectors to reject heat via night-time radiation to the sky and convection to the ambient air. With additional wetting of the surface, radiation is enhanced by the high long-wave emissivity of the water, achieving an additional evaporative cooling effect. In a feasibility study, a high free cooling share in the range of 80–100% was found for both residential single/multi-family use and office use.

A test rig of an on-site membrane bioreactor for greywater treatment used for evaporative cooling spraying on absorbers was installed at WWTP Birsfelden and operated by the FHNW. It was shown that the water treatment can comply with the guidelines for cooling water while using additional chlorine and the required 180 l per night of cooling with a 1.5 m² absorber and roughly corresponds to the local greywater availability.

The work in WP 4 started later than in the other WPs and will continue beyond the end of the reporting period. It is therefore too early to point out specific highlights of this WP.

Contribution to the SCCER's objectives

The technologies investigated in WP 4 relate to the residential rather than the industrial sector, but the targets were set according to the overall SCCER EIP objectives. For production of hot water in households, this corresponds to a decrease of 1.8 TWhth/a by 2035 and 3.2 TWhth/a by 2050. For Swiss WWTP, the corresponding reduction of the net energy demand is 0.070 and 0.12 TWhel/a respectively. With the implementation of existing technology, a reduction of 0.15 TWhel/a can be achieved, despite the planned upgrading of Swiss WWTPs for the removal of organic micro-pollutants. In all, the contribution of this WP to the vision of the SCCER EIP and the Energy Strategy 2050 is fairly low.

The wastewater heat recovery technologies are all available on the market, while the cooling approaches have only shown their functionality in a demonstrator yet. Implementation partners will be essential for these ideas to be pursued further. The cost-effectiveness of the application of wastewater heat recovery technologies was unfortunately not analysed. It must be expected that there will be no commercial viability. Conversely, the decentral cooling approach faces the challenge of limited space on rooftops and comparably cheap existing solutions in terms of compression cooling powered by solar PV without the biological restrictions and a minimum of maintenance requirements.

There was some collaboration in WP 4 within academia and between academia and industry, such as Eawag and Empa, OST and FHNW, FHNW and Eawag and the industry partners Energie Solaire and Joulia.

Assessment of the achievements

WP 4 was based on a recommendation of the Evaluation Panel and started in spring 2017. The original task – to investigate savings in energy consumption for wastewater treatment (< 0.4 TWh/a) – was skipped to concentrate instead on using wastewater for heating and cooling applications. The main topic of the WP was therefore utilisation of the waste heat of domestic wastewater. In addition, investigations were carried out into using on-site purified grey wastewater for space cooling purposes.

Against this background, basically all relevant milestones were reached. Due to the coordinated shift of the work to district water heat recovery, the cost-benefit analysis for greywater heat recovery in households that was originally planned unfortunately had to be abandoned. Some testing had to be reduced due to delays in construction at NEST.

WP 4 turned out to be problematic in terms of identifying big levers for the Energy Strategy 2050. This was due partly to the Swiss geography, in which only a little energy is used to secure water supplies, and partly to the common sewage cleaning requiring minimal wastewater temperatures. No breakthrough application was identified that would allow major energy savings. Niche applications were found to cope with an increasing cooling demand in summer using thermal energy stored in (grey) wastewater for evaporation cooling. Shower drains were claimed to have a large energy-saving impact, if this were realised in most households. However, several simplifications limit the results of this hypothesis, such as the lowering effect on wastewater delivered to the treatment plant, the assumption that most hot water passes through the shower and not through all the other sinks, such as the bath, washing machine, dishwasher, etc.

Despite the limited results of this WP, the scientific quality of the publications, the technical and modelling work meets the highest international standards. Unfortunately, only a few results created novel and innovative scientific knowledge compared with the existing state of the art.

Finances and capacity of the SCCER

The SCCER EIP's activities, and in particular the development of research capacity, had total financing of CHF 34.2m between 2014[14] and 2020. Innosuisse support was CHF 8.1m, while the participating HEIs contributed CHF 10m and the remaining CHF 16.1m came from competitive federal funds (CHF 9.9m) and from contributions by industry partners and international projects (CHF 6.2m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period. Funding from own sources and competitive federal funds clearly exceeded that requirement.

Research Capacity + Operating Expenses + Other direct costs

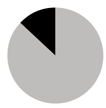
Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**8'104'418**	**10'051'020**	**9'862'666**	**6'178'891**	**34'196'994**
Share in percentage	24%	29%	29%	18%	**100%**
Ratio (Innosuisse = 100%)	100%	124%	122%	76%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	4.9	19	26%
Assistant Professor / Lecturer	2.7	3	90%
Senior Researcher	6.1	22	28%
Post Doc	3.9	7	56%
Technician	1.2	5	23%
PhD student / Research Assistant	25.0	48	52%
Other	0.0	0	0%
Total	**43.8**	**104**	**42%**

Gender ratio

13% female | **87%** male



As at the end of 2020, 104 researchers were involved in the SCCER EIP. This corresponds to 43.8 FTEs. 57% of the active researchers within this SCCER were PhD students or research assistants. 13% of the researchers were female.

[14] Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

Conclusion and outlook

Overall, the SCCER EIP performed very well. The planned capacity build-up was exceeded, and in all WPs there was intensive collaboration between excellent researchers and with industry partners. The SCCER EIP managed to start many supplementary projects with public and also industrial funding. The established network between the ETH, university and university of applied sciences domains worked well, one example of that being the common proposal under the SWEET programme. From a scientific viewpoint, most research results and outputs were of very high quality and easily met the highest international standards. The SCCER EIP's management was able to shift resources to new and upcoming topics that turned out to be highlights of the SCCER EIP, such as concrete recycling. Less-promising topics were also skipped. The research field of wastewater in particular faced the challenge of identifying relevant contributions to the Energy Strategy 2050 by the end of phase 2.

In terms of technology transfer, more patents might have been desirable. The technologies developed, especially in WPs 2 and 3, are very promising and can potentially contribute significantly to the Energy Strategy 2050 – some of them have a fairly high TRL, meaning they could be transferred shortly, while others have a longer-term perspective. Implementation of course depends greatly on the economic parameters, which have mostly not been analysed in a comprehensive way.

Whereas the SCCER EIP has developed the pinch analysis tool and trained users in it to a high standard, so that it needs to be handed over to a service company for a broad rollout, the multiple benefit analysis requires some final applied research to be ready for market introduction.

The experimental investigations into HTHPs and the requested eco-friendly refrigerants should be continued at the newly established test center, and a financially sound industry partner should be identified as soon as possible to put these into practice, as this technology has high potential in the future, e.g. as power to immediate industrial heat (P2H), for charging long-term heat storage up to 95°C or to increase the waste heat of hydrogen electrolysis (60°C) for use in district heating systems (supply temperature of 80°C to 95°C).

Currently, Swiss industry requires about 18% of the total final energy consumption. Although heat represents the lion's share of this (60%), electricity consumption and its share of total energy demand will steadily increase in the next decades. The electrification and efficiency of industrial consumers and decentralised combined heat and power (CHP) fuel cells should therefore be given strong consideration in future, alongside the generation and use of green hydrogen and demand-side management aspects, as the volatility of power generation will also increase. Future research programmes should also address industrial sectors that have not yet been addressed by the SCCER EIP, such as the textile industry or metals processing.

At the same time, an emerging international research field is addressing the biologicalisation of industrial processes. This means, for example, replacing technology based on chemical processes with biological microorganisms that can significantly reduce energy intensity, especially in the process industry. Research in this field also requires a long-term perspective.

Environmental compliance is not only an issue of energy consumption and CO_2 emissions. The nexus of the reduction of environmental loads caused by upstream manufacturing processes and downstream remanufacturing and recycling activities – culminating in a circular economy – and the required energy resources is not thoroughly understood today. Significant long-term research programmes are required to elaborate strategies and technologies to cope with this challenge.

Further Information

LITERATURE

Arpagaus C. (2018): Hochtemperatur-Wärmepumpen. Marktübersicht, Stand der Technik und Anwendungspotenziale. Berlin: VDE VERLAG.

Arpagaus C. (2019): Maestrani setzt auf Energieeffizienz. Foodaktuell.ch specialist portal for the food industry.

Baldini L.: Waste water heat recovery in buildings.

Meyer J.P. (2020): Billy Solar: Skalierbare Einheit für Prozesswärme. In: Solare Wärme – Das Solarthermie-Jahrbuch.

Wellig B. (2020): Intelligent energy solutions – Researchers at the Competence Center Thermal Energy Systems and Process Engineering of the Lucerne University of Applied Sciences and Arts provide innovative thermal energy efficiency solutions. Pan European Networks Ltd.

Wemhöner C., Büsser S., Rominger L. and Meier C. (2020): Kühlleistung von aktivierten Gebäudeoberflächen mit Verdunstung. In: Bichsel J., Sattler M., Rudel R., Steiger O., Tillenkamp F. (eds.): Konferenzband Erneuern! Sanierungstrategien für den Gebäudepark. 21. Status-Seminar, pp. 187–193.

Schiffmann J. (2018): Small-scale, high-speed turbomachinery. researchfeatures.com.

VIDEO

neustark | concrete solutions. today.

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SoE

Supply of Electricity

Action Area
Power supply (supply of electrical energy)

Leading House
Swiss Federal Institute of Technology Zurich (ETHZ)

Participating Institutions
Bern University of Applied Sciences (BFH)
Eastern Switzerland University of Applied Sciences (OST)
Lucerne University of Applied Sciences and Arts (HSLU)
Paul Scherrer Institute (PSI)
Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)
Swiss Federal Institute of Aquatic Science and Technology (Eawag)
Swiss Federal Institute of Technology Lausanne (EPFL)
Università della Svizzera Italiana (USI)
University of Applied Sciences and Arts Western Switzerland (HES-SO)
University of Bern (UniBe)
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SCCER SoE
SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

Synthesis

The SCCER-SoE was dedicated to research related to two technologies – deep geothermal energy (DGE) and hydro-power (HP) – to develop the technological and methodological foundations and to deliver solutions for their optimal contribution to the Energy Strategy 2050 in the years to come.

Challenges in the "Power supply" action area (supply of electrical energy)

One pillar of the Energy Strategy 2050 is to increase the use of renewable sources of energy to meet the given energy demand. In line with the action plan[15] from 2012, the SCCER-SoE was established and dedicated to electricity supply topics. Several areas were identified in which research and development activities are to be strengthened with a clear medium and long-term impact. In this context, the Federal Council decided to focus on the development of the use of DGE and the assessment of CO_2 storage options, as well as the use of hydropower and hydropower infrastructure within the "Supply of energy" action area[16].

The basic research questions posed at the beginning are outlined below.

- Can Switzerland safely extract deep geothermal heat and produce a substantial portion of the national electricity supply (5% to 10% of the national baseload supply) at competitive costs?

- Is the geological capture of CO_2 a viable measure to enable carbon-free generation of electricity from hydrocarbon resources?

- Can hydropower electricity production be increased (e.g. by 10%) under changing demand, climate and operating conditions?

- Can Switzerland maintain, improve and operate the hydropower infrastructure in the long-term future?

The overarching goal of the SCCER-SoE was thus to develop a much deeper understanding of the challenges and opportunities of DGE and hydropower within the Swiss electricity provision system.

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[15] Kaiser T., Hotz-Hart B. and Wokaun A. (2012): Aktionsplan Koordinierte Energieforschung Schweiz. Report commissioned by the Interdepartmental Working Group on Energy (EDI – EVD – UVEK).

[16] Federal Council (2012): Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

Vision and objectives of the SCCER SoE

One of the main objectives was to build a functioning and integrated national competence center comprising research and cooperation partners from the ETH Domain, cantonal universities, universities of applied sciences, key industry partners from the hydropower and geothermal sectors, federal offices and services (swisstopo, Swiss Seismological Service) and the Swiss National Supercomputing Centre (CSCS). This was accompanied by a plan for a significant expansion of the research partners' capacity.

In the field of DGE, the plans involved drilling a first well by 2015 and completing the first pilot and demonstration reservoir by 2016. Plans and site selection for underground rock laboratories and site identification for a first pilot and demonstration project for the geological storage of CO_2 were to be completed.

In the research field of hydropower, the intention was to establish a framework for hydropower R&D, focusing on climate change response and socio-economic drivers of hydropower production and to develop scenarios for demand, market design and Swiss production strategies. Finally, concepts and strategies for the adaptation of hydropower infrastructure to successfully satisfy future operating condition were also included in the work plan, specifically to investigate environmental impacts of future hydropower operating conditions and to assess integrated models that simulate impacts on water resources and full operation of hydropower systems under new operating conditions. The most important new requirements are towards making the operation of hydropower plants more flexible, in order to respond efficiently to the highly fluctuating electricity supply from other renewable sources of energy (e.g. wind power, solar radiation).

What was achieved

Geo-energy and carbon capture and storage (CCS)

One major achievement was the demonstration that permeability can be enhanced in otherwise tight rock by careful hydraulic stimulation, enabling the conclusion to be drawn that successful exploitation of the tight deep underground is basically possible. Two successful drilling campaigns in Geneva for the provision of hot water for heat provision were also realised. Such projects pave the way for the extraction and storage of heat, which is just as important as geothermal electricity generation in reaching the Swiss climate goals. In CO_2 capture and storage (CCS), the results show that CCS can be a part of the Energy Strategy 2050, to help reach the goal of net-zero greenhouse gas (GHG) emissions (climate neutrality).

Hydropower

The initial target of the Energy Strategy 2050 to increase electricity generation from hydropower by 2.8 TWh/a (net) can only be achieved under the most optimistic circumstances. In fact, it is even possible that overall hydropower generation could be reduced due to increasing environmental constraints. New projects, for instance in periglacial areas, therefore need to be realised. In the field of hydropower flexibility, an increase in the reservoir volume of storage hydropower plants results in a 2.4 TWh increase in hydropower supply in winter.

Future electricity generation
An important achievement here was a thorough assessment of the role and potential of PV. PV may contribute almost an order of magnitude more to the future electricity generation than electricity from geothermal energy and the potential growth of hydropower. A reassessment of this potential for rooftops yielded a value of 24 (±9) TWh/a.

Contribution to Energy Research and to the Energy Strategy 2050

The SCCER-SoE delivered successful research into the development of enhanced geothermal systems and developed and implemented innovative exploration technologies and processes that improve the analysis and interpretation of large earth science datasets. The outcome is a higher probability of success in finding a promising geothermal energy resource. The SCCER drove the development of aquifer thermal energy storage in urban regions and laid important groundwork for the development of Switzerland's underground CO_2 storage sites, by customising workflows for CO_2 storage site selection and by demonstrating the in-situ integrity of sealing cap rocks overlying the rock formation that constitutes a CO_2 storage site. In conjunction with the outcomes of JASM, the SCCER-SoE underscored the need for deployment of CCS technologies. It produced pathways to increase hydropower production and utilise the flexibility potential of hydropower generation to meet the 2050 Swiss energy targets, while achieving environmental sustainability in line with the revised water protection act, managing the influence of climate change and operating in European markets. Critically, hydropower has the technical potential to realise the annual generation as set out in the Energy Strategy 2050 and to significantly increase flexibility to facilitate the integration of new renewables. Researchers at the SCCER-SoE have also been instrumental in putting Switzerland on the European and IEA map of technology collaboration and development.

Recommendations

based on the SCCER-SoE's research findings

- In the short to medium term, the exploitation of geothermal energy should focus on the extraction or seasonal storage of heat, as this is the option most closely suited to the market. Stimulation techniques in tight rock for subsequent use as a high-temperature heat reservoir need further development, e.g. related to predictability and minimisation of unwanted seismic effects.
- The renewal, upgrade, extension and optimisation of hydropower facilities, including new schemes in periglacial areas, is fundamental to implementing the Energy Strategy 2050 while reducing environmental and climate change impacts. Thanks to its flexibility and storage options at multiple scales from minutes to seasons, hydropower is the backbone of the Swiss electricity system. Maintaining this central role will foster the integration of fluctuation electricity generation from solar radiation and wind power.

Results

WP 1 – Geo-Energies

Leader WP 1
Prof. Lyesse Laloui, EPFL

WP 1 on geo-energy focused on various underground laboratory research to enhance the usability of rock formations for a subsequent high-temperature heat extraction and on research into various technical, social and political considerations relating to the use of DGE and CCS.

Objectives

- The objectives of this WP – to investigate the potential and viability of DGE to produce a substantial portion of the national electricity baseload – shifted throughout the lifetime of the SCCER-SoE towards the implementation of seasonal heat storage and direct heat production in/from underground in order to reduce CO_2 emissions from burning hydrocarbons, e.g. for heating purposes.

- A further objective was to analyse the viability of geological sequestration of CO_2 as a measure to enable generation of electricity from fossil hydrocarbon resources free from GHG emissions.

- This WP was divided into four tasks: (I) resource exploration and characterisation, (II) reservoir stimulation and engineering, (III) hydrothermal resources and geofluids: exploitation and storage, and (IV) geo-data infrastructure and analysis.

What was achieved

The SCCER-SoE developed modern techniques and piloted innovative workflows that maximise the value of information of geological, geophysical and geochemical data. In this way, this SCCER made a significant contribution to identifying potential geothermal provinces that warrant further exploration.

Accessing the heat requires the creation of a 3D fracture network in a km3-sized rock body by way of stimulation (mostly hydraulic with contributions from chemical and thermal). Using technologies available prior to the SCCER-SoE, the unit technical cost for electricity produced from enhanced geothermal system resources was CHF 0.50 to CHF 0.60/kWh at a weighted average cost of capital of 5.5%. When surplus heat (beyond that used for power generation) generates a second revenue stream, commercial rates of returns for CHP projects are more easily achieved. Major savings could be reached through reductions in drilling costs and more efficient stimulation strategies. Doubling of the heat exchange area per unit volume of injected stimulation fluid lowers the subsurface unit technical cost by approximately 40%.

HIGHLIGHT

ENGINEERED GEOTHERMAL SYSTEMS

The SCCER-SoE's major focus on and fully justifiable highlight was fundamental research related to the development of enhanced/engineered geothermal systems (EGSs). The characterisation of permeability in tight rock, required for percolating heat exchange media (water or CO_2) to extract heat from the hot rock, was successfully demonstrated in the two underground laboratories. The basic processes and piloted stimulation protocols were successfully studied, with the findings suggesting that cost reductions for the development of EGS reservoirs can be achieved by stimulation in commercial projects.

Also supported by the SFOE and Shell Global Solutions International B.V.

The SCCER-SoE successfully investigated the fundamental processes and piloted stimulation protocols that suggest that the unit cost reduction for developing enhanced geothermal systems (EGS) reservoirs by stimulation can be achieved in commercial projects. This will be trialled in two locations, at the US's Frontier Observatory for Research in Geothermal Energy (FORGE) site in Utah and Switzerland's Haute-Sorne site; a contentious attempt to revoke the valid Haute-Sorne permit is currently the subject of a legal challenge by the site operator.

The creation and subsequent characterisation of permeability in tight rock, required for percolating heat exchange media (water or CO_2) that extract heat from hot rock, was successfully demonstrated in two underground laboratories, the Grimsel and – at a much larger scale – the Bedretto underground laboratories. The creation encompassed seminal research into how wells should be successfully completed (i.e. how casing, tubulars and valves need to be deployed in wells), into how stimulation fluids need to be injected to create a system of interconnected cracks and fractures with a diffuse and 3D topology, and into novel geophysical and geochemical methods that allow characterisation and control of a stimulation programme.

HIGHLIGHT

HYDROTHERMAL RESOURCES AND THERMAL ENERGY STORAGE

Another highlight was the combining of the exploration for hydrothermal resources for direct use, particularly in urban environments, with aquifer thermal energy storage. The SCCER-SoE used innovative and site-specific data acquisition campaigns to develop workflows that increase the probability of success not only in finding hydrothermal resources for direct use, but also in exploiting the subsurface for heat storage with a view to accommodating seasonal shifts in energy supply (e.g. high excess heat supply from waste-to-energy plants during summer) and periods of demand for such energy (e.g. high demand for heat in district heating networks during winter months). This is a significant step towards systematic exploration for hydrothermal resources for direct use, particularly in urban environments.

Also supported by Services Industriels de Genève

The SCCER-SoE also implemented newly developed techniques that allow robust short-term forecasting of induced earthquakes and their location and magnitude. These techniques enable forecasting to be incorporated into industrial geothermal operations.

The SCCER-SoE put a major focus – particularly during its second phase from 2017 to 2020 – on combining the exploration for hydrothermal resources for direct use, particularly in urban environments, with aquifer thermal energy storage. Major cities in Switzerland (Bern, Geneva and Basel) face major obstacles to achieving CO_2-free heating/cooling for their population and industry. To overcome these challenges, the valuable findings of the SCCER can provide some initial ideas for solutions.

In connection with subsurface CO_2 storage, the SCCER-SoE emphasised its work on refining the storage potential estimate on the most promising part of the Upper Muschelkalk (a pervasive rock formation occurring at a range of depths throughout Switzerland between Lake Constance and Lake Geneva) and the 20 to 30 m-thick layer known as the Trigonodus Dolomit hydraulically sealed above by the Gipskeuper. Building on the theme of mid-scale in-situ tests in major research infrastructures, the SCCER-SoE investigated the question of cap/seal rock integrity, specifically the Opalinus Clay, a pervasive, tight clay rock that overlies a saline aquifer which is a potential host rock for CO_2 storage. A key question is the impact of (invariably) pre-existing fractures and faults as potential pathways for CO_2 out of the storage rock. Here, this SCCER successfully demonstrated that cap rocks, even when faulted and sheared, do not provide leakage pathways for CO_2.

HIGHLIGHT

CCS

Concerning CO_2 sequestration, the potential storage rock formation, the Upper Muschelkalk, alone has been estimated to have storage potential in excess of 50 million t of CO_2. This value is likely to be a lower bound when compared with the upper bound on the cumulative storage capacity of CO_2 of 700 million t (as determined in an earlier, but much less refined study than that of the SCCER-SoE). The CO_2 storage potential of three further major storage formations with associated cap rocks remains only roughly estimated.

Also supported by the SNSF and the SFOE

Contribution to the SCCER's objectives

A significant portion of the SCCER-SoE's research was dedicated to the question of how to create permeability in otherwise tight rocks by hydraulic stimulation, avoiding – if possible – induced seismicity that can be felt at the surface. Experiments in deep underground labs, first in Grimsel and later in Bedretto, made significant progress towards this goal. However, it is also clear that a full industrial deployment of such EGSs will need more effort to become reality.

None of the big pilot and demonstration projects could have been undertaken by a single institute alone. Joining forces between the ETH Domain, cantonal universities and universities of applied sciences allowed significant strides to be made. The overarching goal of joining forces to develop solutions was thus superbly achieved.

Comparing the achievements and targets for geothermal electricity generation, it must be stated that not all ambitions could be realised. The SCCER-SoE managed to significantly advance the scientific and practical understanding of hydraulic stimulation processes and to demonstrate them at 10 to 100-metre scale. However, it was not possible to put this into industrial practice within the Haute-Sorne demonstration plant. One reason is certainly the administrative hurdles that brought the project to a halt. Another reason is the complexity of the technology. In hindsight, the extension of research on hydraulic stimulation from Grimsel to the scale at Bedretto was and is still needed before industrial projects can be realised with reasonable chances of success. The targets on heat extraction and storage in sedimentary basins were achieved. After the initial work in the Geneva area, a similar project on heat storage was started in Bern, based on the successful results gathered within the SCCER-SoE.

Assessment of the achievements

For DGE, the SCCER-SoE's capacity build-up resulted in a much-improved understanding of the interdisciplinary interplay required to successfully find and develop subsurface reservoirs in a controlled and safe manner. Whereas public funding for geothermal energy research was about CHF 5m in 2013, the numbers for 2019 were in excess of CHF 20m, even without the ramp-up of private, industry funding for DGE. The SCCER-SoE has been the prime driver behind this growth, with high-quality research being funded in a highly competitive funding landscape.

Current levels of investment in research and development are in line with the expected contribution of geothermal energy to the Energy Strategy 2050. Switzerland's research and innovation community has used the SCCER-SoE to position itself very strongly in competitive Horizon Europe 2020 and ERA-NET GEOTHERMICA calls for projects – so much so that Switzerland is now perceived to a major player in Europe's DGE research and innovation community alongside countries such as Germany, the Netherlands and France.

WP 2 – Hydropower

Leader WP 2
Prof. Robert Boes, ETHZ

In Switzerland, hydropower provides about 55% of the electricity supply. Maintaining the present infrastructure, adapting it to changing operating and climate conditions and achieving a 10% increase in production will require innovative solutions and clear political signals to address these challenges successfully.

Objectives

- The aim of this part of the SCCER-SoE was to investigate whether and how a significant increase in electricity production from hydropower (by 4.2 TWh/a) and the provision of flexibility services can support the goals of the Energy Strategy 2050.
- This included aspects relating to the renovation of the existing hydropower infrastructure and changing climatic conditions. The revised water protection legislation also needed to be taking into account. Different ways of realising the various forms of improvement potential were therefore analysed.
- In addition to the construction of new large hydropower plants (both river and reservoir), the possibility of building new periglacial dams was examined. New small hydropower plants and the expansion and retrofitting of existing systems are also essential parts of the necessary expansion to be addressed by the SCCER-SoE. This also includes increasing the efficiency of existing systems and expanding existing reservoirs by raising dam heights.

What was achieved

The work within WP 2 "Hydropower" was grouped into four different tasks. The guiding question within these tasks was to assess how hydropower can deliver additional generation, an additional share of winter generation and greater flexibility.

The potential contribution of new large hydropower plants was studied for both run-of-river and storage power plants. The additional potential from small hydropower plants was also estimated. For existing plants, increased production resulting from modernisation and possible upgrades and extensions was assessed. Finally, the heightening of existing dams, thereby increasing the reservoir volume, was analysed. For areas which are currently covered by glaciers, possible sites for additional new dams and reservoirs were investigated. The need for greater flexibility to integrate "new renewables" into the power system was also considered.

HIGHLIGHT

REALISTIC SCENARIOS FOR HYDROPOWER PRODUCTION IN 2050

The additional potential expected from hydropower was clearly identified. The outcome of the many different hydropower-related projects is a much greater understanding of the complexity of the challenges in maintaining hydropower production and particularly in delivering the desired additional energy generation in line with the Energy Strategy 2050. In particular, the impact of climate change and the demand for more flexibility on different timescales have added substantial uncertainty and revealed deficiencies in understanding; here, the SCCER-SoE made significant and impressive progress with a much-improved understanding of further research and innovation needs.

Also supported by the SNSF, the SFOE, Power Vision Engineering, FMV SA and Groupe E SA

The analysis showed that an increase in energy generation from hydropower by 2050, as expected by the Energy Strategy 2050, is only possible for highly optimistic scenarios and amounts to about 3.1 TWh/a. This means that the majority of the opportunities for additional hydropower generation do indeed need to be implemented and that generation losses due to environmental reasons and water release in support of fish migration need to be limited if this challenging increase in power generation is to be achieved. Less optimistic scenarios – which take into account that some hydropower projects, particularly new ones, will not be constructed for various reasons – result in a stagnation in annual power generation. Should high environmental standards regarding environmental flows and water release to protect fish migration and fluvial floodplains be fully implemented, hydropower generation will decline by up to 3 TWh/a. Similarly, winter generation may be increased by up to 2.8 TWh/winter under highly optimistic scenarios, whereas less optimistic scenarios may lead to an increase of only 1 TWh/winter. The effective storage capacity of hydropower reservoirs may increase by 0.3 to 2.4 TWh/a by 2050 in addition to today's effective storage capacity of 6.5 TWh/a.

HIGHLIGHT

IMPROVE FLEXIBILITY FOR LARGE HYDROPOWER PLANTS

Important achievements were also realised in the field of hydropower flexibility. Significant progress was made jointly with industry partners in understanding the mechanisms and the effects. On a seasonal scale, an increase in the reservoir volume of storage hydropower plants of up to 2.4 TWh was shown to be possible. This extra volume translates directly into a shift in generation into the winter months when demand is highest, due also to the expected growth in heat pumps for domestic heat supply. On the shorter scale, from seconds to hours and days, two pilot and demonstration projects on a small run-of-river and a large storage plant demonstrated an array of technologies that can help plant owners to operate their plants in a safe and economic way.

Also supported by KWO Kraftwerke Oberhasli

Climate change has many different impacts on hydropower generation. Given the hydrological regime and based on today's installed machinery and environmental flows, annual energy generation is estimated to decrease slightly, by 0% to 3%. Today's annual energy generation is presently increased by 3% to 4% because of the ongoing glacier melting. Climate change will also cause a shift from summer to winter generation because of general warming and more rain instead of snow. The frequency of risks of extreme natural events will increase due to climate change. This highlights the importance for studies on impulse waves in reservoirs. While this is highly relevant because of the disastrous consequences, many other aspects have been studied as well, such as the risk of blockage of spillways by floating woody debris in the wake of larger-scale flood events.

A whole set of research projects focused on aspects concerning future operation with increased flexibility and issues arising from licence renewal processes. Higher flexibility in operations will expose pumps, turbines and all other components of the hydropower plant to operating conditions sometimes far away from the design point. Transient conditions become increasingly relevant with components being exposed to loads and conditions not considered in the original design. To better understand the effect of such operations on components such as turbines and penstocks, several research projects were conducted, and tools, technologies and simulation models were developed and implemented.

About 70% of the hydropower plants in Switzerland, representing 27 TWh/a of energy generation, will undergo a relicensing process by 2080. This process includes evaluating of numerous different options as to how the hydropower scheme could be modernised, rebuilt, upgraded and operated in the future. Several research projects helped develop methodologies to significantly reduce the effort that is needed for decision-making.

Contribution to the SCCER's objectives

The achievements of the WP related to hydropower give a much-needed clearer picture on the role that hydropower can play within the Energy Strategy 2050. The targets mentioned in the Energy Strategy 2050 (e.g. annual hydropower generation) were critically assessed. Lumping targets into an annual generation value has questionable meaningfulness. Instead, the temporal distribution over the year is the decisive factor. Here, this SCCER emphasises in particular generation in winter: the share of storage and future storage options are of greatest significance, as these enable flexible electricity generation that can follow demand.

The effects of different drivers on future hydropower potential were quantified, particularly with regard to climate change, environmental flows and mitigation measures for fish protection and guidance. In a number of demonstrators, various hydropower issues were investigated in depth in close collaboration with operators and practitioners. The novel findings of the specific tasks contribute to innovations in the hydropower domain by delivering outstanding solutions, new methods, intelligent tools and smart devices.

The capacity build-up during the eight years of the SCCER-SoE was quite impressive. Knowledge and expertise in certain hydropower-related topics were boosted thanks to multi-year projects taking interdisciplinary and transdisciplinary approaches. The SCCER-SoE funds enabled researchers to be hired at the postdoctoral level over a couple of years. There was increasingly intensified collaboration and regular exchange between the academic institutions involved and operators of hydropower plants, engineering and ecological/environmental consultants, as well as with cantonal and federal authorities. This allowed collaboration to be fostered across language regions and institutions of different backgrounds across Switzerland.

Assessment of the achievements

The SCCER-SoE's objectives with regard to hydropower were fully accomplished. Beyond its own sector, hydropower is now also embedded in the analysis of future electricity generation. This activity gave a broadening perspective and also addressed overarching effects and long-term scenario modelling: pathways addressed aspects common to all different electricity generation options and identified options for robust solutions with broad public acceptance. This analysis also enabled the consideration of electricity generation from solar radiation and wind power in the different scenarios.

Several very large EU and ERA-NET-funded projects were a highly welcome outcome of the SCCER-SoE's joint research efforts and are testament to the SCCER-SoE's ability to mobilise interdisciplinary and even transdisciplinary research groups. These projects made use of and built on the high level of collaboration between different institutions and disciplines that was developed throughout the duration of the SCCER-SoE.

WP 3 – Future Electricity Generation

Leader WP 3
Dr. Peter Burgherr, PSI

A major area of activity of the SCCER-SoE was a comparative assessment of current and future, technology-specific electricity generation potential in Switzerland, along with the associated power generation costs and lifecycle GHG emissions and the related societal and environmental burdens.

Objectives

The main topical focus of the SCCER-SoE was on research relating to DGE and electricity generation from hydropower. However, a supporting and to some extent complementary activity provided a comprehensive, systemic approach to analysing the transformation of the Swiss energy system, and to supporting implementation of the Energy Strategy 2050. The research activities sought to create an integrated framework for:

I. the assessment of risk, safety and societal acceptance (later integrated into JA Integrated development processes for hydropower and deep geothermal projects: regulatory, political and participatory perspectives (IDEA-HDG), as it relates to hydropower and DGE) and

II. a comparative overview of current and future technology-specific electricity generation potential in Switzerland and the associated power generation costs, lifecycle GHG emissions and other environmental burdens, setting up a global observatory of electricity resources and the SCCER-SoE modelling facility (both later integrated into JASM).

What was achieved

The SCCER-SoE correctly identified the re-evaluation of rooftop PV potential as a major highlight with major untapped potential. This result has been important in the development of Switzerland's Energy Perspectives 2050, setting scenarios to be used by policymakers.

HIGHLIGHT

MODELLING OF ENERGY POTENTIAL AND ECONOMY

A Swiss-wide modelling platform using complementary and distinct models to answer questions regarding a future net-zero GHG emissions energy system was established, latterly in conjunction with JASM. This platform has the ability to harness the joint power of different modelling approaches including both system-wide and sectoral perspectives. The development of electricity wholesale price modelling, investigation of the major influences on Swiss wholesale electricity prices and a hydropower dispatch optimisation model all merit a mention. The latter facilitates the modelling of seasonal energy storage devices with a quasi-stochastic statistical model of electricity prices.

Also supported by the SFOE

A more practical highlight – and a very useful and advanced technological innovation – was the developing and maturation of a risk management system suited to lowering the risk of felt and damaging manmade earthquakes during the construction and production phases of subsurface reservoirs.

Building on the well-established knowledge that hydropower has very low GHG emissions intensity and a highly favourable carbon footprint, but also a very high initial investment, the value of hydropower to the energy system is difficult to account for and therefore the levelised cost of electricity is not necessarily an appropriate measure. Other indicators therefore need to be developed.

In a highly relevant field for the hydropower industry, the global observatory and JASM (see page 248) demonstrated how much solar energy could be generated in Switzerland and how the generation from solar energy and wind power needs to be combined with hydropower, particularly storage and pumped storage. The results regarding high-mountain PV capacity and how this could be combined with hydropower and other sources of electricity are of particular interest. It was demonstrated that more storage capacity is needed to integrate new renewables into the electricity provision system, but that electricity prices and markets are not suited to supporting the necessary development and investment decisions. The work was also strongly connected with other SCCERs. Furthermore, these activities need to be an ongoing effort taking new technological developments, European and global decisions, etc. into account and updating the models as new information becomes available.

HIGHLIGHT

MANAGING RISKS OF INDUCED SEISMICITY

A risk management system suitable to lowering the risk of felt and damaging manmade earthquakes during the construction and production phases of subsurface reservoirs – the adaptive traffic light system (ATLS) – was developed and brought to maturity. Here, the SCCER-SoE pioneered the robust implementation of such a challenging earthquake forecasting scheme (much like weather forecasting), which yields higher forecasting capabilities on a scale of a few hours, decreasing with time into the future. The development, implementation and proof of the usefulness in various operation applications (e.g. in DGE) are among the most important elements in any permit process and in obtaining a social licence to operate from affected stakeholders.

Also supported by the SFOE

The broad array of technologies, thematic areas and methodological frameworks developed and applied within the "future electricity generation" domain are central to a sustainable and resilient future Swiss energy system that meets the goals of the Energy Strategy 2050 and the climate targets that Switzerland has committed to.

Contribution to the SCCER's objectives

The broad array of technologies, thematic areas and methodological frameworks developed and applied within the "future electricity generation" domain are central to a sustainable and resilient future Swiss energy system that meets the goals of the Energy Strategy 2050 and the climate targets that Switzerland has committed to.

In particular, this research supports the implementation of the Innovation roadmaps, the development of integrative solutions, and the testing and installation of innovative technologies, taking a nexus approach combining technology assessment, scenario modelling and societal acceptance based on adequate and innovative modelling approaches and methods.

In this WP, the SCCER-SoE instilled an unprecedented willingness to collaborate among different academic institutions and laboratories, hydropower utilities, DGE companies, private consultants, manufacturers and suppliers, policymakers, local authorities, etc. Prior to the SCCER-SoE, there was no coherent hydropower and DGE research and development community in Switzerland, but rather individual groups that worked largely independently of each other. The SCCER-SoE brought them together and all stakeholders were motivated and invited to contribute. This level of coherence and collaboration across disciplines, academic institutions, etc. exceeded expectations and demonstrated that the SCCER-SoE as a whole was much greater than the sum of its parts.

Assessment of the achievements

The research activities carried out under the "future electricity generation" umbrella were strongly connected to the valuable work of other SCCERs. These successful research activities also led to the establishment of collaborations with a broad range of partners and stakeholders, including:

- The private and public sector in Switzerland (e.g. Geothermie Schweiz, Services Industriels de Genève, ewb, Geo-Energie Suisse SA, the SFOE, the Canton of Geneva, etc.),

- International cooperations (e.g. IEA Technology Collaboration Programme (TCP) on Hydropower, the Chilean Ministry of Energy (Patagonia), the Future Resilient Systems (FRS) programme of the Singapore ETH Centre, Dialogue on European Decarbonisation Strategies (DEEDS), World Energy Scenarios for the World Energy Council (WEC), the Geldinganes project (together with DESTRESS), Utah FORGE),

- Use of large-scale research infrastructure (e.g. Grimsel, Bedretto) and modelling and experimental platforms (Renewable Management and Real-Time Control Platform (ReMaP), Energy Systems Integration Platform).

These collaborations established within the SCCER-SoE are continuing in numerous projects that are already ongoing or will start later in 2021. The network established between the eight SCCERs and JAs also provides an essential basis for the SFOE's new energy research instrument (SWEET).

Finances and capacity of the SCCER

The SCCER-SoE's activities, in particular the development of research capacity, had total financing of CHF 125.2m between 2014[17] and 2020. Innosuisse support was CHF 30.2m, while the participating HEIs contributed CHF 44.3m and the remaining CHF 50.7m came from competitive federal funds (CHF 30.1m) and contributions by industry partners and international projects (CHF 20.6m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period. Funding from own sources and competitive federal funds clearly exceeded that requirement.

Research Capacity + Operating Expenses + Other direct costs

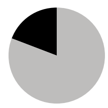
Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**30'150'029**	**44'336'153**	**30'092'794**	**20'598'955**	**125'177'931**
Share in percentage	24%	35%	24%	17%	**100%**
Ratio (Innosuisse = 100%)	100%	147%	100%	68%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	6.1	27	23%
Assistant Professor / Lecturer	4.2	8	52%
Senior Researcher	22.3	47	47%
Post Doc	29.2	35	83%
Technician	3.2	4	80%
PhD student / Research Assistant	41.1	55	75%
Other	1.2	2	60%
Total	**107.3**	**178**	**60%**

Gender ratio

19% female | **81%** male



As at the end of 2020, 178 researchers were active in the SCCER-SoE. This corresponds to 107.3 FTEs. 38% of the active researchers within this SCCER were PhD students or research assistants. 19% of researchers were female.

[17] Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

Conclusion and outlook

Geo-energy

Switzerland has risen to become one of the most important countries in geothermal research, especially in the domain of hydraulic stimulation testing, which has been rather neglected in recent years. Mastering these methods and developing new schemes will have a large impact on future stimulation. The SCCER-SoE programme had a major impact on the scientific reputation of Switzerland. It not only created Switzerland-wide collaboration in geothermal research, but also helped to develop a new worldwide reputation in this challenging and innovative area. This international reputation is now visible at several levels: from participating in and leading EU research programmes to collaborating with international industry. Care must be taken to maintain this competence in the years to come.

The possibilities for academic institutions are not restricted to self-managed projects like the Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG), but could entail an incremental approach fostering industrial cooperation. Within the SCCER-SoE, the industrial collaboration was mostly focused on one joint venture of seven Swiss companies constituting Geo-Energie Suisse SA. A scientific partnership with industrial projects in foreign countries would be one option to maintain the current level of knowledge. The utilisation of geo-energy resources at shallower depths would represent a focus on the direct use of geothermal energy.

Such an approach also offers broader possibilities. Even if the expected scientific output from such projects cannot be compared with the broad findings in a new research field (e.g. geothermal testing in underground rock laboratories), there is a need for academic research. Besides the fact that such geothermal concepts (direct use) require a sophisticated testing and exploration programme with high social competence, they could also be aligned with activities in the framework of heat storage (deep aquifer thermal energy storage, ATES). This topic is definitely not yet fully explored. Such projects could also open up pathways for increased industrial contribution.

Hydropower

Hydropower will remain a central pillar in the Swiss electricity generation portfolio in the future. This technology, which has a similarly small carbon footprint to electricity from solar radiation and wind power, is the only one that can provide flexibility and storage at variable timescales from seconds to months while being fully renewable. Successful implementation of the Energy Strategy 2050 by exploiting the challenging expectations of hydropower will not be easy to realise, as the available potential is limited and there are considerable obstacles that will not easily be overcome.

Therefore, and in accordance with the 20-year roadmap for hydropower research presented at the outset of phase 2 of the SCCER-SoE, a list of research topics is presented, building on what had been started. The SCCER-SoE has helped answer many of these questions and allowed for a much better understanding of many aspects, for which highly ambitious targets were set at the beginning of the SCCER-SoE. As expected, not all questions have been fully answered. With climate change advancing and with technological progress, global strategies and government decisions influencing the existing markets considerably, many questions remain open and new ones have come to light and will continue to gain importance in the years to come. They all require further study amid this highly dynamic context.

The range of hydropower topics is extremely wide. For example, there is a need for fundamental research, such as developing new numerical methods to better simulate transient 3D turbulent flows in hydraulic machines during unsteady operating conditions. Pilot projects on specific hydropower plants are also necessary to test new methods to add flexibility to operations. There is also a need for research into the environmental dimension of hydropower use gaining more and more in importance within Swiss society. Yet time is of the essence: climate change is happening, and glaciers are retreating. There is also much stronger commitment to national and international collaboration before the SCCER, and it is hoped that this momentum can be maintained in the future.

This outlook is in essence an urgent call for the continued provision of funding for research. It also calls for a clear commitment to support education and training for engineers and other experts in hydropower at the highest level. This should be seen as an urgent call to both ETHs, to other cantonal universities and to universities of applied sciences to remain committed to hydropower beyond the end of the SCCER-SoE.

Further Information

LITERATURE

Bäuerle Y., Biollaz S., Calbry-Muzyka A., Cox B., Heck T., Lehnert M., Meier A., Prasser H.-M., Schenler W., Treyer K., Vogel F., Wieckert H.C., Zhang X., Zimmermann M., Burg V., Bowman G., Erni M., Saar M. and Tran M.Q. (2017): "Potentials, costs and environmental assessment of electricity generation technologies." Bauer C. and Hirschberg S. (eds.), Paul Scherrer Institute, Villigen.

Boes R. (2019): Glacier retreat offers opportunities for additional storage hydropower. Energiaplus.com, Swiss Federal Office of Energy.

Denzler L. (2020): "Der Trumpf der Wasserkraft liegt in der Speicherung". Espazium.ch

Fumagalli A. (2016): Hydraulische Stimulationsexperimente mitten im Berg. Aargauer Zeitung

Möll R. (2020): "Dieses Thema müssen wir weiterverfolgen" – Periglaziales Potential. Bulletin.ch

Moscariello A. (2019): Exploring for geo-energy resources in the Geneva Basin (Western Switzerland): opportunities and challenges. Swiss Bulletin für angewandte Geologie, 24(2), 105–124.

Morel P. (2020): Séquestration du CO_2: remettre le carbone à sa place. Espazium.ch.

RFJ (2019): On expérimente au Mont Terri.

SCCER-SoE (2019): Climate change impact on Swiss hydropower production: synthesis report. Swiss Competence Center for Energy Research – Supply of Electricity. Zurich, Switzerland.

The rock crackers. In: ETH Globe (available in English and German).

Synthesis reports

SCCER-SoE (2020): Sources of Primary Electricity Supply, Synthesis Report, ETHZ (in preparation).

SCCER-SoE (2020): Geothermal Energy, Synthesis Report, ETHZ (in preparation).

SCCER-SoE (2020): Swiss Potential for Hydropower Generation and Storage, Synthesis Report, ETHZ (in preparation).

SCCER-SoE (2020): CO_2 Capture and Storage (CCS) – An Essential Element of the Swiss Climate Strategy, Results from the ELEGANCY Project, ETHZ (in preparation).

VIDEO

Erdwärme ohne Beben. Video by 3sat.

SRF Schweizer Radio und Fernsehen (2018): Geothermie: Wie weiter?

RTS Radio Télévision Suisse (2016): Des solutions pour la géothermie profonde.

SRF Schweizer Radio und Fernsehen (2019): Gletscherschmelze: Verlust oder Chance?

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BIOSWEET

Biomass for Swiss Energy Future

Action Area
Biomass

Leading House

Paul Scherrer Institute (PSI)

Participating Institutions

Bern University of Applied Sciences (BFH)
Lucerne University of Applied Sciences and Arts (HSLU)
Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)
Swiss Federal Institute of Technology Lausanne (EPFL)
University of Applied Sciences and Arts Northwestern Switzerland (FHNW)
University of Applied Sciences and Arts Western Switzerland (HES-SO)
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biosweet
Swiss Competence Center for Energy Research

Synthesis

Roughly half of the renewable energy used worldwide comes from biomass. This makes biomass an important option for the provision of green energy. Nevertheless, research activities like the SCCER BIOSWEET are urgently needed to contribute to more efficient biomass utilisation and deliver improved solutions to cover the markets for heat, electricity and fuel.

Challenges in the "Biomass" action area

Although biomass is an important source of renewable energy used widely on a global and European scale, many technological, environmental, economic and organisational/societal challenges are still as yet unresolved. As a very inhomogeneous source of energy, biomass needs pre-treatment and/or well-adapted technological solutions to meet advanced environmental standards, achieve operating convenience and to become compatible with local conditions.

"New" markets for biomass are also emerging, such as the transport sector, with fuels fulfilling specific requirements, as are "new" demands, such as compliance with decreasing limits for particulate matter emissions in heat provision units from solid biofuels. The need to use biogenic resources that have so far not been tapped (e.g. domestic organic waste) is also gaining in importance because the overall available biomass is limited. This means that organic material streams with less-promising fuel characteristics also need to be utilised. The fact that biomass is also in demand from the food market and as a raw material for industry adds to the tensions in this area.

As such, the main challenges in the "biomass for energy" area relate to the technologically efficient, environmentally sound and economically viable conversion of selected types of biomass available within Switzerland into useful energy and/or energy carriers easily usable within the existing "conventional" energy system. This also includes an assessment of the resource side and analysis of the constraints within the energy system today and in the future, taking the Energy Strategy 2050 into account.

Vision and objectives of the SCCER BIOSWEET

The overarching goal of the SCCER BIOSWEET was to contribute to increasing the share of sustainable bioenergy with new and/or improved technologies. Initially, a challenging target of an additional 100 PJ/a was set, on the assumption that an increase in the use of biomass would be possible despite the background of limited resource availability. This basic assumption was made on the economic, environmental and organisational/ societal constraints in Switzerland at the time when this SCCER was designed. Optimistically, the hypothesis was that the legal framework would increasingly support renewable sources of energy, and biomass in particular. However, this did not materialise to the assumed extent. This optimistic energy target was therefore replaced in phase 2 by a more realistic roadmap describing the potential technological development of selected bioenergy provision chains adding up to 100 PJ of bioenergy resources used in Switzerland by 2050 – roughly double the 2016 level.

From this starting point and with the experience gained in executing the work programme, the SCCER BIOSWEET has come a long way since it was launched in 2014. Whereas in the early stages the participating institutes continued their ongoing research, the SCCER teams grew together over time, resulting in increasing synergies and excellent collaborations. In parallel, the number of staff members involved in the various and quite diverse areas of the bioenergy research that was conducted grew significantly, and the topics tackled slowly moved to higher TRLs. The development of the SCCER BIOSWEET was thus fully in line with the overarching goal of the wider Energy Funding Programme.

The number of FTEs allocated to the biomass research executed under the framework of this SCCER also clearly exceeded plans, peaking in 2019. Because the collaboration between the various partners improved significantly over time, there is a good chance that these cooperations can be continued with the SFOE programme SWEET, Innosuisse's flagship initiative, funding from other Swiss federal offices such as FOEN, the Federal Office for Agriculture (FOAG), etc., and internationally within the EU Horizon Europe funding scheme.

What was achieved

The SCCER BIOSWEET contributed significantly to bringing biomass and bioenergy into public awareness and to generating a much better understanding of the possibilities and constraints of the various options for converting biomass to bioenergy. This SCCER demonstrated promising technological solutions through various pilot plants and demonstrators, paving the way for the use of untapped biogenic sources and/or unexploited conversion routes. Additionally, the very inhomogeneous and diverse members of the research community carrying out R&D activities in this field came to know each other much better: barriers were broken down and trust was built up; TRLs were much increased for selected bioenergy options based on fruitful cooperation; an improved appreciation of the interdisciplinary challenges was developed; and promising new ideas were born. As a result, the efficiency of the realised research activities was improved, thanks also to the increasing collaboration with industry.

Overall, the SCCER BIOSWEET showed very plainly that biomass is an important part of the energy transition. These developments will help to bring various bioenergy options closer to the market and will contribute to the overarching goal of defossilising the Swiss energy system. Besides sharpening the role of individual biomass conversion routes for the provision of heat, power and fuel, the potential role of bioenergy as an enabler for a largely renewable-based energy system was strengthened.

Contribution to Energy Research and to the Energy Strategy 2050

Biomass is a very inhomogeneous source of energy characterised by a relative low energy density. The challenge is therefore to process the different organic materials in appropriate and efficient ways to provide useful energy and/or an energy carrier that can easily be used within the existing energy system. Such conversion options need to take technological, environmental, economic and societal constraints and demands into consideration – and to do so throughout the overall provision chain, from the biomass production area (e.g. an agricultural field) all the way through to disposal of possible by-products (e.g. use of wood ash).

Biomass/bioenergy research is by definition very diverse – in terms of the feedstock, the conversion options and the energy market that is addressed. The SCCER BIOSWEET therefore addressed these challenges by assessing several types of organic (waste) materials, tackling different technological fields and applying various scientific disciplines. The result is strengthened interdisciplinary collaboration between very diverse research groups active in Switzerland, which will very probably continue beyond the end of the SCCER's funding period and will undoubtedly contribute to the Energy Strategy 2050, where biomass/bioenergy is very likely to have an important role to play. The versatile research results also showed that bioenergy is an important part of sector coupling.

Recommendations

based on the SCCER BIOSWEET's research findings

- Biogas production from anaerobic digestion processes is technologically mature, and innovative concepts were further developed, promising sound implementation under the local frame conditions in Switzerland. This technology option is therefore basically mature enough to be implemented, especially in using organic side and waste streams to contribute to GHG mitigation.

- The thermochemical methanation process was further developed, and substantial progress was made on understanding this challenging conversion pathway from solid biomass into a natural gas substitute. Nevertheless, this process is technologically demanding and so this expensive possibility seems to be an option for the remote future.

- The use of solid biofuels for heat provision can be increased by using less-promising types of solid biomass in an environmentally sound way (i.e. very low particulate matter emissions). The extended use of such low-cost solid organic material therefore can and should be more strongly supported in Switzerland.

- Although chemicals are largely outside the Energy Strategy 2050's remit, it is recommended that the successful work on biomass depolymerisation and on an improved combination of biological and chemical upgrading processes be continued. If these conversion processes move closer to the market – and due to the given cost/price ratio this is most likely to be for feeding markets for raw materials (i.e. chemicals) – they should help to defossilise the chemical industry. If this proves successful, the provision of transport fuels will be the next step. This promising conversion pathway should therefore be further developed.

- Biomass is an important option to help achieve the challenging goals defined within the Energy Strategy 2050. The assessment of the pros and cons of the various biomass-for-energy options in the context of tensions with other consumers of biomass (e.g. food) is therefore an ongoing process to be continued in the future. Depending on the market penetration of other renewable sources of energy in the years to come, there might be a need to adjust and/or redefine the role of biomass in Switzerland.

Results

WP 1 – Biomass to Biogas

Leader WP 1
Prof. Dr. Urs Baier, ZHAW

One option to bring biomass closer to the market is to convert this organic matter into an easily usable combustible gas. Such a conversion can be realised with biochemical and thermochemical processes. These possibilities might complement each other well because they use different types of organic feedstock in part.

Objectives

- The overarching goal of WP 1 was to develop technologies to convert biomass efficiently into biogas to be used – maybe after a cleaning process, depending on the intended subsequent use of the gas to be sold on the energy market – as an environmentally sound and climate-compatible substitute for natural gas.

- Achievement of this main goal included aspects such as the investigation of substrate pre-treatment technologies to increase the gas yield, high-efficiency customised anaerobic digestion processes, hydrothermal gasification units and advanced high-end analytics as a supporting measure for the other action items.

- Through these work items, this WP made a sound contribution to the overall goal of the SCCER BIOSWEET, as the provision of basically GHG-free, or at least low-GHG, gas of recent organic origin can help considerably towards the achievement of the goals defined within the Energy Strategy 2050.

What was achieved

Of the four general activities carried out within WP 1, hydrothermal gasification (HTG) became the flagship, with outstanding progress from a TRL of 4 to 7. This is also underlined by numerous publications. After years of basic research and the development of a pilot unit at PSI, the breakthrough came during the SCCER BIOSWEET project periods. The reactor in which gasification takes place was optimised through numerous temperature and pressure tests.

Ultimately, however, success was possible thanks to the development of a new salt separator and a significantly improvement in efficiency with a new ruthenium catalyst bound on carbon. Degradation by sulfur compounds was reduced with a ZnO scavenger. Sulfonation of the carbon catalyst was reversed by an external acid treatment. With this progress and success, industry interest increased considerably, notably from wastewater treatment plants and cement factories. This is because this technology promises much higher energy efficiencies than just anaerobic stabilisation with purely biogas production. The high interest of the waste and wastewater market in applying HTG was also shown by the successful securing of highly competitive Horizon Europe 2020 funding.

HIGHLIGHT

BIOGAS CONCEPTS

The agricultural sector in Switzerland is characterised by relatively small farms, preventing cost-efficient biogas production due to limited exploitation of economy-of-scale effects. Innovative concepts for combined anaerobic digestion from organic side streams emerging from different relatively small farms in one region of Switzerland were therefore developed and assessed. These activities may pave the way for increased use of animal manure for biogas provision, due to the exploitation of economy-of-scale effects at the biogas plant and also an improved nutrient management gaining more and more in importance for environmental reasons.
A gaseous fuel is provided which is easily usable with available conversion technologies in a highly efficient way within the existing energy system in Switzerland.

Additionally, the successful research activities carried out in the area of anaerobic digestion helped achieve a much better understanding of the limitations of the available technological solutions and innovative ways to overcome them. This research work was supported by the assessment of the effects of substrate pre-treatment on biogas yields under various frame conditions. However, the analysis of such supportive or pre-treatment technologies to increase biogas yields is not new. In fact, most of these technologies are or have already been applied on an industrial scale, such as micro-aerobic hydrolysis or steam explosion. Nevertheless, some of the "new" approaches (such as separation of high-value streams from sewage sludge) bear the potential to greatly improve the process economy and/or biogas production. In this light, significant progress can be seen in relation to the quantification of the relationship between the influence of heat and microbial hydrolysis on the anaerobic degradation process. The SCCER BIOSWEET also helped to build up additional expertise in this area, stimulating the biogas market in Switzerland and probably helping to develop it further in the years to come.

HIGHLIGHT

BIOGAS SUBSTRATE PRE-TREATMENT

The biogas yield gained during anaerobic digestion can be substantially increased by pre-treatment of the substrate, unlocking the easily digestible biomass components. A steam explosion pre-treatment process was therefore developed and upscaled from a TRL of 4 to 6. Again, a pilot plant was built and operated with clearly visible success. Although the steam explosion process per se is not new, the developments realised within this part of the SCCER BIOSWEET enable a well-recognised increase in biogas yields and thus better exploitation of the limited biomass resource to be achieved – potentially translating into lower biogas provision costs.

Also supported by the SFOE,
an agricultural research institute and the SNSF

Considerable progress was made in the field addressed by the supporting task on advanced high-end analytics, especially on on-site measurement. With the support of an instrument supplier, this task succeeded in developing volatile fatty acids sensors and implementing them into intelligent digester feeding control algorithms. This was clearly a huge step forward towards better controlling the anaerobic digestion process and thus achieving stable biogas yields at a high level, making the process more economically viable.

HIGHLIGHT

HYDROTHERMAL GASIFICATION

The process of HTG was developed from a TRL of 4 to 7, based on a pilot plant that was erected and operated successfully. Within this challenging biomass conversion process, organic matter contained within a watery environment is converted into a gas usable for fuel synthesis and/or as an energy carrier. As such, the basics have been developed to open the door for this promising technology to enter the market in the years to come.

Also supported by the SFOE, Treatech, KASAG,
ExerGo and Afry/Pöyry

Contribution to the SCCER's objectives

The contribution to the overarching goals of the SCCER BIOSWEET and thus to the Energy Strategy 2050 was twofold.

First, biogas was brought to the attention of selected decision-makers within industry and society as a promising energy carrier and an important raw material for the chemicals industry. By carrying out extensive research and development activities in this field, including the development of pre-treatment technologies and of innovative implementation concepts, an excellent basis for a potential market rollout in the years to come has been created.

Second, the collaboration between various research groups that had previously operated more or less independently of each other and with selected companies engaged in the biogas business clearly increased throughout the SCCER BIOSWEET's funding period. Trust has been developed in recent years, allowing the conclusion to be drawn that research in the biogas field might become more efficient and that new, ground-breaking and innovative ideas and smart solutions will arise in future, helping to fulfil the demands defined in the Energy Strategy 2050.

Together with the substantial technological advances and the valuable work on the conceptual level, the successful activities performed within this SCCER form an excellent basis for the subsequent rollout of a biogas technology that is especially suited to the circumstances in Switzerland. Based on the valuable results, the industrial players know very well what is possible and what is impossible – for the technological and process-related aspects, economic constraints, environmental limitations and the available potential at local or regional level.

Assessment of the achievements

The work performed within this WP 1 tackled aspects and topics within the biogas area that are still open and unsolved on a global and/or national level. The research performed was thus outstanding and important within this field, to pave the way towards economic application of this promising technological option. New insights were found, innovative solutions were developed and exciting results were arrived at, including taking local/regional constraints into consideration.

Against this background, the work performed is on a good track with acceptable deviations and will continue – at least to a certain extent – even beyond the SCCER BIOSWEET's funding period. The work performed and the results presented are also in line with the Innovation roadmap developed by the SCCER BIOSWEET consortium. The research results presented can easily compete with the corresponding activities at European and even global level. As such, the consortium performed very well throughout the overall funding period.

WP 2 – Biogas and Wood Gas to Biomethane

Leader WP 2
Dr. Serge Biollaz, PSI

Although biogas can be used in an efficient way with existing conversion technologies, upgrading to biomethane would allow its use as a drop-in fuel to natural gas, to be distributed via the existing natural gas energy system. By doing so, biomethane can help to defossilise the energy systems in Switzerland where natural gas is already used today.

Objectives

The goal of WP 2 supplemented WP 1 with respect to (i) cleaning and upgrading the biogas to biomethane and (ii) converting wood into a synthesis gas to be further converted to biomethane; i.e. both provision pathways provide the same combustible gas.

Biogas contains roughly 50% CO_2. With the addition of hydrogen from water electrolysis powered by green electricity, this CO_2 can be upgraded to methane. The research goal was therefore to maximise the provision of clean biomethane. As biological constraints mean there is scant possibility of converting wood into biogas by anaerobic bacteria, thermochemical conversion into a synthesis gas and subsequent methanation is the only option for such feedstock. Given similarities within the gas cleaning processes, these two different options were addressed within one WP.

The overall goal of WP 1 and WP 2 was therefore the provision of an energy carrier usable as a drop-in substitute for natural gas. While the various pathways investigated in these two WPs in part use very different types of feedstock, always of a low value, they provide a chemically identical energy carrier (biomethane) that can easily be used within the energy system and as a raw material in industry (e.g. the chemicals industry).

What was achieved

WP 2 focused on four main tasks: biogas cleaning, diagnostic toolbox, conversion of biogas to biomethane, and conversion of wood gas to biomethane.

With regard to biogas cleaning, a few promising results at lower TRLs (3 to 5) were achieved. For example, the direct catalytic methanation of synthetic gas was proven in a realistic test at the Werdhölzli sewage treatment plant lasting more than 1,000 hours. This outstanding success was also recognised with the Watt d'Or 2018, the prestigious energy award of the SFOE. The process was later improved by integration of a membrane upgrading system to separate the methane (> 94%) from the gas provided as a whole. The remaining CO_2 and the excess hydrogen were recycled in the catalytic methanation to increase the energy efficiency of the overall process.

HIGHLIGHT

FLUIDISED BED METHANATION REACTOR

A fluidised bed reactor was erected at PSI to investigate the hydrodynamic behaviour of the vertical internals by performing strongly exothermal chemical reactions (e.g. methanation reaction); i.e. the technological challenge is to remove the heat produced during the methanation reaction fast and in full. This impressive and challenging research unit enables a much better understanding of the optimal design of such a fluidised bed methanation reactor to be developed. For example, test trials were performed analysing the heat distribution within the fluidised bed and assessing the risk of a breakthrough. These tests were conducted at pressures of between 2 and 10 bar.

This concept flexibly combining direct methanation and membrane upgrading in a single unit enables switching between a summer and a winter operation mode (depending on the availability of renewable hydrogen), which might significantly improve the economy of the overall system. Power-to-gas (P2G) concepts must therefore become more flexible to enable optimal integration into the future energy system.

The development of a sorbent-based, high-rate gas cleaning pilot plant, "COSYMA", achieving extremely low sulfur values of biogas from sewage sludge and agricultural waste is equally promising. Such low sulfur values are crucial for catalytic power-to-gas conversion. The upgrading unit is currently being tested in Inwil with combined biogas of a dry waste plug-flow digester and a wet agricultural digester.

These promising results were also achieved thanks to the further development and knowledge gain within the various diagnostic tools detecting sulfur impurities. This "Diagnostic Toolbox" – another task developed by PSI – is internationally recognised and helped achieve a much better understanding of the complexity of the biomass substrate and the related sulfur compounds; the latter are challenging to handle within downstream conversion processes in light of the catalyst's lifetime. The sulfur compounds that occur vary greatly depending on the biomass substrate, and they also react quite differently with regard to the catalyst used and the reaction conditions of the gas cleaning unit. Customising the whole biogas cleaning and upgrading process to suit to the particular substrate within catalytic methanation will be one of the future challenges.

HIGHLIGHT

DIAGNOSTIC TOOLBOX

A measurement container enabling the gas composition, and especially selected gas impurities, to be monitored with high accuracy even under less-promising frame conditions was designed and built to demonstrate the successful operation of the demanding measurement equipment developed. This field test at a site of an operational biogas plant in Inwil succeeded in making it very likely that this Diagnostic Toolbox can also be used at other sites under different frame conditions. For example, the equipment was used to successfully perform a long-duration test by measuring the sulfur components contained within the biogas after the first and the second cleaning steps. The measurement results show that the various cleaning steps work well and are reliable.

Also supported by the SFOE

Within the thematic focus "Conversion of biogas to biomethane", one highlight was the technological/economic process assessment of catalytic methanation. Six different processes for the direct methanation of biogas were evaluated to establish their economically optimised operating conditions, absolute costs and profitability. Realistic cost estimates derived by simulations showed that the choice of technology is not the decisive factor for costs; rather, the electricity price is the most sensitive parameter followed by the CO_2 content of the biogas. The model also showed the importance of including post-upgrading steps in the cost estimates.

For the final topic, "Conversion of wood gas to biomethane", the focus shifted during the lifetime of the SCCER BIOSWEET due to low industry interest (uncertain economic boundary conditions). Unfortunately, the scale-up of the process (Ganymeth plant) could not be finished in time, due to the very high requirements of the material containing hydrogen under high temperatures and pressures. Nevertheless, the main technological focus (i.e. the bubbling fluidised bed methanation reactor) was maintained and will hopefully be fully operational later in 2021. In the meantime, an optical measurement technique has been developed to investigate such a bubbling fluidised bed in more detail.

Contribution to the SCCER's objectives

Together with WP 1, this WP provides overall solutions for the provision of biomethane in Switzerland using very different types of biomass feedstock and thus also a wide range of conversion technologies with very different TRLs. The advantage is that all options tackled within these two WPs contribute to the provision of the same energy carrier, which is fully compatible with the existing energy system and clearly GHG-neutral. These activities thus address the core of the SCCER activities.

Although not all options analysed, developed and assessed here might have a similar impact on the future energy system in Switzerland, and as such they might contribute in quite different ways to the Energy Strategy 2050 in some respects, the provision of such a broad variety of different options helps to smooth the road towards increased integration of (waste) biomass into the energy system by substituting a fossil energy carrier (natural gas) to help achieve the GHG reduction targets.

Again, in much the same way as was described for WP 1, the work was performed in a truly interdisciplinary way by very different partners from various research and education organisations, in some cases involving close and fruitful cooperation with selected companies. Another outcome of these research activities is therefore much-improved understanding and cooperation between the various organisations engaged in this area in Switzerland. Clearly, the SCCER BIOSWEET contributed significantly to bringing together research groups that had to date operated completely independently of each other so far; this is in itself an important result and a very encouraging development. This very positive development is highly likely to continue into the future and help to increasingly unlock synergies in the years to come.

Assessment of the achievements

This WP was very successful from a scientific perspective. In particular, the results presented on the thermochemical conversion of a syngas into methane were excellent and enable a much better understanding of the possibilities and constraints of the technological realisation of this strongly exothermal chemical process. Most of the planned work items were also performed on time and/or with slight delays, due for example to malfunctions of certain components, a lack of experience with new and innovative analytical measurement devices, challenges due to lockdown restrictions in the ongoing Covid-19 pandemic and of course the fact that a new and innovative plant does not necessarily operate successfully without any setbacks.

Nevertheless, the work performed is of high value and standard-setting in Switzerland, Europe and even globally in some respects. Even though only part of the Innovation roadmap developed by the SCCER BIOSWEET was successfully tackled, Switzerland maintained its role as the leading country in methanation. If the market develops and natural gas becomes more expensive, this conversion pathway is ready to be used for a clean and environmentally sound form of energy provision.

WP 3 – Biomass to Advanced Heat and Power

Leader WP 3
Prof. Dr. Timothy Griffin, FHNW

For decades, the provision of heat and electricity from solid biofuels has been the "classical" and most widely used form of energy provision from solid biomass. On a global and national scale, this is especially true for heat provision for space heating (and internationally also for cooking) purposes, particularly in rural areas.

Objectives

- WP 3's mission was to enable biomass combustion for heat and power supply within the buildings sector and in industry. This was accomplished through different, strongly interlinked pathways. First, energy valorisation focused on low-grade solid biomass, which has considerable potential but is currently unused due to technical/technological challenges.

- Second, airborne emissions from biomass combustion were further reduced by primary (improved combustion design) and secondary measures (particle filters); such challenges still hinder broad implementation of the available technologies, due again to limited acceptance.

- Third, questions relating to improving system integration and increasing (energy) system efficiencies were addressed; these are important parameters when it comes to real-life operation. This aspect goes hand in hand with the work topic on energy system integration to avoid fossil fuel peak supply, as another option to reduce GHG emissions.

- Finally, this WP also tackled thermal recovery of phosphorus from waste biomass.

What was achieved

Several achievements must be highlighted, such as a continuous determination of the energy content of wood chips, a particle separator integrated into a pellet boiler and the development of a low-emission log burner.

HIGHLIGHT

LOW-QUALITY BIOFUELS

Developing and exploiting possibilities to use (inhomogeneous) solid biofuels that have (very) low fuel quality (e.g. high-ash fuels) and typically unwanted impurities in a technologically efficient, environmentally sound and economically viable way can clearly contribute to expanding the use of (solid) biomass within "new" markets and/or additional niches in Switzerland. The developed devices are also easy to use and enable the set emission limits to be met, most likely improving local environmental performance.

The development of measurement equipment enabling the energy content of wood chips to be determined is simple but striking. Today, the energy content of chips is determined based on metered measurements of heat delivered by the boiler. This means that the supplier of the wood chips can bill only for the useful heat that the consumer is able to produce with their boiler. The innovation is therefore to determine the energy content of the wood chips at the time of delivery based on a reliable method acceptable by the buyer and seller.

During the development of a screw burner for use in energy of ash-rich solid biofuels in small-scale applications, fundamentals of the combustion of such fuels containing a high share of non-combustible components were gathered with a view to using low-grade solid biomass. At present, such solid biomass is rarely used in the size range below 500 kW thermal capacity. Due to the potentially large number of installations of this size, this achievement is of great interest for the Swiss energy system. The main technical outcome, a 150 kW screw burner for the combustion of high-ash solid biofuels, was developed and tested, proving the concept to be a viable technical/technological solution.

A big step forward was made with improved boiler designs and particulate matter removal units that reduce particulate matter emissions by more than 60%, such as the new burner concept for log wood gasifier combustors, which was realised in conjunction with an industry partner. The half or one-metre log wood market is still strongly represented in rural areas, and clean combustion technology removes pressure from the political side to ban this heat generation technology.

An electrostatic particulate matter separator integrated into a wood-burning boiler was also successfully developed. This outstanding activity, again realised in close cooperation with an industry partner, enables the cost of reducing particulate matter emissions from smaller devices to be cut considerably.

Significant progress was also made in new developments such as the pyrolysis of low-cost biomass like horse manure, coffee by-products, grain residues, tree bark and residues from biogas plants. An innovative screw burner was developed especially for solid biofuels with (very) high ash content. A small-scale pellet stove (1 to 4 kW) was also substantially improved by achieving less than 130 mg CO/m3 and 13 mg/m3 of particulate matter measured within the flue gas.

HIGHLIGHT

FLUE GAS TREATMENT

The development of options to reduce particulate matter emissions from small to medium-sized combustion devices for solid biofuels is an important aspect to reducing pollution with potentially cancerogenic compounds, leading to increased acceptance of these appliances within the society in question. The development of a reliable and cost-efficient electrostatic particulate matter separator as a promising secondary measure is therefore another outstanding highlight, enabling a contribution to be made towards the Energy Strategy 2050 in an environmentally sound way.

Also supported by OekoSolve

One important aspect of the research activities conducted into pyrolysis is the inter-linkage of energy production from solid biofuels and possible carbon sequestration services using the biochar produced (if fulfilling the criteria for soil amendment) for carbon sequestration in Swiss agricultural soils. These activities are another example highlighting that research realised within the biomass/bioenergy field can often not be tackled independently of other – non-energy-related – issues.

Last but not least, the development of a high-temperature wood dust burner in gravel driers for asphalt production was another highlight. The staged burner design was again a fruitful collaboration with industry and is now applied by the company in question.

With regard to energy system integration, simulations and real-life measurements were performed in order to gain in-depth knowledge on the operation and the required thermal energy storage size for wood-heating plants. There is great interest from plant operators in improving the design and operation of the overall system (retrofitting and new constructions).

Valuable work was also carried out on quality management systems (such as QM Holzheizwerke), and these standardisation activities becoming a very important channel for disseminating results.

HIGHLIGHT

ENERGY SYSTEM INTEGRATION

A key way of reducing GHG emissions is to improve- integration of the various energy conversion units into the applicable energy provision system to fulfil a certain supply task highly efficiently and with high security of supply. Storage systems may play a key role in this respect, so the work on energy system integration is gaining in importance, especially within energy supply systems based on fossil fuels and in parallel with solid biofuels. This is in part also for economic reasons.

Contribution to the SCCER's objectives

WP 3 adds considerably to growing the bioenergy market, which is mainly dedicated to heat provision, is fairly decentralised and at present exists above all in rural areas. The major task is therefore not to develop new technological solutions and disruptive, innovative technologies; rather, the challenge is to improve or adapt existing boiler technologies to increase the thermal efficiency and the fuel flexibility and to meet the increasing environmental standards to secure improved acceptance by local and regional society.

These important challenges were addressed by the project consortium in a very promising way, through excellent cooperation between various research and education institutions along with selected industry partners. In particular, the latter assumed responsibility for transferring the scientific results achieved and the technological solutions developed swiftly and successfully onto the market in Switzerland.

Thanks to a market that has been in existence for decades and strong participation from industry, this WP is a very good example of how the research and industry sides can cooperate successfully, making highly efficient use of their different strengths. Even though this WP's contribution to the overarching goal of significantly increasing the use of biomass in Switzerland cannot be quantified in a scientific sound way, the successful work performed here will probably contribute considerably to maintaining and increasing the use of solid biomass/solid biofuels within the heat and – to a lesser extent – electricity sector and markets. The successful work to reduce local environmental effects is also highly likely to contribute to much-improved local/regional acceptance.

Assessment of the achievements

Overall, the achievements of WP 3 are excellent. Most important questions were tackled, the challenges were addressed and unsolved problems were confronted. This is true throughout the overall usage chain, from the solid biofuel to the combustion device and flue gas treatment. Thanks to the good cooperation with industry and outstanding collaboration within selected activities, the findings and developments have high TRLs.

The work was largely performed widely in accordance with the original work plan; deviations were thoroughly justified by reasons such as the difficulty in conducting hardware activities on time because of unforeseen effects inherent in performing innovative research activities. The work is very much in line with similar ongoing activities in other countries where solid biofuels are an important option, especially for rural heat provision, and where the environmental effects are intensifying within society, making reductions increasingly necessary.

This WP also demonstrated a very good mix of theoretical approaches with CFD modelling, detailed monitoring of burners to reduce particulate matter emissions, and application projects.

WP 4 – Biomass to Liquid Fuels

Leader WP 4
Prof. Dr. Jeremy Luterbacher, EPFL

The provision of liquid fuels, for example for use in the ground-based heavy-duty mobility sector and/or in aviation, is crucial when it comes to a sizeable GHG reduction within the overall energy system and especially within the transport sector.

Objectives

The goal of WP 4 was to increase the yields (up to 30%) and cost-effectiveness (–40% upgrade costs) of biomass to liquid fuel routes. Lignin – one of the main components of lignocelluloses (e.g. wood) – is so far little used as a source for high-value applications. Limiting factors are the pre-treatment and quality of specific intermediate products, which enable efficient conversion into a valuable liquid fraction.

The exploration of improved chemical conversion options for the pre-treated material is another promising approach to providing hydrocarbons with defined characteristics. The resulting products of the biochemical conversion are being explored as reactants for catalytic transformations to produce bio-based chemicals and fuels.

Because all steps to be realised before the catalytic upgrading are compatible for the production of chemicals as well as for fuels, these development activities are beneficial to the energy transition direct by substitution of fossil-based fuels and indirect by substitution of fossil-based chemicals. Thus, despite this work was not entirely focused on energy, it can contribute considerably to GHG abatement and therefore clearly contributes towards the Energy Strategy.

What was achieved

Lignin is one of the most promising sources of renewable aromatic hydrocarbons. Current methods for its extraction from lignocelluloses result in the rapid formation of carbon-carbon bonds, leading to a condensed lignin that cannot be effectively depolymerised into its constituent monomers. Treatment of lignocelluloses with multifunctional aldehydes during lignin extraction generates an aldehyde-stabilised lignin that is uncondensed and can be converted into its monomers at near-theoretical yields. Monomer yields are typically multiplied by a factor of 5 to 10 with the aldehyde protection. In addition, cellulose and hemicellulose are also efficiently fractionated.

It is essential for the valorisation of lignin to develop a fractionation strategy that efficiently separates it from the cellulose and hemicellulose components contained in biomass while preventing its condensation. By depolymerising cellulose, hemicelluloses and lignin separately, monomer yields were between 76 and 90 mol-% for these three major biomass fractions. By achieving aldehyde-functionalised lignin oligomers and sugars, new platform molecules are provided to be further processed into bio-based fuels and/or chemicals.

HIGHLIGHT

BIOMASS DEPOLYMERISATION

The proof has been provided that biomass depolymerisation can be successfully realised without carbon-to-carbon bonds necessarily being formed – and it has been shown that this is possible not only in the test tube (i.e. in the lab) but also on the kg scale. This is indeed a tremendous step forward, towards the valorisation of solid biomass into high-value products such as high-quality fuels (e.g. jet fuel) and/or bulk chemicals. This outstanding result gained international attention and is indeed one of the scientific highlights of the SCCER BIOSWEET.

Also supported by the SNSF and the European Research Council

Against this background, the major goals within lignin degradation were to convert the polysaccharide fraction of wood into biofuels and valorise the lignin to liquid fuels and chemicals. The results achieved by protecting R-O-R bonds with aldehydes – albeit at a low TRL – are of outstanding scientific value, including when it comes to the use of waste from the food industry (e.g. endocarp biomass). Nutshells and fruit kernels have been tested, and their aromatic monomer yields can surpass those obtained using wood chips by up to 30% in view of their high lignin content.

With the propionaldehyde fractionation procedure, birch wood (extracted and dried) was split into highly digestible cellulose-rich solids, dipropyl xylose and propionaldehyde-stabilised lignin. These materials were isolated from a single fractionation. From the stabilised and fractionated lignin dissolved in methanol/dioxane, a catalytic process was developed to produce C9-alkanes (jet fuel) in a single step. This new process route was patented and forms the base technology of Bloom Biorenewables, an EPFL spin-off created in early 2019 and converted to a joint-stock company in 2020.

HIGHLIGHT

SPIN-OFF COMPANY

Based on excellent basic research and a well-developed plan to transform the gathered research results into possible industrial activities, this WP showed in a very convincing and outstanding way that a business model can be developed even on scientific results that address a very low TRL. Based on this preparatory work, the required seed money was acquired to enable the necessary next (increasingly expensive) development steps, to bring this biomass valorisation approach slowly but surely towards higher TRLs and thus into large-scale production.

Working in conjunction with this company, the production of such products including functionalised lignin, the resulting lignin monomers, cellulose and functionalised C5 sugars was scaled up to a capacity of 2 kg of biomass per day. A further scale-up is being prepared, which will enable up to 20 kg of biomass to be processed per day from early/mid-2021. This technology was entirely developed within the SCCER and is now at a TRL of 5.

HIGHLIGHT

"GREEN" CHEMICALS

Although green chemicals are strictly outside the scope of the SCCER BIOSWEET's original project portfolio, the decision to (first) go to biomass-based chemicals proved both successful and target-oriented. It was logical to develop this promising conversion route towards commercial application and value generation in Switzerland, because the prices that biomass-based green hydrocarbons can fetch as raw materials for fine and/or bulk chemicals are clearly higher than when used as a fuel for transport purposes.

This lignin fractionation process is very versatile. The resulting products of the biochemical conversion can be used as reactants for catalytic transformations to produce bio-based chemicals or fuels. This helps de-risk the investment by bringing down costs.

Furthermore, several techno-economic models were developed for the biomass upgrading by means of the aldehyde-assisted fractionation approach and subsequent catalytic conversions to fuels and chemicals. These models gave an insight into the bottlenecks. Two crucial points were identified enabling commercially viable process development: (1) solvent and reagent recycling and (2) heat integration. With solvent recovery above 98%, proper heat integration and an appropriate plant size (> 100 kt/a of biomass) fuel or bulk chemical prices of CHF 1.0 to 1.5/kg are possible.

As an alternative to the chemical production of fuel precursors, a bioprocess using microbial consortia following a first pre-treatment was also developed and assessed by BFH. The most interesting approach included a two-layered biofilm creating a "natural" lactate platform where light and oxygen niches enabled the co-cultivation of the cellulolytic fungus Trichoderma reesei and the microalgae Chlamydomonas reinhardtii on cellulose producing cellulolytic enzymes without genetically modified organism.

Contribution to the SCCER's objectives

The SCCER BIOSWEET's overarching focus was on energy for heat provision, electricity production and the market for (transport) fuels. However, the provision of biomass-derived products (e.g. bulk chemicals, fine chemicals) for use as raw materials in industry (e.g. chemicals industry) can contribute to GHG reduction, and thus to Switzerland's overarching goals defined within the Energy Strategy 2050, on at least a comparable scale as if organic matter were used purely for energy. The provision of such high-value products can also support the development of biomass utilisation chains for the provision of mass products such as jet fuel. There are therefore good reasons to also tackle such aspects within this SCCER.

Besides GHG reduction, this WP also contributes substantially towards the important goal of defossilising the chemicals industry, for example, and enabling this sector to use domestic green resources. Although the research work is still at fairly low TRLs, it is very likely that – based on the valuable high-end and truly excellent research and the seed funding supporting the company founded to increase the TRL in the months to come – this new technological approach will move closer to the market. If this development succeeds, Switzerland will have pole position in valorisation towards high-value products, especially for lignin.

The techno-economic analyses also contributed to a much clearer and more realistic view on the pros and cons of this conversion route, especially on the background to the economic constraints within the energy/industrial system in Switzerland.

Assessment of the achievements

The basic research activities carried out within this WP were superlative from a scientific point of view by national and international standards. Without a doubt, the progress made represents cutting-edge research that is outstanding even from a European and global perspective. Even more impressively, this research was developed to higher TRLs fairly fast. The process has already been upscaled into the kg range.

The original goals have therefore unquestionably been exceeded. If the goal of the company founded in 2019 is also achieved and bulk as well as fine chemicals are produced from lignocellulosic biomass, this activity will probably be the biggest success story of the SCCER BIOSWEET. The same is also true of the challenging research, which combines biological and chemical processes in a truly innovative way. This approach has also proven highly effective and – if the developments still in progress prove successful – will clearly contribute towards more efficient and more diverse use of organic matter in increasingly wide markets.

WP 5 – Biomass and the Energy Transition

Leader WP 5
Prof. Dr. François Maréchal, EPFL
Dr. Oliver Thees, WSL

Research into the biomass and the energy system as a whole/ the energy system under transition is important and also crucial to answering the question of which niches are most promising niches for biomass, taking environmental and economic constraints (along with societal demands) into consideration.

Objectives

- The overall goal of WP 5 was to conduct an in-depth assessment of the role and possibilities of biomass/bioenergy (i.e. potential) within the Swiss energy system, which is embedded in the European energy system. This also includes identifying and evaluating possible contributions by biomass in relation to the ongoing energy transition up to 2050 and maybe even beyond.

- This challenging modelling task was performed with a dynamic optimisation approach coupled with predictive modelling; such an approach promises realistic and resilient results and enables robust conclusions to be drawn afterwards.

- To enable a sound and reliable answer to the open research questions to be found, a transparent assessment of the additional, sustainable biomass potential in Switzerland was also carried out, using a high spatial distribution and the latest available data. A valuable analysis of this kind also allows the local/regional possibilities of increasing biomass use for local/regional energy provision to be analysed.

What was achieved

The two parts of this WP – the detailed analysis of additional, sustainable biomass potential in Switzerland and the dynamic optimisation approach coupled with predictive modelling of the overall energy system – unlocked strong synergies by providing databases that are valuable for all stakeholders seeking to gain a better understanding of the possibilities and constraints within the energy system today and in the years to come.

The basis was laid by a study into the potential of woody and wet biomass for 2035 and 2050. This assessment was not the first of its kind but provided very carefully evaluated data. It was followed by a demolition wood evaluation and an analysis of the geographical distribution of biomass availability. Another analysis assessed the usable wood fuel potential, taking account of ecological constraints and other aspects beyond the purely technical. Its findings included showing that a modest increase of CHF 0.01/kWh would expand the accessible wood potential by 1 million m3/a. Identifying clusters and spatial hotspots of the available biomass resources also helps in developing centralised and decentralised conversion options to suit the location and framework conditions (see also the online map).

HIGHLIGHT

POTENTIAL ASSESSMENT

The assessment of the biomass potential, taking spatial as well as ecological and societal constraints into consideration, is important for a realistic rating of the possibilities and constraints of biomass/bioenergy within the overall energy system. Providing this information to the interested audience via maps that are easily accessible online can clearly contribute towards increased use of biomass via a much better understanding of the existing organic material streams in relation to the nature of this biomass and the amount/mass. This also includes the potential change (increase, decrease) in this potential in the years to come, taking climate change expectations and possible shifts in agricultural and forestry activities into consideration.

The first application of this dataset was in a model study by the Canton of Aargau into "Replacing fossil fuels and nuclear power with renewable energy". The results show that the sustainably available renewable energy sources in this canton will not be sufficient to cover the forecast energy demand in 2035, with present or future biomass conversion technologies. At best, 74% of the energy demand could be met by renewables. Biomass can increase the degree of self-sufficiency by up to 13%. Depending on the scenario used, at least 26% to 43% of the predicted total energy demand is lacking, particularly for mobility purposes.

The development of a modelling platform for the representation of biomass conversion technologies was based on an existing system called "Energyscope". This computer platform is able to assess numerous choices and provide information on their energy and economic performance. Unfortunately, the biomass part was initially not fully integrated. The major task of the modelling activities to be performed was therefore to integrate all biomass pathways, including the conversion of wet (e.g. anaerobic digestion) and dry (e.g. gasification, pyrolysis) biomass. This included, for example, developing a generic model describing the conversion of dry and wet biomass into synthetic natural gas (SNG), its distribution to buildings as fuel for heating and the contribution of P2G systems for seasonal electricity storage. Based on this updated modelling tool, 18 different energy services were evaluated. Important factors were the available potential of the biofuels, the fossil carbon substitution by biomass (carbon flow) and the economy of the different technologies.

HIGHLIGHT

BIOENERGY CONTRIBUTION WITHIN THE ENERGY SYSTEM

Analysis of the energy transition and of the role that biomass/bioenergy can potentially play is quite important for implementation of the Energy Strategy 2050, making it a major part/result of this SCCER. Furthermore, such an in-depth analysis of the interrelationships within the overall Swiss energy system, with a particular focus on biomass/bioenergy that can easily be used in the heat market, for electricity provision and in the mobility sector, and with various provision chains using very diverse biomass resources, is far from trivial. This is even more true if the various markets for biomass outside the energy sector (e.g. food, raw material) are also taken into consideration – as becomes very evident on analysing the very interesting results presented so far.

Also supported by the SFOE and Gaznat

Within the study "Carbon flows in the energy transition", a methodology was developed to monitor and assess the energy and carbon flows in the Swiss energy system. Since the energy system needs to be defossilised to reach the legal GHG reduction goals, emphasis was given to renewables and biogenic carbon-containing resources (e.g. biomass, waste). This data will be also integrated in the calculation tool "Energyscope" in order to track both energy and carbon flows during the design of different scenarios for future energy policies. A selected number of scenarios have already been presented, investigating future actions towards nuclear phase-out, defossilisation, CO_2 taxation, etc. with regard to energy and carbon emissions. This model is of high interest for energy planning at national, cantonal and even district level. The results of the thousands of test runs of the model, varying all the possible factors, yielded a map of multiple solutions to achieve net-zero emissions by 2050.

Contribution to the SCCER's objectives

This part of the SCCER BIOSWEET bridges the gap between different areas of biomass and bioenergy research. This field is characterised by huge inhomogeneity, due to very different types of organic materials which compete to some extent with each other and with the non-energy biomass markets, very diverse conversion routes and energy markets that vary widely, as well as the overall energy system – all against a background of increasingly strict legal constraints.

The analysis of the available biomass, broken down into small areas of a few hectares, together with the modelling tool that integrates these results enables the exploitable potential of biomass for energy under the given political frame conditions to be analysed, outside of competition with the food and feed sector and as a raw material for selected industries. Amid these tensions, this WP constitutes an integral part of the work by assessing and analysing the role and contribution of the different biomass to bioenergy options within the context of the overall energy system.

This challenging task would not be possible in a sound and transparent way without a reliable way of assessing the existing biomass potential with a high degree of disaggregation. Together with the energy system analysis, these research activities are indispensable in any research programme addressing biomass for bioenergy. This research work also helps to assess and rank the results obtained by the other WPs within the context of the overall energy system, to gain an idea of the leverage that exists to contribute towards the Energy Strategy 2050.

Assessment of the achievements

The achievements and results of this WP provide new insights into the possible contribution that increased use of sustainable bioenergy could make within the Swiss energy system. Additional evaluation of social and political interdependencies – as well as various legal constraints and support measures – enabled extended conclusions to be drawn concerning the possible role of biomass within the overall energy (and industrial) system in Switzerland.

This valuable and important work was performed more or less according to schedule, taking the challenges linked to the Covid-19 restrictions into consideration. Additionally, from a methodological and thus a scientific point of view, the modelling approach realised here follows the latest methodical developments and represents the most advanced state of science and knowledge; some new and innovative approaches have even been developed and implemented within the overall model approach. Given that these activities were specifically performed for Switzerland, it is hard to draw an international comparison. Nevertheless, the modelling work was undoubtedly outstanding from a methodological perspective.

Finances and capacity of the SCCER

The SCCER BIOSWEET's activities, and in particular the development of research capacity, had total financing of CHF 76.1m between 2014[18] and 2021[19]. Innosuisse support was CHF 19.4m, while the participating HEIs contributed CHF 28.1m and the remaining CHF 28.6m came from competitive federal funds (CHF 12.8m) and contributions by industry partners and international projects (CHF 15.8m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20/21 period. Funding from own sources clearly exceeded that requirement.

Research Capacity + Operating Expenses + Other direct costs

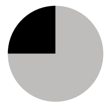
Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**19'418'983**	**28'090'368**	**12'797'793**	**15'775'970**	**76'083'114**
Share in percentage	25%	37%	17%	21%	**100%**
Ratio (Innosuisse = 100%)	100%	145%	66%	81%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	3.1	9	34%
Assistant Professor / Lecturer	2.5	4	63%
Senior Researcher	14.7	28	52%
Post Doc	7.6	10	76%
Technician	8.8	16	55%
PhD student / Research Assistant	33.6	46	73%
Other	0.5	3	15%
Total	**70.8**	**116**	**61%**

Gender ratio

25% female | **75%** male



As at the end of 2020, 116 researchers were involved in the SCCER BIOSWEET. This corresponds to 70.8 FTEs. 47% of the active researchers within this SCCER were PhD students or research assistants. 25% of the researchers were female.

[18] Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

[19] Due to the Covid-19 pandemic Innosuisse allowed the SCCERs and JAs to use Innosuisse funds also from January to March 2021. Not all SCCERs and JAs made use of this possibility.

Conclusion and outlook

Biomass is a very diverse energy carrier characterised by very different fuel characteristics, depending on the source used (e.g. wood, manure, sewage sludge, organic household waste, straw). These differences mean that one single conversion technology cannot be used for all biomass; each biomass material stream essentially needs its own specifically adapted technological solution. However, the fact that biomass is stored solar energy enables biomass to be used within the heat, electricity and/or fuel market whenever there is a need. What is more, the use of biomass in energy provision is not at all new, and there is therefore a lot of experience and expertise; nevertheless, changing demands within the energy system and evolving legal constraints always require new solutions and improved use concepts. Given these interrelations, biomass is the renewable energy carrier that is most widely usable within the energy system.

Against this background, the SCCER BIOSWEET contributed substantially to developing the foundations for wider use of biomass within the overall energy system. This was true of the various options to convert biomass into a combustible gas that is easily compatible as a drop-in substitute for natural gas, of the further development of heat provision devices, e.g. for improved environmental performance and an expanded resource basis, of the conversion of biopolymers such as lignin into bulk and fine chemicals (and into fuel in the longer term), and of the assessment of the most promising places for biomass and bioenergy within the overall energy system. All of these action items tackled as part of the successful work of this SCCER are important and needed to bring this option into more niches that are closer to the market, and to develop a deeper understanding of the possibilities and constraints.

Some of the most important results from the two funding periods, in addition to those outlined for the various WPs, are as follows:

- The use of solid biofuels for heat provision remains important within the heat market; the improved combustion devices developed support this.

- "New" conversion pathways may have the potential to use unexploited resources and to unlock additional markets; however, such innovative processes are still a long way from being developed to higher TRLs that will enable a real market impact to be made.

- Biomass is stored carbon removed by photosynthesis from ambient air. If the ambitious GHG reduction targets are to be met in the future and the energy system is to be defossilised, increasing value will be placed on biogenic carbon. Under these conditions, concepts using biogenic carbon in a highly efficient way, e.g. by adding hydrogen from water electrolysis into the conversion process, will increasingly gain in importance. The SCCER BIOSWEET showed some promising examples of this.

- Good cooperation with industry partners is essential to bringing new findings and innovative solutions to the market; the work performed has shown that such a concept can be quite successful.

- The SCCER BIOSWEET also disseminated information on the progress of research through a newsletter and on its website. Ad-hoc information-sharing (e.g. workshops, folders) attracted the industry interest. This was also true for projects realising a pilot and demonstration phase. However, KTT takes time; fast results cannot be expected.

- This SCCER supported the education of bachelor's, master's and PhD students. These people are very likely to gravitate towards industry and use their knowledge to contribute to a more climate-friendly energy system in Switzerland.

Biomass will also play an important role within a defossilised energy system in the future – especially given that hydrocarbons produced by electricity and CO_2 are being increasingly discussed as prices fall, in particular within the PV sector. Here, biomass can be a sustainable carbon source within such Power-to-X (P2X) concepts.

Within this context, the challenges relating to biomass research that the SCCER BIOSWEET has already partly addressed can be summarised as follows. These topics will also need to be tackled in research work beyond this SCCER.

- Increasing the carbon usage efficiency of biomass conversion options, e.g. by integrating green electricity into the overall conversion process.

- Improving the environmental performance of biomass conversion technologies, especially in relation to increasingly low particulate matter emissions.

- Reducing the costs of systems for biomass provision and use even further by exploiting the synergies between the resource and the demand side.

- Developing "new" provision chains for the use of biogenic material streams that have so far been little used.

- Identifying and optimising the role of biomass and bioenergy within the overall energy system, which faces a substantial transformation process in the coming years.

- Due to numerous constraints, bioenergy will always contribute only a certain share towards covering overall energy demand within an energy system. To exploit these contributions, the government needs to define adequate frame conditions, keeping in mind, for example, the possible contribution to GHG reduction and the role in supporting rural development.

Further Information

LITERATURE

Ballmer I., Thees O., Lemm, R., Burg V. and Erni M. (2015): Erneuerbare Energien Aargau. Sind die Ziele der nationalen Energiestrategie im Aargau erreichbar? Welche Rolle spielen dabei die einzelnen Erneuerbaren und insbesondere die Biomasse? WSL reports, 29. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research WSL.

Banks C.J., Heaven S., Zhang Y. and Baier U. (2018): Food waste digestion: Anaerobic Digestion of Food Waste for a Circular Economy. Murphy, J.D. (ed.): IEA Bioenergy Task 37, 2018: 12. ISBN: 978-1-910154-58-8.

Bäuerle Y., Biollaz S., Calbry-Muzyka A., Cox B., Heck T., Lehnert M., Meier A., Prasser H.-M., Schenler W., Treyer K., Vogel F., Wieckert H.C., Zhang X., Zimmermann M., Burg V., Bowman G., Erni M., Saar M. and Tran M.Q. (2017): "Potentials, costs and environmental assessment of electricity generation technologies." Bauer C. and Hirschberg S. (eds.), Paul Scherrer Institute, Villigen.

Erni M., Thees O. and Lemm R. (2017): Altholzpotenziale der Schweiz für die energetische Nutzung. Ergebnisse einer Vollerhebung. WSL reports, 52. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research WSL.

Li X., Damartzis T., Stadler Z., Moret S., Meier B., Friedl M. and Maréchal F. (2020): Decarbonisation in Complex Energy Systems: A Study on the Feasibility of Carbon Neutrality for Switzerland in 2050. Frontiers in Energy Research, 8: 549615.

Mosberger L., Gröbly D., Baum S. and Baier U. (2018): Biogene Güterflüsse – update 2014 Massenflussanalyse der Biomasseflüsse der Schweiz. Federal Office for the Environment (FOEN), Bern.

Ropp J., Stäger T., Röthlisberger R. (2018): XyloChips – Continuous measurement of woodchips energy content. In Nussbaumer T. (ed.): 15. Holzenergie-Symposium: Netzintegration, Vorschriften und Feuerungstechnik. ISBN 3-908705-36-3.

Shahab R.L., Brethauer S., Davey M.P., Smith A.G., Vignolini S., Luterbacher J.S., Studer M.H. (2020): A heterogeneous microbial consortium producing short-chain fatty acids from lignocellulose, Science 369 (6507), eabb1214.

Shuai L., Amiri M.T., Questell-Santiago Y.M., Héroguel F., Li Y., Kim H., Meilan R., Chapple C., Ralph J. and Luterbacher J.S. (2016): Formaldehyde stabilisation facilitates lignin monomer production during biomass depolymerisation, Science 354, 329.

Thees O., Burg V., Erni M., Bowman G. and Lemm R. (2017): Biomassepotenziale der Schweiz für die energetische Nutzung. Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET. WSL reports, 57. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research WSL.

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FURIES

Future Swiss Electrical Infrastructure

Action Area
Grids and their components, energy systems

Leading House

Swiss Federal Institute of Technology Lausanne (EPFL)

Participating Institutions

Bern University of Applied Sciences (BFH)
Eastern Switzerland University of Applied Sciences (OST)
Lucerne University of Applied Sciences and Arts (HSLU)
Swiss Federal Institute of Technology Zurich (ETHZ)
Università della Svizzera Italiana (USI)
University of Applied Sciences and Arts Northwestern Switzerland (FHNW)
University of Applied Sciences and Arts of Southern Switzerland (SUPSI)
University of Applied Sciences and Arts Western Switzerland (HES-SO)
Zurich University of Applied Sciences (ZHAW)

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SCCER – FURIES
Shaping the FUtuRe SwIss Electrical InfraStructure

Synthesis

The SCCER-FURIES is the scientific arm of the Energy Strategy 2050 for the "power grids" research area. Its vision is to develop technologies enabling the seamless and sustainable powering of Swiss homes, businesses and communities, based on traditional and new renewable energy resources.

Challenges in the "Grids and their components, energy systems" action area

The future energy supply in Switzerland requires a thorough understanding of the design and operation of a complex electrical network with a multitude of centralised and decentralised actors, taking into account the international interactions[20]. The action plan identified six broad areas where research should be stepped up or started: electric grids and their stability; integration of renewable electricity into the electric grid; high-voltage direct-current transmission systems and components; integration of renewable energy into buildings and districts; holistic design of energy systems; and lifecycle assessment of energy systems. The SCCER-FURIES focused on the network and grid angle.

Renewable energy generation from wind and solar can only be predicted, but not controlled in the same way as conventional plants. The points of generation are spatially distributed, and the electricity is typically fed directly into the distribution grid. This leads to technical challenges regarding the operation of the distribution grids and the transmission grids. It also requires novel technical grid components, enabling new ways of operation or monitoring. Energy consumers may also have flexible consumption schedules. Matching this flexibility to the production of renewable energy would alleviate the operational challenges for the grid but entails new technical challenges and a need to closely involve end-users.

In addition, network operation is subject to regulations that were designed for the present conventional energy system. Identifying regulatory obstacles to the implementation of new grid-related solutions is therefore an important research area.

Vision and objectives of the SCCER FURIES

The SCCER-FURIES was the scientific arm of the Energy Strategy 2050 relating to the "power grids" research area. The SCCER-FURIES's vision was to develop competences and technologies enabling the seamless and sustainable powering of Swiss homes, businesses, industries and communities.

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[20] Kaiser T., Hotz-Hart B. and Wokaun A. (2012): Aktionsplan Koordinierte Energieforschung Schweiz. Report commissioned by the Interdepartmental Working Group on Energy (EDI – EVD – UVEK).

The objective for 2016 (phase 1) was to develop key innovative solutions to enable the development of massive, distributed generation, reducing the associated grid cost, and to improve the reliability and security of the entire electrical network. The objective for 2020 (phase 2) was to demonstrate the most promising innovative solutions in pilot and demonstration projects with industry partners. These objectives served the requirement to integrate 24 TWh of new renewable energy into the Swiss energy system, derived from the Energy Strategy 2050. The Smart Grid roadmap, released by the SFOE in 2015, was a reference for the development of the SCCER-FURIES's activities, particularly during phase 2.

With respect to the "Coordinated Energy Research in Switzerland" action plan, the SCCER-FURIES aimed to create or integrate competences in Switzerland to address key research areas. In some of these research fields – grid monitoring and dynamic control, multi-terminal AC-DC transmission and distribution, control of massive distributed generation and distributed storage, demand-side response, and standardisation and grid control – the target was to build up more research competences in Switzerland.

Other research fields already were well-developed in Switzerland but needed more collaboration between research groups or between industry and academia to become effective for the targets of the SCCER-FURIES and the Energy Strategy 2050. These fields were power electronics and switching, multi-energy grids, power systems planning and architecture, and technologies for power systems components.

The research scope was unchanged in phase 2, although the work was geared more towards implementation and collaboration with network operators and with the other SCCERs. In 2018, the work plan was enhanced with activities under the Digitalisation action plan[21], aiming to develop in-country ICT competences and marketable solutions in various areas, implementing state-of-the art digital technologies for electrical infrastructure digitalisation.

What was achieved

The SCCER-FURIES's main achievement was fulfilling the initial vision of growing from a network of loosely coupled research groups to a real competence center that has built capacity and includes academia and partners from industry, the public sector, other SCCERs and various international partners. Researchers from the ETH Domain, the universities of applied sciences and cantonal universities collaborated strongly under the SCCER-FURIES umbrella.

A total of 119 actors were involved in the SCCER-FURIES over the years, and more than 250 people cooperated and developed their expertise. The SCCER-FURIES produced 731 peer-reviewed scientific papers, 307 master's theses and 92 PhD theses.

[21] See the webpage of the State Secretariat for Education, Research and Innovation.

194 projects were carried out, and 20 patents were filed, with six licences being sold. Eight spin-off companies were founded.

While phase 1 concentrated on building up capacity, phase 2 placed more focus on large-scale demonstrators and laboratories in several sites all over Switzerland. These proved attractive to collaborators from industry and the public sector and will continue to serve as research platforms after the SCCER programme has ended.

On the strength of its attractive setup and large network, the SCCER-FURIES also attracted Swissgrid as an industry partner. This was essential to the success of a major part of the activities, as most are directly or indirectly linked to questions around the transmission grid.

In respect of regulations, the SCCER-FURIES successfully involved the regulator ElCom to its activities, enabling it to receive valuable feedback on regulatory obstacles or consequences regarding the novel solutions for grid operation. This was essential to the applicability of the research, as regulatory topics will be as decisive as the technical questions in this regard. A White Paper on regulatory barriers is one of the results of this interaction.

Contribution to Energy Research and to the Energy Strategy 2050

One of the SCCER-FURIES's key contributions to the implementation of the Energy Strategy 2050 is that the center formed a nucleus for grid-related research for a broad range of stakeholders including academic partners, industry, authorities, society and the international community, leading to build-up of the necessary competences in Switzerland.

Diverse partners from universities of applied science, cantonal universities and the ETH Domain collaborated in combinations of fundamental research and practical applications, enabling the vertical integration of research from the development over validation to transfer into Swiss industry. Joint objectives and activities were derived based on a common Innovation roadmap and worked on in interregional and interdisciplinary collaborations. These activities were fully aligned with the SFOE Smart Grid roadmap and will contribute to the enhancement of the grid as required under the goals of the Energy Strategy 2050.

The center also contributed to these goals by serving as a platform for information exchange with decision-makers. This is essential as some solutions, particularly those relating to end-customers, will need to overcome regulatory and societal barriers. To this end, the SCCER-FURIES established communication channels with the Swiss power regulator ElCom and implemented a KTT plan addressing all relevant stakeholders.

The SCCER-FURIES's work is also visible internationally via publications and memberships, thereby facilitating the establishment of international collaborations, and promotes coordinated participation in power grid research to international consortia.

Recommendations

based on the SCCER FURIES's research findings

- The SCCER-FURIES built up a large, coherent, interdisciplinary pool of researchers who can create solutions and strategies for adapting the power grid as the central infrastructure for the energy transition. It is important to maintain this research network with established contacts with network operators, the regulatory authority and industry as well as with the European and international expert community throughout the whole period of the energy transition.

- The regulator should enable market mechanisms that leverage local dispatch in distribution grids. Together with distributed sensing technologies for grid awareness and the integration of synthetic inertia from power electronic components, this is essential for the implementation of distributed renewables. End-users should be included in the development of these market mechanisms, as their acceptance of grid-friendly energy management and renewable generation is key.

- Swiss policymakers should revise the renewable energy targets toward a higher share of PV, given the price evolution and research findings on PV systems. Only system management that includes rising consumers such as electric vehicles and heat pumps will enable a higher share of PV to be achieved within the Swiss energy system; planning and implementation need support from financial incentives.

- Switzerland needs more integrated network coupling with its neighbouring electricity markets to improve the capability for cross-border trading and more granular levels of market clearing to reduce network congestion limitations. Measures to strengthen the Swiss transmission system against the loss of a few transmission elements should be considered in this context.

- Power electronic solutions are key to future storage, conversion and power quality solutions, such as novel active network management with storage and soft open points, circuit breakers with shorter interruption times, and high frequency magnetic elements with reduced losses and increased power density. Distribution system operators (DSOs) and own equipment manufacturers (OEMs) should actively pursue these technologies.

Results

WP 1 – Regional Multi-Energy Grids

Leader WP 1
Prof. Dr. Mario Paolone, EPFL

WP 1 dealt with the operation and equipment of smart grids. In phase 1, the focus was on the development of methods for monitoring and operation. In phase 2, the results were demonstrated in real-world demonstrators. WP 1 delivered essential contributions to the implementation of the Energy Strategy 2050 and to the aims of the Digitalisation action plan.

Objectives

WP 1's goals were reflected in its five subtasks:

- S1.1 "Advanced monitoring infrastructure for distribution networks" focused on improved observability of local electricity grids through real-time measurements and state estimation, for use in control strategies for distributed energy resources, new fault detection methodologies and databases for forecasting models.
- S1.2 "Advanced control strategies for distributed energy resources" focused on strategies of real-time control, energy management and self-consumption of locally generated renewable energy by controlling clusters of heterogeneous resources such as battery energy storage systems, distributed generation and demand-side management.
- S1.3 "Prosumers' probabilistic forecasting" focused on predictive control with a higher level of optimality than conventional feedback control. This makes use of predictions of electricity consumption and renewable generation at a low aggregation level on timescales from seconds to intra-hour.
- S1.4 "Planning regional electricity and multi-energy grids" focused on the development of planning guidelines for regional energy systems, with cogeneration and storage of heat and electricity, to increase efficiency and the capacity for upstream provision of ancillary services.
- S1.5 "Provision of upstream grid ancillary services" focused on enabling policymakers to form evidence-based regulations for the developed solutions, in close collaboration between scientists and the SCCER-FURIES industry partners.

What was achieved

Several results and innovations were developed in WP 1, of which only the most important can be presented here.

For the phasor measurement units (PMU) solution, both hardware and software were improved and validated at the Romande Energie electric network in local balance demonstrator (REeL Demo). PMU installation is six times faster and ten times cheaper than before, and software enables up to 12 channels to be processed in parallel with a total processing latency lower than 1 ms.

GridEye monitoring solutions were improved and validated in the REel project. The data was used for model-less evaluation of the quality of supply in and across LV grids, for grid planning analysis and for performing battery storage sizing.

HIGHLIGHT

ROMADE EMERGIE DEMO

REeL Demo is a permanent platform to test and validate solutions for monitoring, operation and control of future active power distribution grids. As the largest SCCER-FURIES demonstrator, with a total budget of CHF 20m, it involves ten academic groups, three implementation partners and local authorities. The demonstrator covers the urban, rural and buildings scales, linking regulated operations and free market initiatives. Due account was taken of interaction between grid stakeholders and raising public awareness of the smart grid technologies. Three demo sites were selected: an urban area in the town of Rolle; a rural area in the area of Aigle; and an energy community in the village of Chapelle-sur-Moudon. They have served as test and demonstration sites in many SCCER-FURIES projects and have provided the visibility needed to attract collaboration partners.

Also supported by the SFOE and Romande Energie

Under the Digitalisation action plan, user and system requirements for clustering of energy consumers and grid assets were defined. The clustering is adaptive to grid and market condition changes. Algorithms for data reduction and unsupervised online clustering data mining were also investigated, with a special focus on datasets for transmission systems.

With respect to the advanced control strategies, the Commelec grid agent solution was developed further. It now can control energy resources (batteries, heat pumps, boilers) and has a shadow agent for forecasting the active and reactive power of uncontrollable nodes.

A prototype customer energy management system (CEMS) was developed, based on a low-voltage microgrid connecting emulated flexible buildings and distributed generation and storage appliances (GridLab Demo).

Under the Digitalisation action plan, smart contracts and the associated market design were developed so that the rules of the market generate a unique Nash equilibrium, guaranteeing that participants have no economic incentive to deviate from the suggested bidding strategy.

In its third task, the WP's researchers developed an algorithm for the probabilistic forecasting of day-ahead energy demand at households and distribution grid level. An algorithm estimating the PV generation as a function of the global horizontal irradiance was selected from among four alternatives and is used for disaggregation of PV generation of a group of prosumers and validated at the Chapelle-sur-Moudon demo site.

HIGHLIGHT

ARBON DEMO

Arbon Demo has about 100% coverage of smart meters (10,000), producing data which can be used for several purposes. The demo aims to integrate innovative solutions in a realistic city environment. The smart grid demo has autonomous voltage regulation based on state estimation of the grid; dynamic load management for grid stabilisation and provision of balancing power based on a multitude of resources; and online maps with a grid state overview. In addition, the technological solutions are supplemented by establishing appropriate business cases.

Also supported by Siemens and Arbon Energie

A platform for automatic trading within an energy community based on distributed control was designed. This platform takes into account power and voltage constraints in a subset of measured nodes in the distribution grid.

With regard to dispatch planning, the operation of a distribution feeder with heterogeneous prosumers was developed and experimentally validated, both on real-world installations on the EPFL campus and at the Aigle demo site. The distribution grids had conventional consumption and distributed PV generation.

An integrated approach was developed to optimally design and schedule building energy systems in evolution scenarios for future grids. It combines GIS, process integration techniques and power flow analysis, covering the heating systems and network constraints.

The key result with regard to the provision of upstream grid ancillary services is a framework for sizing the required active and reactive power reserves of transmission system operators (TSOs, Swissgrid for Switzerland) from regional energy networks. A linear optimisation methodology was used to determine the capabilities of an active distribution network for the provision of both active and reactive power reserves to TSOs. This approach was validated at the Aigle demo site.

Contribution to the SCCER's objectives

WP 1 contributed decisive results, feeding into the SCCER-FURIES's success towards implementing the Energy Strategy 2050, which can be closely mapped to the targets of the Smart Grid roadmap. The results cover a wide range of TRLs. More than 300 peer-reviewed scientific papers were published within WP 1 during the funding period. The authoring institutions thereby not only contributed significantly to the advancement of science in this field, but also strengthened their reputations, which will serve as a strong basis for future research into topics of relevance for the Energy Strategy 2050.

Six spin-off companies were also founded during the same period. These cover a wide range of different aspects of grid planning and operation: Zaphiro Technologies offers a novel real-time monitoring system for grid operations; Hive Power company commercialises a blockchain-based platform for mutually beneficial energy-sharing communities; Aurora's Grid is active in storage system aging assessment; ExerGo aims to develop the fifth generation of district heating and cooling systems using CO_2 as a heat carrier; GridSteer commercialises the Commelec solution which computes optimal power setpoints for a heterogeneous set of energy resources; and Urbio aims to valorise decision-making tools for the planning of urban energy systems. This clearly shows that WP 1 also produced results that were already relevant for implementation and had the necessary TRL.

Cooperation with implementation partners, especially via the large-scale demonstrators, enabled many of these results and is likely to continue to a substantial degree after the end of the funding period. Cooperation between partners from different academic institutions worked very well and helped to cover the wide range of activities – from fundamental topics to implementation projects.

Assessment of the achievements

WP 1 adhered well to the original work plan and adapted it to new requirements and learnings. Few items had to be cancelled due to lack of funding or problems such as a reorganisation at a partner.

Work deliverables that were added or changed concerned the protection of DSOs against cyber-attacks (added to address an industry partner's needs); replacing planned simulation studies with data analysis on the LV network of the Arbon demonstrator (due to changed priorities for the industry partner); three new deliverables on battery-related activities, answering a market need for second-life usage considerations for batteries. Only few deliverables had to be changed or dropped due to changed priorities or lack of funding.

WP 1 is well-embedded in international research networks – in 2020, WP 1 partners were involved in ten ongoing EU projects under H2020 and ERA-NET programmes. Prof. Paolone, who served as Executive Committee member of the European Energy Research Alliance (EERA) and leader of SCCER-FURIES WP 1, ensured the dissemination of WP 1's activities.

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WP 2 – Bulk Multi-Energy Grids

Leader WP 2
Prof. Dr. Petr Korba, ZHAW

WP 2 aimed to provide the transmission system operator, Swissgrid, with simulation tools for low-inertia energy grids with a high share of renewable energy sources, the quantitative evaluation of local and international market potential, and assessment of planning options for power storage and generation, including the risks arising for power grid operation.

Objectives

WP 2's goals were reflected in its five subtasks:

- S2.1 "Maintaining system stability and reliable operation of the Swiss power system" provided a set of recommendations and future actions to Swissgrid and policymakers, aimed at maintaining stability of the Swiss power system in the face of the future energy challenges.

- S2.2 "Economic benefits of different market structures" delivered a theoretic benchmark for the operation of the future European power system from the Swiss perspective. This benchmark was used for a quantitative assessment of the economic benefits of different market structures and the coordination between European grid operators.

- S2.3 "Coordination among grid levels" developed a simulator for optimal coordination between transmission and distribution levels. Grid outage risks due to different transmission phenomena were assessed.

- S2.4 "Techno-economic performance of distributed storage": the technical and economic performance of the distributed energy storage solutions and optimisation of gas power plant siting supported by the gas network as a long-term storage option were investigated.

- S2.5 "Risk assessment of power grids" analysed the feasibility of the scenarios set forth by the Energy Strategy 2050 document with respect to the risks of operations, including grid dependency on real-time measurement.

What was achieved

In S2.1, several algorithms were developed for stability analysis of low-inertia energy grids with a high share of renewable energy sources, and novel control algorithms to counter power system oscillations were developed and tested on demonstrators.

HIGHLIGHT

NOVEL CONTROL APPROACHES FOR LOW-INERTIA POWER GRIDS

A key concern of power transmission and distribution operators is the loss of inertia problem, arising from removing conventional generators from the grid and replacing them with new renewable energy sources – these are interfaced with the grid through fast-acting power electronics. The aim of this project was to explore advanced control strategies to assure the frequency stability and robustness of tomorrow's low-inertia power grid. It was a highlight of WP 2 (provided by S2.1) that new approaches to controlling these low-inertia networks can now be developed and evaluated using simulation, be emulated and be based on real-world data. The REE-Lab in particular should be highlighted here, as it provides a comprehensive environment for implementation-relevant tests, with a real-time PDC platform, a hardware emulator of a power system, integration of real local products, and a real-time simulator.

Large disturbances such as a European Network of Transmission System Operators for Electricity (ENTSO-E) system split were investigated with regard to stability with varying shares of converter-based generation. Three demonstrators were developed:

1. A dynamic hardware emulator of an electrical power system, consisting of lab-scaled synchronous generators and real-market components for monitoring, excitation, protection and control, and hardware models for transmission and renewable generation.

2. A dynamic real-time simulator using official data from ENTSO-E with 23,000 buses, 30,000 branches, 11,000 loads, and 1,200 generators.

3. A phasor data concentrator (PDC) collecting real-time measurements provided by PMUs from partner universities in 17 different countries in Europe and the Americas. The data collection enables online testing and offline monitoring by algorithms using real measurements.

In S2.2, a theoretic benchmark for the operation of the future European power system from the Swiss perspective was developed to quantify the economic benefits of different market structures and of coordination between European grid operators.

The value of flexible reserve requirements for varying levels of renewable penetration was also evaluated. The work yielded insights into the benefits of future improvements to the Swiss electricity market, improved coordination between the Swiss and EU markets and enhancements to the reserve markets for enabling the large-scale integration of renewables. However, the question of whether Swiss electricity demand will stabilise at around 60 TWh in 2050 remains unresolved. A more detailed analysis will be necessary to support this figure by facts. Strong indicators that challenge this electricity demand figure include e-mobility, increased demand by information technology and climate protection measures.

The computer simulator developed in S2.3 enables essential questions on the coordination of transmission and distribution levels, and on phenomena with relevance for the prevention of a grid collapse to be investigated.

HIGHLIGHT

STABILITY ASSESSMENT OF FORTHCOMING POWER NETWORKS WITH LARGE-SCALE INTEGRATION OF RENEWABLE ENERGY SOURCES

In the context of the SCCER-FURIES, a WP 2 researcher at ZHAW secured an SNSF Ambizione energy grant for power system dynamics. The project started in January 2018 and aims to achieve a dynamic power systems model, undertake stability analysis or identify system bottlenecks and perform a stability assessment of the power system based on the future scenarios envisaged in the Energy Strategy 2050 and for Europe.
The algorithms and mathematical tools developed were integrated into software, and recommendations were formulated for decision-makers.

Also supported by the SNSF

An optimisation problem was formulated to establish optimal usage of the available flexibility to fulfil balancing requests from the TSO to the DSO by inherently determining the price of flexibility. A software optimisation tool was also implemented for the solution of security-constrained optimal power flow problems. It finds an optimal operational state that guarantees that the whole power system can work under the nominal long-term cost-efficient operation plan but can also remain in its operational state when some of the predetermined contingencies occur.

S2.4 contributed to the quantification of the technical and economic performance of distributed energy storage system solutions within the Swiss power system, optimised siting of gas power plants and simulated operation of Swiss electricity and gas networks. Key results were a two-step generation planning framework, solving siting and sizing of renewable energy sources and gas-fired power plants (GFPPs), and siting and sizing of P2G facilities in two subsequent steps. An iterative optimisation procedure for the simulation and optimal placement of future grid-level energy storage systems was also developed.

S2.5 made contributions to risk assessments regarding grid dependence on real-time measurements, on the communication infrastructure, and on the assessment of the stability of the scenarios of the Energy Strategy 2050.

HIGHLIGHT

SECURITY OF SUPPLY IN GRID OPERATIONS HEAVILY DEPENDENT ON REAL-TIME MEASUREMENTS AND COMMUNICATION

In future low-inertia grids, the system operation will depend heavily on the reliability of real-time measurements on the grid state and the communication to and from grid components. Security of supply was investigated for failures of transmission lines, transformers, hydro power plants, GFPPs and P2G facilities. The results demonstrate the feasibility of transitioning to a fully renewable Swiss power system even after accounting for conservative security-of-supply constraints, which is the main research highlight of this work.

Also supported by Horizon 2020

Security of supply was investigated with reference to expected energy-not-served (ENS) and demand-not-served (DNS) incidents following the outage of single components. Failures of transmission lines, transformers, hydro power plants, GFPPs and P2G facilities were examined at multiple times. The results demonstrate the feasibility of transitioning to a fully renewable Swiss power system even after accounting for conservative security-of-supply constraints, which is the main research highlight of this work.

A cyber-attack model was developed for power grids, and attacks on automatic generation control (AGC) were simulated. The power system transmission components with the highest impact on the security of supply when attacked were identified.

Contribution to the SCCER's objectives

WP 2 contributed decisive results, feeding into the SCCER-FURIES's success towards implementing the Energy Strategy 2050, which closely maps to the targets of the Smart Grid roadmap.128 peer-reviewed scientific papers were published, contributing significantly to the advancement of science in this field and increasing the visibility of WP 2's research groups.

As WP 2's tasks mainly addressed the Swiss TSO Swissgrid, only a small share of results were implemented. However, the spin-off company Ensiplan was founded, providing IT solutions for utilities, automating their planning activities and increasing their interaction with public authorities and communities during the permit process with the use of 3D visualisation and virtual reality.

In addition, close collaboration with industry partners permitted the transfer of some key results from the lab to the market. These include a new software and algorithms for advanced voltage control in distribution grids, and a tool for planning and optimisation of transmission lines, which is in use at Swissgrid.

While the siting and sizing optimisation results of S2.4 do provide insights for optimised national or international energy and power system designs, they lack an addressee, as there is no entity planning on these scales. Future work would have more impact if it were aimed at scales where such stakeholders exist.

KTT of WP 2 findings took place regularly, through workshops with academic and industry partners, as well as subtask meetings and bilateral project meetings with all Swiss industry partners. Eight new master's, bachelor's and PhD courses at ETHZ, universities of applied sciences and cantonal universities were developed. DynPower, the annual international workshop on power system dynamics, reached 50–265 participants from academia and industry per year from up to 46 countries.

WP 2 brought together partners from the ETH Domain, cantonal universities and universities of applied sciences. There was close strong interaction between WP 2 and WP 1, including within the digitalisation activities. It also collaborated with other SCCERs, including Mobility, CREST and HaE. WP 2 was also involved in JA White Paper P2X, leading to the publication of a White Paper and a Supplementary Report for power-to-product technologies (see page 273).

Assessment of the achievements

WP 2 adhered well to the original work plan and made a few well-justified adoptions; these were linked to changed priorities at implementation partners or in order to focus more on work that was relevant for implementation.

WP 2's international relevance is reflected by two filed patents and more than 128 peer-reviewed papers. WP 2 partners are collaborating with 12 international partners in EU projects, e.g. in the ERA-NET SG+ CloudGrid project. In collaboration with the SFOE, SCCER-FURIES partners from WP 2 represent Switzerland in the International Smart Grid Action Network (ISGAN), which is the only global, government-to-government forum on smart grids. WP 2 partners' involvement in international activities enabled the exchange of knowledge with international partners and ensured the scientific relevance of their proposed solutions.

WP 3 – Multi-Terminal AC-DC Grids and Power Electronics

Leader WP 3
Prof. Dr. Patrick Favre-Perrod

WP 3 aimed to provide validated approaches for hybrid AC-DC systems in the areas of fault management, coordinated planning and operation, power electronic converter concepts, and coordinated operation of ancillary services in future grids. Phase 1 focused on methods for monitoring and operation. In phase 2, the results were demonstrated in real-world demonstrators.

Objectives

WP 3's goals were reflected in its three subtasks:

- S3.1 "Multi-terminal HVDC system design" focused on the completion of the design, assembly and commissioning of the high-current source for the ETH high-power electronics laboratory and concluded with AC/DC interaction studies.

- S3.2 "Fault detection and clearing in multi-terminal HVDC" focused on novel methods of fault location and the investigation and development of hybrid circuit breakers for DC applications.

- S3.3 "Enabling component and converter technologies and applications" worked on innovative controls and structures for power electronic converters and system-related benefits of power electronics in terms of ancillary services and fault isolation.

WP 3 planned and realised the "SCCER-FURIES lab network", seeking to link the infrastructures of SCCER-FURIES partners working on AC/DC technologies, to facilitate testing of innovative solutions. Five major technological prototypes were to be demonstrated in this laboratory network: building blocks of DC circuit breakers, an optimised solid-state transformer (SST), a fault location device for MV networks, a soft open point and scalable MMC modules for a flexible DC source.

What was achieved

In S3.1, a high-performance DC test source for DC grid components and DC test source controller were developed. The individual stages of the test source and its control system were commissioned and tested on a step-by-step basis. The test source is now functional at full scale. Simulations for coordinated AC/DC network development were completed in a sub-transmission case study.

HIGHLIGHT

SOFT OPEN POINT FOR REEL LV DEMONSTRATOR

Soft open points (SOP) can increase the capacity of a distribution network to host renewable energy sources. An SOP placed between the ends of two feeders enables one to pass from a radial to a ring topology, so that the benefits of both configurations can be combined: the power flow between the feeders can be balanced, the voltage profiles can be controlled and availability can be improved in the event of faults. This project resulted in the development distribution network and SOP models, including control strategies for the SOP; assessment of the impact of the SOP on the network and the resulting improvement in voltage and overload management, and also of the achievable increase in hosting capacity; and the development of two LV SOP prototypes: one for laboratory purposes and another that has been deployed to Romande Energie's network. The SOP concept is flexible, cost-effective and compatible with existing equipment, making integration into microgrids with fast control possible.

Also supported by SFOE and Romand Energie

S3.2 established the concept for a hybrid circuit breaker with adaptable pulse current. A test setup for the disconnector part was built, and simulations on the dielectric strength of the disconnector were completed. Results showed that auxiliary circuits are suited to improving interruption performance of active current injection circuit breakers.

On the topic of ultra-fast disconnectors (UFD) for (hybrid) HVDC circuit breakers, a test bench to investigate the contact resistance was built and its ratings were improved incrementally. The work included an academic exchange with Georgia Institute of Technology (Atlanta, USA) on the topic of contact material for UFD applications.

A substation-based fault location device was developed, based on electromagnetic time reversal (EMTR). The concept was experimentally validated on a real distribution line of Groupe e. The simulation time for fault location was reduced, and the approach was extended to several branches. The concept was also extended to locate lightning-originated flashovers on overhead transmission lines.

In S3.3, a concept for a high-power DC-DC modular multi-level converter prototype employing Scott transformer connections was designed and developed. Using the same hardware platform, activities relating to the development of medium-voltage high-performance modular multi-level active rectifier-based converters are ongoing.

The "Design for a flexible DC source" (FlexDCS) submodule was completed, and inter-capacitor balancing was experimentally verified.

The high-frequency behaviour of magnetic and conducting parts of an SST was modelled. Efficiency measurements of the magnetic core transformer yielded results close to designed values. An air-core-based SST was designed and constructed, the magnetic core transformer was constructed and tested, and a 40 kV SiC "Super-Switch" intelligent power module was proposed and designed.

HIGHLIGHT

SUBSTATION-BASED FAULT LOCATION DEVICE BASED ON EMTR

The main objective of this project was to develop a fault location device by integrating the time re-versal theory into an embedded hardware platform. The proposed method was validated in several realistic cases using numerical simulations. Experimental validation using different set-ups including reduced-scale coaxial cable system and de-energised overhead distribution lines was also carried out to evaluate the performance of the developed approach. The developed fault location device would be able to identify the precise fault location using a single measurement system, installed at the primary substation.

Also supported by Streamer International AG

In the PASREN (provision of ancillary services from regional energy systems) project, network and resource modelling for three case studies in collaboration with Groupe e were completed. Full-year scenarios for the provision of frequency reserve and reactive power under various conditions and priorities were proposed.

In a demonstrator project at the REeL Demo site, the preliminary design for a soft open point (SOP) was finalised, and several candidate locations were evaluated with Romande Energie. Protection studies were performed for MV and LV application scenarios of the SOP. A fully functional 15 kVA prototype was realised and tested at the GridLab in Sion; a more advanced 50 kVA prototype was prepared for deployment in Chapelle-sur-Moudon. A state estimator and LV fault location system for smart metering data was also tested for various use cases in the REeL demonstration network

Contribution to the SCCER's objectives

WP 3 contributed essential results, feeding into the SCCER-FURIES's goals in working towards implementation of the Energy Strategy 2050, in line with the targets of the Smart Grid roadmap. More than 130 peer-reviewed scientific papers were published within WP 3, contributing significantly to the advancement of science in this field, and increasing the visibility of the corresponding research group.

Within the WP 3 framework, the following innovative solutions reached a high maturity level: a toolbox for simulation of components for SSTs; a small-scale modular multi-level converter; a 100 kW prototype demonstrating the functionality of a hybrid transformer; a device for locating faults using EMTR, developed in collaboration with Streamer International; a framework for evaluating the technical and economic potential for provision of ancillary services by distributed resources; a novel device for the interconnection of normally opened network structures (SOP); an experimental test source for high-current testing; and a new concept for a high-power DC-DC modular multi-level converter prototype.

KTT activities in WP 3 included the joint White Paper on direct current technologies by all WP partners, showing how the individual contributions of the partners fit into the general status of R&D in DC technologies in Switzerland. In addition, four technical workshops were held at WP level, and WP 3 participated in two special sessions on the SCCER-FURIES at international conferences. WP 3 produced three contributions to study programmes at HES-SO and delivered four ad-hoc courses to various organisations (TSO, public administration, industry).

WP 3 brings together partners from the ETH Domain and universities of applied sciences for the design, development and testing of innovative solutions, including the SCCER-FURIES AC/DC lab network, which improved the use of WP 3 partners' existing infrastructure. Three thematic workshops on transformers took place in collaboration with WP 4.

Assessment of the achievements

There were no major modifications to WP 3's activities compared with the original work plan. The weighting of the activities evolved, placing more emphasis on SOP deployment (as a consequence of the changed organisation of the REeL project) and less on activities relating to in DC systems in the second phase of the SCCER-FURIES.

WP 3's high international relevance and scientific quality is reflected by seven filed patents and more than 130 peer-reviewed papers, which is remarkable given that some of the research is close to product development and has confidential aspects. WP 3 partners are involved in international projects and initiatives enabling knowledge exchange with international partners and ensuring the scientific relevance of their proposed solutions. For instance, Prof. Rachidi is a member of the Swiss Academy of Science and the Advisory Board of the Institute of Electrical and Electronics Engineers (IEEE) Transactions on Electromagnetic Compatibility, as well as President of the Swiss National Committee of the International Union of Radio Science. Prof Dujic serves as the Chair of the IEEE Power Electronics Society (PELS) Swiss Chapter, and Prof. Carpita is a member of the Electric Power Engineering (EPE) International Scientific Committee.

WP 4 – Grid Components

Leader WP 4
Prof. Dr. Jasmin Smajic, OST

WP 4 aimed to provide power component companies with improved devices and tools for the study of their performance and integration into the system to cope with the challenges of the future Swiss electrical infrastructure.

Objectives

WP 4's goals were reflected in its subtasks:

- S4.1 targeted a new approach to simulating fluid-structure interactions using overlapping meshes for the purpose of studying turbine-generator coupling. This is a detailed problem that can be considered in the context of hydropower plants and is relevant for new operation modes of hydropower plants in future grids.

- S4.2 covered reliability, monitoring and fault detection in different application areas. It focused on component insulation, transient voltage distribution across the transformer winding during lightning impulses, and the development of a pulse generator for insulation stress testing.

- S4.3 focused on grid integration of PV and storage with a wide range of activities on different aspects, including testing and design of PV components and systems; systemic studies on cost potential for PV plants, and concrete paths for renewable integration into the Swiss energy system towards the goals of the Energy Strategy 2050.

What was achieved

In S4.1, the new approach to simulate multiphysics problems with overlapping meshes was implemented in libraries and a simulation environment that has shown good scalability. The approach can therefore be used to study turbine-generator coupling.

S4.2 led to novel methods for the simulation and calculation of phenomena that have been incorporated into software tools. The new simulation method for propagation and development of streamer inception was implemented in COMSOL. The calculation of transient voltages in transformers exposed to lightning impulses was integrated into OST software and verified experimentally. A semiconductor-based pulse generator with 5kV and 40kHz was developed for insulation stress tests and was tested successfully on oil-impregnated paper insulation in mineral oil and synthetic ester. It was demonstrated that galvanic separation has no influence in inverters and optimiser electronics. An extensive simulation study of electromagnetic compatibility (EMC) of large PV arrays was undertaken to provide practitioners with installation guidelines.

S4.3 produced a number of results with a direct impact on grid integration of PV and storage, including a unique multi-tracker PV inverter test bed, test procedures and tests for inverter batteries, quick disconnect devices, cross-compatibility of PV connectors, DC-PV strings with respect to fire hazards, utilisation of overload operation of PV inverters and PV inverters with snow melting capability. A new, non-galvanically separated converter topology was also developed, and rotatable PV systems for installation on agricultural land were piloted. Bidirectional charging of electric vehicles primarily from PV was prototyped.

HIGHLIGHT

VFT STRESSES IN OIL-IMPREGNATED PAPER

The pulse generator with 5kV and 40kHz frequency for insulation endurance tests was successfully tested at the OST high-voltage lab for stress tests on Weidmann's oil-impregnated paper insulation for power transformers. These experiments help to estimate the lifetime of the transformer insulation exposed to high du/dt produced by power electronics.

Also supported by Weidmann Electrical Technology

In addition, several studies were carried out into various PV-related questions. They included lifetime calculations of PV systems, indicating that 25 years is probably an overly low assumption for some installations. The PV electricity price evolution was examined, predicting a target value of CHF 0.03/kWh. This is a very interesting and promising result, although it should be taken further, comparing against costs for system services for operation of an electric energy system.

In addition, S4.3 covered the important topic of PV recycling, which is often overlooked when considering PV.

HIGHLIGHT

CAPACITIVE COUPLED PAIR (CCP) CONVERTER (BORGNA CONVERTER)

This new converter turns on when the power semiconductors have low current and turn off when there is no voltage over them. This eliminates the switching losses even if the switching frequency is low, which reduces electromagnetic interferences. The PV LAB demonstrated feasibility, with high efficiency and low EMC in a 2 kW unit. A European patent application was filed for the Borgna Converter.

In the "SimZukunft" case study for the city of Burgdorf, the most favourable path for the complete decarbonisation of Switzerland was investigated. It was shown that overproduction of PV electricity at midday and in summer must be curtailed or consumed by flexible loads in combination with decentralised storage systems.

HIGHLIGHT

STUDY ON 100% RES WITH >40 TWH PV ELECTRICITY

The "SimZukunft" case study on the role of small Swiss cities in the Swiss national energy transition sought to identify the cheapest way to achieve full decarbonisation in Switzerland. It concluded that the overproduction of PV power at noon and in summer needs to be curtailed or consumed by flexible loads in association with decentralised storage systems. For the example of the city of Burgdorf, it illustrated how a 100%-decarbonised Switzerland is possible and outlined the path towards transformation into 100% renewables at the low-voltage grid level.

Also supported by the SFOE

Contribution to the SCCER's objectives

WP 4 contributed essential results, feeding into the SCCER-FURIES's goals in working towards implementation of the Energy Strategy 2050, in line with the targets of the Smart Grid roadmap. The multiphysics simulation covered in S4.1 is relevant but deals with one of the more marginal problems in the context of the Energy Strategy 2050. About 100 peer-reviewed scientific papers were published within WP 4, contributing significantly to the advancement of science in this field and increasing the visibility of the corresponding research group.

The company Algo4U, established in 2018 as a spin-off of USI-ICS, specialises in customised algorithmic and software solutions for engineering, simulation, optimisation and data analytics.

The following innovative solutions also reached a high maturity level: KODEWA, commercialised by Swissframe, is a decentralised system for hot water production in multi-storey houses, which can offer grid support or PV self-consumption. In collaboration with Belenos, a multi-string PV module was developed enabling better integration of applications with partial shadowing e.g. on building façades. A PV solar tile was developed in collaboration with Meto-Fer for better integration into inclined roofs; commercialisation is ongoing. A reliability assessment for novel SiC power semiconductor modules was carried out and extended for bidirectional testing. A unique test facility for multi-input PV inverters was developed and is open to utilities, installation companies, producers of PV inverters, consumers and their organisations.

Assessment of the achievements

The work plan was well adhered to, with only few, accepted changes towards goals that are more focused on implementation, in line with WP 4's general focus on topics with higher TRLs.

The international relevance of the work in WP 4 is reflected in two patents and about 100 peer-reviewed papers, also demonstrating its good scientific quality in the diverse scientific fields covered by WP 4. WP 4 leader Prof. Muntwyler represented the SCCER-FURIES in the IEA's Implementing Agreement for Co-operation on the Hybrid and Electric Vehicle Technology Collaboration Programme (HEV TCP). He also represents Switzerland in three tasks in the TCP.

During the funding period, WP 4 also successfully worked on strengthening links between its partners from different domains, including enabling multidisciplinary activities. Given that many of the challenges in implementation of the Energy Strategy 2050 are in this cross-domain area, WP 4 also strongly contributed to the success of the SCCER-FURIES in the international arena.

Finances and capacity of the SCCER

The SCCER-FURIES's activities, and in particular the development of research capacity, had total financing of CHF 97m between 2014[22] and 2021[23]. Innosuisse support was CHF 28.7m, while the participating HEIs contributed CHF 28.6m and the remaining CHF 39.7m came from competitive federal funds (CHF 20.3m) and from contributions by industry partners and international projects (CHF 19.4m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding within the overall 2014–20/21 period. Funding from own sources clearly exceeded that requirement.

Research Capacity + Operating Expenses + Other direct costs

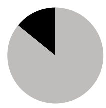
Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**28'650'762**	**28'550'707**	**20'315'589**	**19'435'714**	**96'952'772**
Share in percentage	30%	29%	21%	20%	**100%**
Ratio (Innosuisse = 100%)	100%	100%	71%	68%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	5.5	35	16%
Assistant Professor / Lecturer	0.3	4	8%
Senior Researcher	22.5	49	46%
Post Doc	19.2	27	71%
Technician	1.7	7	24%
PhD student / Research Assistant	91.9	141	65%
Other	0.1	1	5%
Total	**141.0**	**264**	**53%**

Gender ratio

14% female | **86%** male



As at the end of 2020, 264 researchers were involved in the SCCER-FURIES. This corresponds to 141.0 FTEs. 65% of the active researchers within this SCCER were PhD students or research assistants. 14% of the researchers were female.

22 Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

23 Due to the Covid-19 pandemic Innosuisse allowed the SCCERs and JAs to use Innosuisse funds also from January to March 2021. Not all SCCERs and JAs made use of this possibility.

Conclusion and outlook

The SCCER-FURIES was very successful in building up a substantial and excellent research capacity. The key to success for the Energy Strategy 2050 is a well-trained new generation of engineers. At the same time, lifelong, continuous education of practising engineers is essential to creating a general understanding of innovative solutions. The SCCER-FURIES's new educational and training tools are an important step in this direction.

For engineers and scientists to make an impact on solving current infrastructure problems, close cooperation between all educational institutions, such as the ETH Domain, universities and universities of applied sciences, plus implementation partners and the public sector, is required. The SCCER-FURIES made an important contribution to this goal. This included ease of access to laboratories at the partner institutions; and the large-scale demonstrators in particular proved an effective platform for facilitating partnerships between academia and implementation partners. It is important that these demonstrators and laboratory infrastructure will not only continue to be used for new research and implementations in the future, but also keep up the momentum of the now very coherent Swiss smart grids research community. Only this systematic way of continuing the work will ensure that the same convergence between research and application is maintained.

The SCCER-FURIES's target audience consisted of manufacturers of grid components and systems and network operators. The successful establishment of a well-conceived KTT supported the inclusion of many partners in shared research and development projects, closing the gap between the academic and industrial worlds. Many interesting and highly innovative proposals, solutions and systems were communicated via the KTT concept during the two phases of the SCCER-FURIES.

One important category that requires further work is digitalisation. The work already carried out in the past funding period should serve as a basis for intensified work in the future, as the issues relating to the digitalisation of energy supply, including security, are key to the transformation of the energy system.

Successful realisation of the Energy Strategy 2050 in the area of power infrastructure will require private and industrial end-customers to be included in the discussions. Unless the future strategy can show a win-win situation for all stakeholders, any change is likely to encounter opposition. Acceptance problems experienced regarding the siting of battery storage when setting up a demonstrator site for the SCCER-FURIES is just one example of this. Future work should therefore give high priority to projects that have the potential to show the needed win-win scenarios for implementation and attract the attention of policymakers to the developed solutions.

As part of the continental European synchronous system, Switzerland's opportunities to implement the Energy Strategy 2050 also depend on developments outside Switzerland: transmission capacity between countries, imports, exports, inertia of the whole synchronous system and flexibility on the part of other countries all affect the conditions under which Swiss networks can operate. Future scenarios should be tackled jointly with other European TSOs so that the market solutions in the EU and Switzerland do not conflict.

The SCCER-FURIES has already developed concrete topics for further research after completion of phase 2. These include multiple timescale forecasting; energy conversion and protection devices; operational planning, maintenance, control and monitoring of active distribution grids; the stability and operation of transmission grids; and the design, coordination and evaluation of local electricity market and price systems. All WPs have compelling ideas of the topics they will develop further in their respective fields. It is positive that the topic of the energy market is included, as only the transition to renewable energy requires further development of the market design.

Additional topics that should be considered for future activities in the SCCER-FURIES's area are projects supporting the development of rollout plans for smart metering and the formation of energy communities on a broad basis. The potential use of extra-high-voltage (EHV) cables in the transmission system should also be scientifically studied to clarify if there is an upper limit for the inclusion of EHV cables compared with overhead transmission lines.

Within the work of the SCCER-FURIES, it also become clear that some topics which go beyond the scope of the SCCER-FURIES need addressing.

- First, a resilient study of predicted energy demand in 2050 must be started. The data that is currently published needs to be enhanced to reflect, for example, e-mobility, environmental control, energy demand by future communication systems, etc.

- Second, a complete study on the limits of PV and wind energy plants (WEPs) in Switzerland should be carried out, considering all barriers such as minimum distances between WEPs and houses.

- Finally, the future work on DC should focus more on systems, e.g. reference designs would be more of a research question than operating equipment, where industry is more in the lead.

In conclusion, the SCCER-FURIES achieved a lasting impact on the power system domain in Switzerland and laid the foundations for a strong network between academia, industry and the public sector that will contribute strongly to implementation of the Energy Strategy 2050 even beyond 2020.

Further Information

LITERATURE

Borgna L., Gfeller D. and Muntwyler U. (2019): Der Borgna-Konverter – Eine neue Topologie für hocheffiziente Schaltregler. Bulletin.ch.

Cherubini P. (2017): Automating the distribution grid. Energiaplus.com, Swiss Federal Office of Energy.

Galland O., Kalantar-Neyestanaki M., Eggenschwiler L., Favre-Perrod P. and Cherkaoui R. (2020): Maintenir l'équilibre, à l'avenir aussi. Utiliser les énergies renouvelables pour stabiliser le réseau. Bulletin.ch.

Herzog A. (2015): An innovative response to the challenge of storing renewable energy.

Maillard C. (2018): Un labo pour tester les bugs électriques. La Région, 2247.

Medici V. (2018): Blockchain-secured energy management. Energiaplus.com, Swiss Federal Office of Energy.

Muntwyler U. (2017): 1. PV-Industrietag in Burgdorf. Energiaplus.com, Swiss Federal Office of Energy.

Plesinak J. and Sarantakos G. (eds.) (2021): Shaping the future of Swiss electrical infrastructure. Activity report SCCER-FURIES 2017-2020.

Zehnder S. and Buff D. (2018): Leerlauf vermeiden – Reduktion von Energie und Kosten bei Transformatoren. Bulletin.ch.

WHITE PAPERS

Carpita M., Favre-Perrod P., Razzaghi R., Wang Z., Paolone M., Rachidi F., Dujic D., Christe A., Milovanovic S., Utvic M., Galland O., Allani M., Schultz T., Franck C.M., Tsolaridis G. and Biela J. (2019): Direct current technologies for Switzerland's electricity transmission and distribution.

SCCER-FURIES (2021): Regulatory Barriers for the implementation of smart grid solutions in Switzerland.

RADIO INTERVIEW

Jacquod P., Panciatici P and Paolone M. (2017): L'électricité, un monde aussi complexe que fascinant. RTS Radio Télevision Suisse.

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HaE

Heat and Electricity Storage

Action Area
Storage

Leading House

Paul Scherrer Institute (PSI)

Participating Institutions

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Eastern Switzerland University of Applied Sciences (OST)
Lucerne University of Applied Sciences and Arts (HSLU)
Swiss Federal Institute of Technology Lausanne (EPFL)
Swiss Federal Institute of Technology Zurich (ETHZ)
Swiss Federal Laboratories for Materials Science and Technology (Empa)
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Synthesis

In order to meet the climate protection goals, the future energy system must be based on renewable rather than fossil energy sources. Most renewables draw their energy from intermittent sources such as the sun and wind, which are dependent on the weather and the season. Such an energy system therefore requires a large amount of long-term and short-term HaE storage.

Challenges in the "Storage" action area

A growing share of renewable energy makes short-term and seasonal storage increasingly important. The action plan recommended concentrating future research on areas including the potential of compressed-air storage and (electro-)chemical energy storage such as H2 storage, synthetic gases and liquids, and batteries with high energy density. Based on this recommendation, the Federal Council defined the following areas for a potential SCCER in the Dispatch on the "Coordinated Energy Research in Switzerland" action plan[24]: fundamentals of power storage; batteries; efficient electrolysis; heat management; and mechanical, chemical and pneumatic storage technologies[25].

The SCCER HaE picked up and combined these research challenges, structuring the field into five WPs (see chapters below). While four WPs provided scientific and technological progress in the corresponding fields in close cooperation with industry partners, the fifth WP contributed the overarching view, including technological, economic and societal assessments and a consistent evaluation of the various demonstrators of this SCCER. Another major task was cooperation with other SCCERs, JAs and public authorities on better integrating storage technologies into the future energy system.

Vision and objectives of the SCCER HaE

The SCCER HaE's vision was of a completely defossilised energy system based on renewable energy supported by storage technologies and sector coupling. Within this broad framework, the vision was to develop technological solutions for various short-

[24] Kaiser T., Hotz-Hart B. and Wokaun A. (2012): Aktionsplan Koordinierte Energieforschung Schweiz. Report commissioned by the Interdepartmental Working Group on Energy (EDI – EVD – UVEK).

[25] Federal Council (2012): Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

term and long-term storage options, to provide as much information as possible through scientific results, demonstrators and assessment approaches, and to create a community of highly knowledgeable industry and research experts. The long-term aim was therefore to build up competences and technologies to help the Energy Strategy 2050 succeed. To be prepared for unpredictable conditions 30 years from now, the portfolio of storage solutions and competences has to cover a wide range and requires a sound scientific basis.

An analysis of today's energy consumption indicates that 50% of end-energy is used for heating purposes (domestic and industrial), 37% for transport and about 13% for various other applications. On the supply side, less than one-third of end-energy is electricity (including nuclear power); two-thirds is based on fossil carbon. To reduce consumption of the latter, all sectors need to be defossilised, by replacing fossil sources with renewable forms of energy such as PV, biomass, water and wind power and by increasing efficiency. Since the availability of waterpower and biomass is limited, PV and wind power need to be greatly expanded. However, these sources are strongly weather and season-dependent, meaning that the energy system needs large storage capacity.

Efficiency gains in the heating sector can be achieved using electric heat pumps and adapted storage systems. In the transport sector, new concepts such as electric vehicles based on batteries or fuel cells will replace the majority of today's cars and lorries. Aeroplanes and long-distance vehicles may rely on fossil-free synthetic fuels. In any case, more alternative energy from fossil-free sources is urgently needed, making better solutions for heat storage, batteries, hydrogen production and storage, and power-to-synthetic fuel processes an issue of key importance.

What was achieved

The SCCER made essential contributions, improving the technical performance of various energy storage systems in terms of efficiency, storage density or energy provision and investigating their significance for society. Feasibility was demonstrated in pilot plants, and marketability was also explored. Initially, many approaches were pursued at all levels. The most promising technologies were developed further to the next TRL, while others were discarded because they are still too fundamental to be relevant for the Energy Strategy 2050. In this process, solutions for the two major challenges were developed:

1. Short and medium-term storage of electricity and heat: the low-cobalt content Li-ion battery and the adiabatic compressed-air storage are two representative examples.

2. Seasonal balancing by means of heat storage or chemical energy sources. Examples are different heat storage concepts for buildings, which were investigated and developed into functional systems, and chemical energy carriers including hydrogen, the use of CO_2 as raw material for renewable methanol and methane, and the formic acid cycle.

The SCCER also created tools to answer critical questions regarding systemic issues and environmental compatibility. In various scenarios it was determined how the storage solutions should be developed, temporally and spatially, in order to sustainably satisfy energy demand at all times.

Contribution to Energy Research and to the Energy Strategy 2050

The SCCER started from a research landscape that was an archipelago of small independent islands but developed substantial synergies and avoided duplicating efforts. Fruitful collaboration between HEIs, such as universities of applied sciences, cantonal universities and institutions of the ETH Domain was established, including knowledge and staff exchanges, joint projects and publications. New professorships and research groups were established at EPFL, BFH, ETHZ, HSLU and UniBe. In phase 2 alone, a total of 43 PhD and 48 master's theses were completed, thus considerably increasing the number of young experts in the energy sector.

New infrastructure was built at demonstrator level and integrated into the national data network. Eight startups were founded in the various areas of this SCCER. The SCCER HaE researchers also collaborated with 48 international academic partners, nearly 100 international and national industry partners, including big players such as Shell, MAN and BASF, and 27 utility providers. The quality of the research work was generally very high by international standards.

All in all, this SCCER's contribution to the realisation of Energy Strategy 2050 is very important: it provided not only storage and conversion technology at TRLs ready for industrial implementation, but also tools for system assessment in relation to economic and environmental implications. The predictive tools are essential for both policymakers and industry.

Recommendations

based on the SCCER HaE's research findings

- Policymakers should create incentives to invest in renewable energy and storage by adopting duties and taxes for unsustainable technologies, applying a full-cost approach. Alternatively, they should subsidise sustainable technology to equalise the costs for comparable use cases – or do both – to avoid adverse conditions. This would lead to new business models and facilitate investment decisions for storage technologies.

- The legal framework should be adapted to allow for new concepts for storage systems, power-to-gas and power-to-liquid. The same applies to spatial planning and building legislation, which needs to take large underground storage installations into account. These are important for seasonal heat storage and adiabatic compressed-air storage.

- Research into materials has the great potential to make conversion more efficient and thus reduce energy storage costs. Corresponding funding opportunities should be ensured.

Results

WP 1 – Thermal Energy Storage

Leader WP 1
Dr. Andreas Haselbacher, ETHZ

About 50% of Swiss final energy is consumed for space heating, hot water and cooling in buildings and for industrial processes. Thermal energy storage key to substituting fossil with renewable primary energy sources, integrating the heating and electricity sector via heat pumps, and increasing the efficiency and flexibility of industrial processes.

Objectives

- Today, 80% of private households' energy consumption is for heat generation, and fossil fuels have high shares of the mix. The Energy Strategy 2050 suggests that 450,000 heat pumps with heat storage will be installed in Switzerland by 2035.

- Seasonal thermal energy storage can avoid considerable quantities of CO_2 emissions. The SCCER targeted decentralised, sensible latent heat and chemical storage facilities with reduced losses in buildings to increase self-consumption of energy from PV systems and relieve the power grid during periods of strong solar radiation. Within the SCCERs more broadly (HaE, CREST and FEEB&D), system configurations were evaluated.

- Industrial process heat also largely (70%) depends on fossil sources. Currently, this sector needs 19 TWh annually for process heat at different temperature levels, equating to 8% of total Swiss energy consumption. Thermal energy storage is an enabler for integration of renewables and increased process efficiency. Research focused on advancing short-term (hourly) latent heat storage. Tailored storage facilities for low-temperature industrial applications and combined sensible/latent heat storages for AA-CAES were developed.

What was achieved

Seasonal thermal energy storage requires cheap materials and small long-term losses to be cost-efficient and energy-efficient. SCCER partners investigated three different concepts:

Sensible heat storage is fairly cheap but has low efficiency. In their research, the SCCER partners concentrated on solutions that can be built in or near buildings, and ideally also as retrofit solutions for existing buildings. Storage tanks integrated into buildings should be as compact as possible. The tank volume can be reduced by up to 30% simply through optimised control of the charging and discharging processes.

HIGHLIGHT

DEMONSTRATOR FOR SENSIBLE HEAT STORAGE: 100 M^3 HEAT STORAGE TANK IN A BASEMENT ROOM.

HSLU and Swisspor analysed existing thermal insulation concepts and developed a new one. Underground rooms such as unused cellars or spaces used previously for oil tanks can be thermally insulated and sealed so that they can be filled with water and converted into seasonal heat storage. The materials developed consist of a combination of extruded rigid polystyrene foam and rigid polyurethane foam – materials normally used to insulate buildings. In this way, an unused basement room was converted into a 100 m3 water tank. The material used is designed for a maximum water column of six metres, a temperature of up to 65°C and a service life of 50 years. The storage is charged with heat from a heat pump or from solar collectors. Investigations are now examining how temperature and pressure in the tank can be increased to achieve higher energy density and improved economic performance.

Latent heat storage uses the phase change of a material, in this case melting of ice, to charge the storage medium. In combination with solar heat and heat pumps, ice storage systems can be used both for heating (as a heat source for heat pumps) and for cooling (as a heat sink for free cooling). To prevent a layer of ice forming on the heat exchanger during discharging, a “de-icing” processes was successfully developed and tested. A 200 m3 demonstrator was implemented in a residential and commercial park office building.

Another concept for seasonal heat storage is sorption storage based on caustic soda (lye). The major advantage of such a concept is loss-free storage and high storage density. Only liquids are involved in the process; these can be pumped into movable tanks. Power and total energy amount can be scaled independently. Aqueous sodium hydroxide solution has achieved the best performance so far and is inexpensive.

Fundamental research revealed a deeper understanding of the liquid sorption process under technically relevant conditions. The research team tested several designs for a horizontal tube bundle falling film system, optimised the flow and sorption processes of the liquids, and improved heat transfer and surface wettability. A second design approach used vertically mounted, spiral-finned tube heat and mass exchangers. Although not yet been complete, these studies have already led to design optimisations. The insights gained will be used to build a storage system with a discharge capacity of 5 kW for a single-family home.

HIGHLIGHT

ENCAPSULATED PHASE CHANGE MATERIAL FOR WATER STORAGE TANKS AND FORMATION OF A SPIN-OFF

This novel and promising latent heat storage development has already led to a spin-off company (COWA). Capsules that contain phase change material are filled into the water storage tanks of existing heaters, quadrupling the storage capacity. This helps to increase self-consumption of PV electricity in combination with a heat pump.

Also supported by BMS Energietechik AG and Gebert Rüf Stiftung

For hot water supply and industrial heat storage, energy density is less important than for seasonal storage; here, the discharge power is the key for the application. The SCCER set out to develop affordable and sustainable high-power latent heat storage systems that can be charged and discharged quickly and flexibly with high capacity. The team pursued four concepts: immersing of the heat exchanger in the storage material, storage in capsules, handling of phase change material in dispersion, and direct contact of latent heat storage material with heat transfer fluid. The first concept is the most advanced and is already commercially available.

SCCER researchers combined their expertise in the development of latent heat storage for high temperatures. The work focused on macro-encapsulated (steel) metal alloys. Experimental and modelling work included four scales: at interface scale, long-term material stability was investigated; generalised heat transfer correlations were derived from phase change modelling of the encapsulated material; a unit-scale setup was used to assess heat transfer; and advanced latent heat storage can be evaluated in a MJ-scale test bed.

Finally, the world's first pilot project of an advanced adiabatic compressed-air energy storage (AA-CAES) application was successfully tested. Exploiting a disused transport tunnel of the Alp Transit project, the plant stored 1 MWh of electric energy. An overall plant model allowed for technical and economic evaluation. Integrating thermal storage led the overall electric storage efficiency of this pilot plant to be increased from 50% to 75%, even though the additional thermal storage only accounted for 6% of the investment costs (see more under Highlights).

HIGHLIGHT

HIGH-TEMPERATURE PHASE CHANGE HEAT STORAGE UNIT FOR THE AA-CAES PROJECT

The combination of sensible and latent heat storage made the advanced adiabatic compressed-air storage project (AA-CAES) a success that was visible worldwide. For the 170 kWth phase change unit, an alloy of aluminium, copper and silicon was encapsulated in 296 stainless steel tubes. The teams at EPFL and SUPSI tested ageing in experiments lasting several months to predict ageing effects. A thin ceramic protective layer inside the stainless steel shell extends the service life. Porous ceramic foams on the encapsulation significantly improved the heat-transport properties and made the storage unit more compact. ETHZ developed the 5 MWth sensible storage system using a packed bed of pebbles and systematically investigated methods for thermocline control.

also supported by the SNSF, the SFOE, Sika Technology AG, Amberg Engineering AG, MAN Energy Solutions Schweiz AG, BKW, ALACAES, Azelio, EngiCer SA, deCavis and Alacaes

Contribution to the SCCER's objectives

This WP further developed various heat storage concepts and realised them in demonstrators, thus proving the feasibility of implementation from a scientific and engineering perspective. Seasonal sensible heat storage was developed with implementation partners, demonstrating that transfer into practice is already ongoing. For others, such as high-temperature heat storage, industry partners need to be heavily involved to bring the technologies to TRL 9, since manufacturing and mass production issues are the next steps. The WP’s three startups (Scaloric, COWA and Synhelion) demonstrated successful KTT. Communication between industrial process owners and the research community was enforced by contributing to the Forum Energiespeicher Schweiz and by organising an annual conference on heat storage for stakeholders. All these activities are fully consistent with the SCCER HaE’s objectives.

As was the original intention, very close collaboration between different institutions developed under this WP. The collaboration of ETHZ, EPFL and SUPSI in the AA-CAES project and the combination of different funding programmes (NFP70, Innosuisse, SCCERs and the SFOE) are perfect examples of synergies and added value. The collaboration on the sorption-based storage concept between Empa and OST, building on their previous collaboration in the EU project COMTES and the IEA SHC Task 58/ECES, is a further case in point. Joining forces with WP 5 and other SCCERs to identify technological and economic prospects for energy storage in buildings led to a better understanding of the relevance for the Swiss energy system, not only in the heating sector but also for the integration with renewable electricity. In addition, this WP developed very strong industrial collaborations with various national and also international enterprises (e.g. MAN).

Assessment of the achievements

Overall, this WP's research into thermal energy storage within the SCCER HaE was well focused on applications with high relevance for the Energy Strategy 2050. All the results are very valuable, and many are at high TRLs. The collaboration between the various working groups, the assessment group and other SCCERs and with industry partners was exemplary and hence successful in all respects.

Nearly all activities progressed well in accordance with the original work plan and resulted in numerous demonstrators. Only the development of the chemical heat storage approach based on sodium lye proved more challenging than expected; a step back to a lower TRL was necessary, causing some delay. Nevertheless, the promised 5 kW demonstrator unit will soon be implemented at Empa's NEST building.

On international level, the results of this WP are state-of-the-art, and in some cases even world-leading. For example, the AA-CAES development and the high-temperature heat storage concepts are unique selling points of this SCCER. Organisations in Japan and Austria are highly interested.

WP 2 – Advanced Batteries and Battery Materials

Leader WP 2
Prof. Dr. Petr Novak, PSI

Battery storage plays an increasingly important role in today's society, not only for numerous mobile electrical instruments in households and industry, but also for various transport issues – not least electric vehicles. Batteries have therefore become a key issue for industrial development and energy strategies.

Objectives

- Rechargeable batteries are highly important for the Energy Strategy 2050, since the increasing integration of intermittent renewable electricity into the mobility and electricity grid sectors requires storage of electricity under various conditions. This makes the environmental and economic aspects of batteries fundamentally important. Three key parameters are relevant for the use and impact of batteries: energy density, durability and cost. These parameters depend mainly on the set of materials the battery is composed of. Within WP 2, anode, cathode and electrolyte materials were investigated for lithium-ion (Li-ion) and sodium-ion (Na-ion) batteries, complemented by manufacturing research to optimise manufacturing processes.

- Li-ion batteries are in wide use and manufactured in large volumes. Even incremental improvements are quick to be implemented in the near future. The same is true for manufacturing concepts designed to be plugged into existing processes. Na-ion-based systems are on the fringes of market implementation in certain niches, but this is a promising system, composed of readily available materials and suitable for high-power applications.

What was achieved

For the Li-ion system, the researchers succeeded in developing new cathode materials with low cobalt content and an optimised particle size. They only contain one-third cobalt – a critical raw material which is toxic, expensive and also geopolitically problematic because of ethical concerns regarding cobalt mining. The research team can now produce several hundred grams of this superior cathode material per batch. The results promise that scaling up towards mass production is possible within the next few years.

HIGHLIGHT

THICK ELECTRODES FOR INCREASED ENERGY DENSITY ON CELL LEVEL

Thick positive and negative electrodes with high energy density were developed. For instance, Empa and ETHZ, in conjunction with the industry partner Belenos, demonstrated high areal capacity and initial coulombic efficiency with high-mass-loading graphite-based electrodes. Combined with high-mass-loading cathodes, also developed within WP 2, such batteries achieve a capacity of about 90% after 300 cycles, suitable for applications with few cycles. The researchers are currently developing an electrolyte with higher conductivity of lithium ions, which should enable more cycles, at faster speeds using thick electrodes. These electrodes are components of a demonstrator cell in a pilot plant and are in line with international battery roadmaps towards 275 watt hours per kilogram and a storage capacity twice as large as the current standard graphite-based anodes.

Also supported by Belenos

Lower cobalt, and thus higher nickel, content in the cathode materials allows better use to be made of the available lithium. As a result, the energy density of the battery increases, while the overall costs are reduced. However, there is a disadvantage that cathode materials with little cobalt content decompose the electrolyte faster due to the enhanced surface reactivity. To solve this problem, novel electrolyte additives were developed which are stable in the more reactive low-cobalt and nickel-rich environment. The batteries now reach about 90% of their original capacity after 400 cycles. This is still far too low for mass production, but researchers all over the world expect that low-cobalt or even cobalt-free lithium-ion batteries will come onto the market within a few years. Thus, a cobalt-free material with high specific capacity has been successfully synthesised, paving the way to completely cobalt-free batteries.

Given the ongoing efforts to build Li-ion batteries with higher volumetric energy and power densities, the research into enhancing Li-ion transport within compressed high-mass-loading electrodes at fast cycling conditions is imperative. WP 2 researchers demonstrated that the rate capability of graphite electrodes with high areal capacity can be considerably improved by laser patterning, specifically by the fabrication of arrays of vertically aligned channels serving as diffusion paths for rapid Li-ion transport. The resulting laser-patterned graphite electrodes delivered a volumetric capacity enhanced by 14% compared with that of non-patterned electrodes.

HIGHLIGHT

MANUFACTURING OF BATTERY CELLS

Manufacturing processes today are not optimised and not very flexible when it comes to dimensional customisation of the cell geometry. In WP 2, a process model for a battery factory was created and parametrised by BFH with input from an industry partner. Rate-limiting steps and costly processes were identified and optimised in this way. The success of this approach could reduce costs by 50%. For the customisation of cell geometries, laser cutting was suggested and the hardware was assembled and optimised for high throughput. For multiple cells, the stacking process of the material – the rate-limiting step – was also optimised, making the process faster and more precise than the original z-folding.

Na-ion batteries are very promising for future battery generations, partly because the resources needed for this technology are geopolitically easy to access. WP 2 therefore investigated Na-ion batteries from the very beginning. The basic principle of operation is identical to that of Li-ion batteries but, due to the different characteristics of Na compared with Li-ions, the electrode materials and the electrolytes need to be redesigned to be suitable for the Na-ion system.

HIGHLIGHT

LIFECYCLE ANALYSIS OF NA-ION BATTERIES

The achievements regarding Na-ion batteries in phase 1 and early phase 2 made it possible to compare the properties of Na-ion battery cells achievable in the near future with Li-ion batteries as they are today. Comparing the lifecycles and studying the economic characteristics showed that Na-ion batteries based on the known materials would not be competitive with Li-ion batteries in terms of specific energy, costs and production-related GHG emissions. The research team therefore decided to look for radically new materials to push Na-ion batteries to a higher level of performance. Novel Co-free and Li-substituted materials are now under investigation and are expected to lead to the realisation of competitive Na-ion batteries.

Anode materials: The task here was to find a material that stores the relatively large sodium ions. Carbon has proved particularly suitable, though not in its ordered form of graphite but rather in a disordered form, as it occurs in coal. The researchers found biowaste to be a highly interesting alternative. This can reduce costs and contribute to a sustainable circular economy. Such anodes achieved a very high specific charge and have high discharge rates, giving hope for high-performance batteries.

Cathode materials: The researchers decided to modify the proven layered oxides in such a way that they could do without cobalt. The result of the development efforts is a cobalt-free electrode, which is inexpensive, non-toxic and exhibits good electrochemical properties.

In parallel, the researchers examined variants with environmentally friendly water-based electrolytes with high concentration of salt. Such concepts are interesting for applications where safety is of paramount importance and energy density is not crucial. They extended the stability window of the electrolyte from 1.23 to more than 2 volts, thereby ensuring a higher specific energy than for conventional water-based battery cells. Applying this in combination with selected electrode materials, the development team achieved very good results with exceptionally high capacity and excellent cycle stability.

Contribution to the SCCER's objectives

Batteries are key elements of the future energy system, because they are relevant for short-term balancing of supply and demand in the electric grid, for e-mobility and for many other energy applications. Economic and lifecycle aspects call for long-lasting and stable systems based on readily available materials. The progress made in this WP, both on Li-ion and Na-ion type systems and on the manufacturing technology, contributes to the Energy Strategy 2050.

The material upscaling and the development of low-cobalt electrode materials are results on advanced TRLs, which are ready to be implemented by industry. Collaboration with Belenos, Battrion and others is ongoing. In terms of dissemination and KTT, the establishment of the BATTMANN association is another highlight, connecting private enterprises, research and public institutions along the value chain.

The initial goals were essentially reached, but some readjustments were substantial. For instance, a shift in priorities occurred early in phase 2, based on the results obtained in collaboration with WP 5. The focus was shifted towards low-cobalt electrode compositions and more fundamental activities related to the sodium-ion system.

The WP increased its international visibility, e.g. by organising the Swiss Battery Days and through publications in peer-reviewed journals. The research topics were in line with the battery development roadmaps of various international organisations and represent the state of the art.

Assessment of the achievements

High-level scientific results were achieved in WP 2, ranging from fundamental studies into battery materials right through to the development of pilot cell production. The interaction between the scientific/technical part of the programme and the societal aspects produced some very interesting results providing a good base for decisions on possible battery materials. The efforts of this WP were well focused compared with the widespread nature of international activities. However, transfer activity suffered from a lack of large Swiss manufacturers of battery cells.

In summary, WP 2 is an important part of the entire SCCER HaE, as large-scale batteries will be an integral part of a renewable energy system, requiring competence in the field. It is hoped that now the research is established in the participating institutions and good collaborations have been formed, this research will be continued successfully. Young scientists and entire research groups will be available to support the energy transition when knowledge on batteries is required. The build-up of competence within Switzerland is thus one of WP 2's major achievements.

WP 3 – Hydrogen Production and Storage

Leader WP 3
Prof. Dr. Andreas Züttel, EPFL

Hydrogen is highly likely to play a very important role in future energy systems and hence is of prime importance for the Energy Strategy 2050. Hydrogen will be an important energy carrier, needed for fuel cells for transport, delocalised stationary electricity production and direct combustion and as feedstock for power-to-gas/fuels/chemicals.

Objectives

Despite its importance for future energy systems, hydrogen also has shortcomings which currently limit its use: sustainable production is an economic challenge, and hydrogen storage is still problematic because the small volumetric energy density of gaseous hydrogen limits its application due to transport and safety issues. The WP tackled both aspects through material research and by studying processes.

- For hydrogen production, alkaline electrolysis, photo-catalysis and a chemical discharge of a redox flow battery were developed.
- Hydrogen storage was addressed by two different approaches: one is based on hydrogen in complex hydrides (chemical bond) and on hydrogen adsorption (physical, Van der Waals interaction); the other uses formic acid as a liquid hydrogen carrier, formed and decomposed by a catalytic process.

What was achieved

The global share of hydrogen production by water electrolysis is currently only 4%; 95% is produced from fossil fuels. However, green hydrogen produced by electrolysis using electricity from renewable sources is needed for climate protection. The main reasons for the small proportion of electrolysis are the low current density and a low degree of purity. WP 3 thus focused primarily on the development of cost-effective electrodes with improved oxygen evolution reaction (OER) properties and on the improvement of separators for alkaline electrolysers.

HIGHLIGHT

UNINTERRUPTABLE POWER SUPPLY SYSTEM BASED ON FORMIC ACID

WP 3 researchers developed long-lasting catalysts that do not require expensive, rare raw materials or additives to split off hydrogen from formic acid. Together with an industry partner (GRT Group), a system was set up that converts formic acid into CO_2 and hydrogen with sufficient speed and purity. This refrigerator-sized system called HYFORM-PEMFC contains everything that is needed to generate electricity from formic acid, including a compact reformer that provides enough hydrogen for an 800 W fuel cell, which generates electricity – cleanly, safely and energy-efficiently. The patented system is now in production and serves as an uninterruptible power supply for remote locations. Such a hydrogen storage concept is sustainable if the formic acid is produced climate-neutrally using optimised catalysts and processes as pursued by WP 3.

One important measure is the electrical voltage at which the electrolysis takes place. The difference between the actual and the theoretical voltage – the overpotential – limits the efficiency of alkaline electrolysers. WP 3 investigated a number of materials, including phosphates, borates and oxides, all of which showed a sufficiently low overpotential and a satisfactory OER performance. Metallic electrodes based on iron, nickel and/or cobalt also re-emerged as promising cost-effective anodes due to their simplicity and the formation of a highly active oxy-hydroxide surface catalyst layer. Systematic investigation enabled the ideal anode composition to be identified, supporting the optimisation of commercial devices.

Two further methods to produce green hydrogen were developed, both embedded in a concept to store hydrogen. The first uses formic acid that has been produced climate-neutrally as storage fluid and splits off the hydrogen, e.g. for use in a fuel cell, keeping the remaining CO_2 for reuse. The second is based on a dual-circuit redox flow battery which can also release hydrogen in a very controllable manner.

The challenge of storing hydrogen is to compress the very large volume of the gas at room temperature to a small volume by adding as little weight as possible. Traditional approaches compress the gas to high pressure or to liquefy it below –241°C. WP 3 researchers selected a third option, also being pursued in other laboratories worldwide, i.e. increasing the density of the gas molecules by having them interact with another material. Three different routes were successfully followed.

One route is chemical binding in complex hydrides. Some hydrides, e.g. aluminium or sodium borohydride, a liquid at room temperature, reach large hydrogen densities far beyond the densities of compressed or liquid hydrogen. However, for these borohydrides the binding energy is slightly too high to release hydrogen at ambient temperature when it is needed as gas again. In addition, the remaining elements of the borohydrides tend to crystallise and hinder reabsorption of hydrogen. Crystallisation was successfully prevented by depositing small islands of sodium borohydride on graphene, and through interaction with an ionic liquid hydrogen desorbs at a much lower temperature.

HIGHLIGHT

DUAL-CIRCUIT REDOX FLOW BATTERY

An alternative way to produce hydrogen as part of an energy storage system is via the modification of a redox flow battery. WP 3 developed the concept of a dual-circuit redox flow battery into a demonstrator. On the negative side of the electrochemical cell, an electrolyte is oxidised on a molybdenum catalyst, producing hydrogen with almost 100% efficiency. On the positive side, a different electrolyte is reduced in a second electrochemical cell that is a kind of electrolyser but needs an electric boost to raise the potential for water splitting. This "electrolyser" has the advantage that the "charged" electrolytes can be stored until hydrogen is demanded or, if electricity is needed, the electrolytes can also be discharged like a battery.

Also supported by the Centre de Recherches Energétiques et Municipales CREM, the City of Martigny and Sinergy

The second route was physisorption of hydrogen in graphene oxide carbon nanotubes. This graphene oxide with a tubular structure of nanosize stores five weight percent hydrogen at room temperature at a pressure of 50 bar. This corresponds to the storage capacity of a composite tank at 700 bar. The hydrogen is also easily released from the storage material. Collaboration with an industry partner was therefore started in order to commercialise this storage concept.

An alternative third approach was the development of a compressor for metal hydrides working without moving parts. An appropriate metal hydride absorbs hydrogen at a temperature of 20°C and a pressure of 3 bar and releases it again at 100°C with 25 bar or at 225°C with 200 bar. The pressure of the hydrogen can thus be increased simply by increasing the temperature. This compressor technology is already being commercialised by GRZ Technologies SA, an EPFL startup, in cooperation with Burckhardt Compressor and Messer Switzerland.

HIGHLIGHT

SMALL-SCALE DEMONSTRATOR

To assess the feasibility of an fully independent energy system, different types of solar cells, batteries, electrolysers, methanol, a metal hydride storage, a compression system and a CO_2 capture unit were plugged together. The average power of the installation was set to 2 kW, corresponding to the energy consumption of a single person. The installation enabled the energy flows and the interaction between different components to be studied, comparing the performance of competing technologies and establishing a database from the real world. The operating parameters pressure, temperatures and energy flows were also recorded at different locations to enable system modelling and advanced optimisation.

Also supported by the Canton of Valais, Gaznat SA, Energie Sion Région (ESR, now OIKEN) and Diamond Lite S.A.

Contribution to the SCCER's objectives

The sustainable provision and storage of hydrogen could become the backbone of a sustainable energy system. The investigated approaches to storing hydrogen and to producing it with electrocatalysts or photocatalysts based on abundant materials contributes to this vision and the Energy Strategy 2050. Transfer into practice is already taking place, the automotive industry is interested in hydrogen storage, and a startup for hydrogen compression and storage (GRZ) was founded. The findings on electrode composition for the oxygen side of electrolysers is about to be transferred to industry, while the prototype for a formic acid-based uninterruptable power supply (HYFORM-PEMFC) was integrated into the GRT Group's portfolio. The technology on nanomaterial for hydrogen storage was successfully licensed to Aaqius for a period of three years. This, the startup and the methanation reactor developed with GAZ Nat are good examples of successful KTT. In terms of knowledge transfer, also the HYDROPOLE association and the annual conference, taking place alternating in Switzerland and Japan, should be mentioned.

WP 3 successfully worked on innovative electrode materials and new approaches for electrolysis based on renewable electric power as well as on electrochemical and photochemical production technologies. Upscaling from lab units to prototypes/demonstrators and then industrial scale was successfully pursued. It emerged that deeper knowledge of the highly relevant catalytic steps at interfaces was central for success. New studies on reversible hydrogen storage processes resulted in the discovery of sorption of hydrogen by solids made of oxidised graphene and carbon nanotubes.

Assessment of the achievements

Two of the main aspects of the hydrogen topic are generation of green hydrogen and better storage. Both aspects were thoroughly addressed in WP 3's work plan and treated in an appropriate, highly innovative and very successful way. This work resulted not only in internationally highly respected publications and conference contributions (by invitation), but also in two international and two national patents, four spin-off companies, intensive collaboration with industry, and several prototypes and demonstrators, including the industrial prototype HYFORM-PEMC. In addition, strong ties with municipalities in and around Sion were developed, including the installation of a hydrogen fuelling station.

This WP's progress surpassed the original work plan. The development of the dual-circuit redox flow batteries encountered some unforeseen challenges on the positive side. In terms of international competition, the WP is at the cutting edge of research and internationally highly recognised. The WP 3 groups collaborated with the battery materials group on the topic of ionic liquids and with the assessment group (WP 5).

WP 4 – Catalytic and Electrocatalytic CO_2 Reduction

Leader WP 4
Prof. Dr. Christophe Copéret, ETHZ

More than 5% of fossil oil is currently used in the chemicals and pharmaceutical industry, where hydrocarbons cannot be substituted. Complete substitution in the transport sector is also unlikely from today's perspective. We will therefore need hydrocarbons which can be produced climate-neutrally by CO_2 reduction in the future.

Objectives

To defossilise the chemical and pharmaceutical industries and the mobility sector completely, the required hydrocarbons have to come from biomass, or be synthesised from CO_2 and water. The amount of biomass in Switzerland is fairly limited. This means we will certainly have to produce hydrocarbons by means of CO_2 reduction and so must improve the existing production processes considerably, making them more efficient and competitive.

This WP's research was dedicated to major progress in this direction. The concept of using CO_2 as a starting point was in fact underexplored when the SCCER was constituted. The plan was to take some known fundamental chemical/electrochemical reactions at TRL 1–2, and develop them into processes able to be implemented at technically relevant scales.

Three main routes were investigated:

- homogeneous catalytic reactions involving CO_2 and transforming them into heterogeneous catalytic processes;
- thermochemical processes of CO_2 and hydrogen on supported metal catalysts;
- electrochemical processes, to convert CO_2 and water in an electrolyser configuration into hydrocarbons.

What was achieved

Collaborating research teams in WP 4 investigated the hydrogenation of CO_2 to methanol using copper (Cu)-based heterogeneous catalysts at medium pressures and temperatures. Currently, most CO_2 hydrogenation catalysts are based on Cu for CO hydrogenation to methanol. Despite more than 50 years of research, the roles of the various components are still poorly understood. In particular, these catalysts suffer from low activity and stability under CO_2-rich conditions and are less selective towards methanol synthesis. Alternative Cu-based catalysts have shown promising catalytic activities that greatly vary with catalyst composition. The origin of the increased activity and selectivity of Cu-based catalysts for CO_2 hydrogenation was successfully investigated. Detailed spectroscopic studies on these tailored catalysts enabled the roles of each promoter at molecular level to be understood and guiding principles to be elaborated. The role of copper nanoparticles was shown to be critical for the selective conversion of CO_2 to methanol.

HIGHLIGHT

INDUSTRIALLY VIABLE HETEROGENEOUS SYSTEM

In one of the processes investigated, CO_2 is dissolved in a liquid phase and reacts with a relay molecule such as an amine, which is subsequently converted to methanol with the addition of hydrogen, while regenerating the original amine. The binding of CO_2 and the elimination of methanol via an intermediate can also be carried out with the help of a homogeneous catalyst. In both cases, a key challenge has been the separation of the product and the reuse of the catalyst and/or amine. The research group directed its research efforts towards industrial viability, successfully producing the catalytically active compound in the form of a solid that is more easily separated from the liquid. The investigations resulted in a startup, Plastogaz SA, which formed a business case around the efficient transformation of different types of plastic waste, e.g. polypropylene, polystyrene, polyethylene and mixtures thereof, into methane. The founders are in the process of raising funds to develop and commercialise the process.

Also supported by the SNSF and the Gebert Ruf Stiftung

These insights enabled improved catalysts made of copper nanoparticles and tailored supports to be developed, which demonstrate unprecedented methanol selectivity under milder conditions compared with conventional industrial catalysts. The finding led to an Air Liquide award and research grant and to the start of a research programme with Air Liquide.

WP 4 proved that CO_2 electrolysis is possible and that this process can be successfully performed in the laboratory. This concept is particularly noteworthy because the choice of the catalyst determines the desired product of the reaction. For example, with gold a co-electrolyser of this kind produces carbon monoxide; with copper, methane. Different hydrocarbons can be generated by varying the current density. The catalyst also determines how energy-efficient the process is. At the beginning of the project, the reliable knowledge was scarce. Combined efforts and strong collaboration revealed, for example, that a copper oxide catalyst preferentially produces ethylene due to its greater roughness. Building on these findings, researchers are currently focusing on various catalytic materials with different compositions and structures, such as aerogels, which have extremely porous structures.

HIGHLIGHT

ELECTROCHEMICAL CO_2 REDUCTION BROUGHT FROM THEORY INTO A DEMONSTRATOR

Another focus was on the technical implementation of electrochemical co-electrolysis. Two processes had to be coupled: the reduction of CO_2 on the cathode side and the oxidation of water on the anode side – separated by an electrically insulating, ion-conducting layer, the electrolyte. In recent years, the researchers have succeeded in developing a completely new cell design for CO_2 electrolysis with CO_2 in the gas phase. This solves a critical, hitherto unresolved problem, i.e. avoiding CO_2 migrating to the anode side in an undesirable way. This is achieved by introducing a bipolar membrane system (electrolyte) in a newly developed cell design. This system not only suppresses the pumping of CO_2 to the anode side, but also improves overall efficiency considerably. The concept has been patented. The group is currently working on further improvements, for example to increase the selectivity for specific hydrocarbons, or to refine the water management.

Also supported by the SNSF and Shell

WP 4 also explored ionic liquids as a promising class of electrolytes, able to dissolve large concentrations of CO_2 and act as co-catalysts in the reduction of CO_2. Through systematic studies, the research group succeeded in defining the key features of ionic liquids that result in optimal activity.

Further efficiency losses in CO_2 electrolysis are caused by the slow reaction at the anode. To accelerate the kinetics, the noble metal catalysts usually contain iridium dioxide – the most powerful and stable catalyst for this reaction. However, iridium is expensive and rare. To make CO_2 electrolysis economical, new electrocatalysts must be found. For operation in acidic environments, researchers developed nanoparticles made of iridium dioxide with an average diameter of 1.5 nanometres. They achieved the same performance with reduced iridium content. "Pyrochlores", which also contain base metals, were investigated as an alternative. These are highly active and stable in the OER even with a considerably reduced amount of iridium.

More catalysts are available in alkaline environments. One well-known family – metal oxides in perovskite structure – was found to be very promising. The research team produced perovskite nanoparticles with these materials for the first time, some of which demonstrated excellent performance in terms of stability and electrochemical activity, including in commercial facilities. They worked more reliably than a traditional iridium oxide catalyst.

Contribution to the SCCER's objectives

The WP 4 researchers invented and demonstrated new ways to provide sustainably produced, climate-friendly hydrocarbons, thus offering opportunities to defossilise the chemicals and pharmaceutical industry and the transport sector. Hydrocarbons are also a convenient option for seasonal energy storage. The achievement, taking the very fundamental concepts of CO_2 chemistry and developing processes close to industrial implementation, is an invaluable contribution to the Energy Strategy 2050. The relevance of this research direction is confirmed by the industrial engagement from large chemicals (BASF), oil industry (Shell) and process development (Air Liquide) players. Market implementation of the finding was also actively pursued by the startup Plastogaz SA.

Intra-WP collaboration was well-established, and many tasks were shared among various groups within the WP. One prominent example is the electrode synthesis and material characterisation by one partner at a low TRL, complemented by the setup development and characterisation by another partner at a higher TRL. This WP also collaborated with the battery materials group on the topic of ionic liquids.

The collaboration with implementation partners was also remarkable, since this WP's research was more fundamental in nature than that of other WPs. Big players in the oil industry are interested in and support the research through cash contributions and expertise. While SMEs are attracted by higher TRLs, R&D operations of large, international companies are interested in collaborating on more future-oriented research topics.

Assessment of the achievements

The work by the WP 4 researchers was very good. They essentially fulfilled all promises of the initial work plans. WP 4's research has high international recognition and is highly regarded by the research departments of large companies. The results obtained are innovative and original, i.e. at the forefront of international research and development. This is borne out by the high number of leading publications in highly ranked journals and by numerous invitations to WP 4 scientists to international conferences.

Furthermore, the research is oriented towards increasing the TRL, collaborating with industry laboratories to improve real production processes and to establish processes that are economical, resource-saving and environmentally friendly. Although some of the results are still far from implementation in the present energy system, they are highly relevant for its future development and hence for the Energy Strategy 2050.

WP 5 – Assessment of Energy Storage

Leader WP 5
Prof. Dr. Jörg Worlitschek, HSLU

Requirements for and benefits of energy storage – whether thermal, electrical or chemical – must always be assessed in the wider context of the energy system taking socio-economic and environmental aspects into account. This enables distinct technological advances and technology demonstrations to be made on the way to market introduction.

Objectives

The assessment of energy storage was planned and performed on three nested levels: technology, energy system and socio-economic. It enables strategic planning and supports Swiss policymakers and industry in taking timely action.

The activity was strongly supported by embedded and interlinked technology and system demonstrators at TRLs of 4–7. There were strong links with the SCCER CREST, JASM and JA Coherent Energy Demonstrator Assessment (CEDA)

- At the technology level, the research sought to provide a comprehensive and consistent environmental and economic assessment of energy storage technologies for various applications.
- At the energy systems level, the analysis aimed to enable the feasibility and value of energy storage to be determined, depending on geographical scale and boundary conditions.

What was achieved

Tools and models to assess the socio-economic questions related to the energy system were developed and then refined and extensively applied. A large base of field data was established, and energy system models were created. The findings were published in many peer-reviewed publications.

HIGHLIGHT

RENEWABLES INTEGRATED INTO THE SWISS ELECTRICITY SUPPLY SYSTEM «ISCHESS»

In one of the processes investigated, CO_2 is dissolved in a liquid phase and reacts with a relay molecule such as an amine, which is subsequently converted to methanol with the addition of hydrogen, while regenerating the original amine. The binding of CO_2 and the elimination of methanol via an intermediate can also be carried out with the help of a homogeneous catalyst. In both cases, a key challenge has been the separation of the product and the reuse of the catalyst and/or amine. The research group directed its research efforts towards industrial viability, successfully producing the catalytically active compound in the form of a solid that is more easily separated from the liquid. The investigations resulted in a startup, Plastogaz SA, which formed a business case around the efficient transformation of different types of plastic waste, e.g. polypropylene, polystyrene, polyethylene and mixtures thereof, into methane. The founders are in the process of raising funds to develop and commercialise the process.

Also supported by the Research Center for Energy Networks, the Competence Center Energy and Mobility (CCEM) and swisselectric research

At technological level, an important study was performed into the climate and cost-related performance of storage technologies, specifically batteries, AA-CAES, pumped hydro and P2X. This study is a milestone, not only because it was a collaboration between all groups within WP 5, but also because it classified the different technologies and their sweet spots. Batteries were found to be most economical and climate-friendly for short-term storage, while P2X is best suited to seasonal storage. AA-CAES and pumped hydro have similar characteristics and outperform the other storage technologies for medium-term storage requirements.

Power-to-gas was investigated with regard to lifecycle analysis (LCA) and economics. Na-ion and Li-ion batteries were compared in collaboration with WP 2. The results of the latter study were important as they concluded that Na-ion batteries have half the energy density of and therefore need twice as much material as Li. Although the materials needed for Na-ion batteries are less toxic, less critical and release less GHG in their production, the lack of energy density renders Na-ion technology less climate-friendly and more expensive than today's Li-ion technology. The findings triggered a reassessment of the WP 2 roadmap and stressed the benefit of interdisciplinary research.

Various analyses of storage technologies at energy system level investigating costs and economics were performed within the SNSF Swiss Store project. Examples include decentralised prosumer-based battery storage, but also large decentralised storage. On the way from technology to system level, a broad assessment of thermal energy storage (TES) was conducted for the sector coupling of renewable energy at residential scale. The study confirmed the superiority of thermal storage over batteries on cost and environmental impact grounds. TES was found to be a perfect match for further integration of renewables and reducing the carbon footprint of the heating sector.

HIGHLIGHT

DEMONSTRATORS

The prototypes and demonstrators developed and assessed in this WP prove the maturity of the technologies and provide important figures for future decisions, layouts and investments. The ESI (PSI), HEPP (OST), Mobilis (EPFL, Sion), SSDS and NEST/Mobility demonstrators are highlights not only for the SCCER HaE, but also for other SCCERs (Mobility, BIOSWEET, FEEB&D) jointly working in JA CEDA. All demonstrators were actively advertised as showcases for new technologies and presented to the public via guided tours, an important part of KTT. On the technological side, new concepts, such as high-temperature electrolysis to boost the efficiency of methanation, gas purification and sensor technology proved their roadworthiness. The results from demonstrators led to improved data for system modelling and to real-life information required for economic assessments.

Also supported by several organisations and companies

Within the ELEGANCY project, the role of hydrogen (and other storage and flexibility options) within the Swiss energy system was evaluated for different scenarios, including a net-zero CO_2 emission system by 2050. The analysis showed that deep defossilisation based on substantial expansion of renewable electricity generation – predominantly intermittent solar PV – requires a lot of energy storage: hydrogen, synthetic fuels and other flexibility measures such as demand-side management. Negative emission technologies, permanently removing CO_2 from the atmosphere, are also needed in net-zero scenarios. In general, energy storage and other flexibility measures reduce system costs and dependency on energy imports and increase resilience.

The top level of the assessment activities related to the design of policies to support innovation and new technologies. It was found that for young technologies the learning curve (change in cost as a function of installed quantities) varies widely, from almost no cost reduction as volume increases up to 30% per doubling of the volume. Watching the learning curve helps to assess the potential and competitiveness of future technologies.

Finally, this WP together with representatives of other WPs played an essential role in JA White Paper on the Perspectives of Power-to-X technologies in Switzerland (see page 273). The White Paper and the Supplementary Report summarised the cost, environmental impact and sector coupling aspects of the P2X technologies.

Contribution to the SCCER's objectives

WP 5's numerous models and data collections make an invaluable contribution to the implementation of the Energy Strategy 2050. The various parts of the complex energy system and the economic and social dependencies of the electricity, heat and mobility sectors require interdisciplinary approaches and flexible modelling tools to guide the transition. WP 5 provided numerous tools and assessments to guide the necessary decisions.

Industry has already taken up some of the results; for example, utility providers found niches to produce methane from hydrogen and CO_2. The Swiss gas industry organisation (VSG)'s announcement that it will increase the share of renewable gas to 30% by 2030 and the erection of a power-to-gas plant in 2021 indicate that the concepts will be implemented.

Within KTT, the demonstrators are opportunities for guided tours for public, politicians and industry, and therefore play an essential role in dissemination. The ESI platform even acts as a mobile demo unit that is taken to fairs and exhibitions. WP 5 had a large number of industry partners, and the connections were well established.

WP 5 enjoyed strong links with the other WPs, especially WP 1 and WP 2, and with most other SCCERs; hence numerous joint publications and project proposals were developed. The collaboration with other SCCERs benefited from JA CEDA and JASM. The collaboration between a cantonal university (Geneva), the ETH Domain and universities of applied sciences (OST and HSLU) developed very successfully.

The implementation partners, public and policy sectors, utility providers and SMEs worked extremely well together. A consortium with more than 50 industry partners was established for a SWEET proposal in the field of power-to-gas. The utility providers participated in WP 5 by giving access to data for the models, thus making the modelling possible. In 2017, the Forum Energiespeicher Schweiz (FESS) was founded by AEE Suisse together with members of the SCCER HaE.

Assessment of the achievements

It is clear that the overall aim of WP 5 and its assessments, i.e. to provide feedback to other WPs within the SCCER HaE, other SCCERs, industry, society and politicians, was achieved very successfully. This was evident in part from the significant increase in collaboration with public sector partners at regional and national level in Switzerland, whose contributions were largely in cash. Other examples of successes were the particularly fruitful cooperation with JASM, which produced results that could be used in the context of the overall programme.

WP 5's activities and results were in line with the original work plan. The assessment methods and quality of the results were compatible with international standards. Regarding the demonstrators, the activities were highly recognised internationally and are state of the art. Seven papers were released from 2017 onwards, and these had been cited about 200 times by the end of 2020. All results were of high international quality and held significant relevance for the Energy Strategy 2050.

Finances and capacity of the SCCER

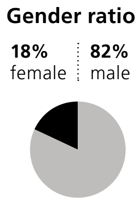
The SCCER HaE's activities, and in particular the development of research capacity, had total financing of CHF 100.5m between 2014[26] and 2021[27]. Innosuisse support was CHF 27.5m, while the participating HEIs contributed CHF 35.5m and the remaining CHF 37.5m came from competitive federal funds (CHF 18.5m) and from contributions by industry partners and international projects (CHF 19m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20/21 period. Funding from own sources clearly exceeded the requirement.

Research Capacity + Operating Expenses + Other direct costs

Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**27'504'473**	**35'549'491**	**18'508'143**	**18'950'512**	**100'512'619**
Share in percentage	27%	35%	19%	19%	**100%**
Ratio (Innosuisse = 100%)	100%	129%	67%	69%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	3.8	17	22%
Assistant Professor / Lecturer	5.0	10	50%
Senior Researcher	15.6	31	50%
Post Doc	25.9	34	76%
Technician	7.4	15	49%
PhD student / Research Assistant	71.8	102	70%
Other	2.8	3	93%
Total	**132.3**	**212**	**62%**



As at the end of 2020, 212 researchers were involved in SCCER HaE. This corresponds to 132.3 FTEs. 54% of the active researchers within this SCCER were PhD students or research assistants. 18% of the researchers were female.

[26] Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

[27] Due to the Covid-19 pandemic Innosuisse allowed the SCCERs and JAs to use Innosuisse funds also from January to March 2021. Not all SCCERs and JAs made use of this possibility.

Conclusion and outlook

The two main objectives of this SCCER were to build up capacity in energy research and align Swiss energy research in the field of energy storage to best support the Energy Strategy 2050 through the results achieved. Both objectives were reached very successfully, and numerous high-quality results of significant relevance for the Swiss energy system were achieved. The focusing and alignment of the research landscape established by the SCCER programme needs to be maintained in the design of the programmes to come. Collaboration and interdisciplinarity are key factors for success. Maintaining the cooperative spirit is one of the upcoming challenges for future innovation.

Solutions for short, medium and long-term (seasonal) energy storage are required to eliminate dependence on fossil energy carriers. The intended reduction in GHG emissions will necessarily entail implementing forms of renewable energy that are dependent on the weather and season, and hence increases in long-term storage of energy. Short and medium-term storage technologies are available or almost ready for the market. Seasonal concepts, meanwhile, have passed the proof of principle and proved feasible in small-scale demonstration projects but still have a lot of room for improvement. The Energy Strategy 2050 roadmap provides for the required developments of the seasonal concepts for market readiness. The more advanced concepts (TRL 6–9), e.g. at demonstrator level, lack upscaling know-how, manufacturing and durability experience, and economic assessments, required for business case development. Such upscaling development requires strong consortia of industry partner(s) who will take the risk of further exploring this technology on a larger scale, and academia to support the process, contributing improvements, innovations and alternatives. To some extent fundamental (material) questions will come up at the same time, to be answered with lower-TRL approaches. The SCCER's broad industrial network is a sound basis for such ventures.

The demonstrators, currently on the kW scale – such as the ESI platform, the many heat storage concepts and the more advanced hydrogen production and storage technologies – belong in this category. The assessment of energy storage is also one of the most advanced subjects. Although the demonstrators are mainly in the academic research domain, they do advise public and private organisations. Typically, projects up to demonstrator level (TRL 6) involve fairly high research and engineering costs. The challenge here is getting implementation partners interested in sharing the costs associated with the hardware. The work on hydrogen production and storage, and electrocatalytic CO_2 reduction is just entering this phase. The foundation of start-ups in the fields of hydrogen storage (GRZ), heat storage (COWA) and polymer-to-gas conversion (Plastogaz SA) and the continuation of collaborations with Shell and BASF for electrocatalytic CO_2 reduction indicate the prospects for future business cases.

The more fundamental approaches at TRL 5 and below have to tackle questions relating to materials –an area for universities and large research institutions. Here, the collaborative work of the SCCER continues, e.g. in the NCCR Catalysis. The competences accessible via the SCCER network are of great interest to the R&D departments of large industrial companies. This is demonstrated, for instance, by the collaboration with Air Liquide and Shell. Nevertheless, support for fundamental research through public funding is needed. Advanced battery concepts, (electro)catalyst development and hydrogen storage are cases in point. Efficient CO_2 capture (from the atmosphere), which is needed to replace fossil sources, remains a rewarding research area.

In summary, all topics pursued by the SCCER are relevant for the Energy Strategy 2050 and suitable for advancement to the next TRL. In particular, seasonal storage and materials research are long-term challenges to be addressed for the Energy Strategy 2050. The SCCER HaE's partner groups have done a great job, both in performing their research at a very high state-of-the-art level, resulting in excellent, internationally recognised output, and in technological solutions verified by numerous demonstrators and prototypes, startups and even industrial products. Cooperation with industry was exemplary and very fruitful. Unexpectedly strong collaborations between the various academic institutions (i.e. ETH Domain, cantonal universities, universities of applied sciences) were developed during both funding periods, and it is hoped that they will be maintained in the future. Collaborations between the various working groups were, barring some examples where it could have been much better. Outreach to the public and policymakers and the proportion of female researchers in leading positions and in the public representation also need much more attention in the future.

Further Information

LITERATURE

Dubacher J. (2018): Tour de suisse. (Available in French and German).

Fromm K. and Park H.G. (2019): New Materials for Future Batteries. (Available in German, French and English).

Gröschel M. and Hennemann L. (2018): Neue Wege in die Energiezukunft. 5232 Magazin des Paul Scherrer Instituts, 8–20 (German and French).

Jorio L. (2018): Wasserstoff – das Benzin von morgen?

Klose R. (2017): Revolution im Untergrund. EmpaQuarterly 55, 8–11.

Klose R. (2017) Sommerwärme für die Wintersaison EmpaQuarterly 55, 12–13.

Klose R. (2018): Günstig und sicher – Die Salzwasserbatterie.

Rinaldi A., Soini M., Streicher K., Patel M. and Parra D. (2021): What investments in renewable generation and energy storage are needed to drive the decarbonisation of the Swiss residential heating sector?

Schmidt T.J., Roth J., Lutz P. and Ludgate U. (eds.) (2016): Heat & Electricity Storage Annual Report 2016. Swiss Competence Center for Energy Research Heat and Electricity Storage (SCCER HaE).

Schmidt T.J., Roth J., Lutz P. and Ludgate U. (eds.) (2017): Heat & Electricity Storage Annual Report 2017. Swiss Competence Center for Energy Research Heat and Electricity Storage (SCCER HaE).

Schmidt T.J., Roth J. and Lutz P. (eds.) (2018): Heat & Electricity Storage Annual Report 2017. Swiss Competence Center for Energy Research Heat and Electricity Storage (SCCER HaE).

Schmidt T.J., Roth J., Lutz P. and Busa A. (eds.) (2020): Handbuch Energiespeicher. Swiss Competence Center for Energy Research Heat and Electricity Storage (SCCER HaE).

Zogg C. (2019): "Impact Award" für Empa-Projekt Flüssiges für Festkörperbatterien.

VIDEO

Fertig ist die Lauge, video by 3sat (2018).

NFP 70 – Stromspeicherung über adiabatische Luftkompression, video by the Swiss National Science Foundation (2016).

Wohnen der Zukunft, video by SRF Schweizer Radio und Fernsehen.

Wasserstoff – der Brennstoff der Zukunft?, video by ServusTV.com.

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Mobility

Efficient Technologies and Systems for Mobility

Action Area
Efficient concepts, processes and components in mobility

Leading House

Swiss Federal Institute of Technology Zurich (ETHZ)

Participating Institutions

Bern University of Applied Sciences (BFH)
Eastern Switzerland University of Applied Sciences (OST)
Paul Scherrer Institute (PSI)
Swiss Federal Institute of Technology Lausanne (EPFL)
Swiss Federal Laboratories for Materials Science and Technology (Empa)
University of Applied Sciences and Arts Northwestern Switzerland (FHNW)
University of Applied Sciences and Arts of Southern Switzerland (SUPSI)
University of St.Gallen (HSG) (2017–2020)
Zurich University of Applied Sciences (ZHAW)
Lucerne University of Applied Sciences and Arts (HSLU) (2014–2016)

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Dr. Michael Bürgi, ETHZ (2014–2016)

Synthesis

This synthesis of the achievements and impact of the SCCER Mobility focuses on the second funding phase from 2017 to 2020. More than 200 researchers from the ETH Domain, cantonal universities and universities of applied sciences performed joint research in close collaboration with industry and public authorities.

Challenges in the "Efficient concepts, processes and components in mobility" action area

Motorised traffic accounts for more than a third of all energy consumption and CO_2 emissions in Switzerland (SFOE[28]). The Energy Strategy 2050 therefore aims to reduce mobility-related energy consumption and CO_2 emissions. With this in mind, the authors of the action plan recognised that besides stepping up research into different technologies such as the electrification of vehicles, lightweight components or fuel cell drives, efforts also needed to focus on researching efficient mobility concepts. These concepts are based on an overall vision of mobility services provided by a globally optimised, combined and interconnected transport system[29]. These aspects were taken up by the Federal Council when it defined the "Efficient concepts, processes and components in mobility" action area. However, the overall goal can only be achieved if technological change is accompanied by behavioural change. This means that a mobility action field must consider both the supply and demand sides within the mobility system in order to actually be able to develop holistic solutions. That said, it is important to accurately consider which areas of technology and user/society must be brought together to create a systemic view.

Vision and objectives of the SCCER Mobility

The general vision of the SCCER Mobility was a climate-neutral mobility system in which technologies and services are used in a sustainable and efficient manner, i.e. with the smallest possible energy input and making full use of "green" energies. Against this background, the SCCER Mobility pursued two key objectives:

1. to develop a better understanding of the complex dynamics of the transport system through integrated research into new technologies, socio-economic development trends and mobility behaviour;

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[28] See the SFOE website.
[29] Kaiser T., Hotz-Hart B. and Wokaun A. (2012): Aktionsplan Koordinierte Energieforschung Schweiz. Report commissioned by the Interdepartmental Working Group on Energy (EDI – EVD – UVEK).

2. to analyse the interdependencies between the transport and energy systems, map their importance for the achievement of Switzerland's energy and climate goals and make them accessible for the development of scenarios.

In addition to technology-specific research and development – battery systems and power electronics for e-mobility, thermoneutral fuel cell technology and greater efficiency of internal combustion engines, lightweight structural components and improved vehicle energy management – with regard to the transport system the SCCER Mobility also encompassed research into energy infrastructures, monitoring and user communication, and spatial planning, but also into social and economic dynamics in the transformation process and integrated assessments of mobility systems.

Building on the results of the first phase, a supplementary goal in the second phase of the SCCER Mobility in particular was to enhance and intensify interaction with market stakeholders along the TRL scale. Another key aim was to deepen interdisciplinary collaboration in order to ultimately form a consistent and coherent research network that is also perceived as a competence center by external parties.

Phase 2 was extended via digitalisation and ICT projects on both the demand and supply sides. Each project related to a specific line of action in the SCCER Mobility strategy, namely (1) the reduction of vkm/pkm (Automated Driving (AD) Sensor Testing Vehicle and Decision Support System for Personalized Ride-Sharing Services projects); and (2) efficient coupling between the electricity grid and mobility patterns (Smart Mobility Data Platform and Optimizing the potential impact of personal and autonomous electric mobility on grid stability projects).

What was achieved

Research activities were divided into five Capacity Areas (CAs): three technical and two economic and user-related:

(A1) Systems and Components for E-Mobility

Besides application-oriented results, one key achievement was the new research platform for battery systems.

(A2) Chemical Energy Converters

An evaporation cooling system for fuel cells was investigated and developed; the methodological approach was supplemented by cell-level modelling to extend experimental analysis. Work on the efficient use of methane gas led to improved combustion systems.

(A3) Minimization of Vehicular Energy Demand

Results from this area are already finding practical applications in various companies in Switzerland.

(B1) Design, Demonstration and Dissemination of Systems for Sustainable Mobility
Methods and models developed here support the increasing interdependence of the energy and mobility systems and permit faster deployment of energy-efficient means of transport in the population and logistics sector.

(B2) Integrated Assessment of Mobility Systems
Existing models were extended to assess the performance of a wide spectrum of drivetrains and fuels with regard to the environmental, economic and social dimensions of sustainability. Research in this area revealed real-world mobility patterns and the potential of nudging behavioural change.

Digitalisation action plan
One particular outcome of the Smart Mobility Data Platform project was the development of a complete data acquisition platform with cost-effective data acquisition hardware, a data transmission network, data storage and visualisation.

Contribution to Energy Research and to the Energy Strategy 2050

In terms of content, the SCCER Mobility generated new technological knowledge on products at different points on the TRL scale and services for selected areas of application. This has created potential for a contribution to the Energy Strategy 2050, but realisation will depend on successful implementation and penetration of these new products and services.

The SCCER Mobility also made an important contribution to the education and training of academic staff. This will provide a solid basis for long-term and continuous further development and will help foster interdisciplinary research in the field of mobility. The evidence for capacity development in phase 2 was the completion of 41 PhD theses and 235 Master's theses between 2017 and 2020. Successful research cooperation networks were established, and there were fruitful collaborations between different HEIs such as universities of applied sciences, cantonal universities and institutions in the ETH Domain.

The intensive cooperation with industry partners confirms not only the research field's relevance for industry but also its maturity. The outcomes of the SCCER will become even more visible over the coming years thanks to several products in sectors such as agriculture or mining. Beyond these technical achievements, research conducted by the SCCER Mobility made it clear that the transition to sustainable mobility must rely on all systemic aspects of the mobility system. Although technology will require ongoing improvement, energy and climate goals cannot be achieved without behavioural change.

Recommendations

based on the SCCER Mobility's research findings

- **Incentives and attractive offers are a must**
  A combination of soft and financial incentives, new policies and a wider range of mobility-as-a-service (MaaS) solutions and associated infrastructure are needed to reduce transport demand in general and drive the shift from fossil fuel-based powertrain technologies to renewable and environmentally friendly modes of transport.

- **Flexibility through sector coupling**
  To cover future demand for power storage and hence increase the flexibility of the energy system, the transport sector must be comprehensively coupled with other electricity-consuming sectors, in particular the building sector.

- **Individual mobility and more**
  While car manufacturers appear to have embraced the systematic electrification of individual mobility, other key transport domains such as local freight distribution, air transport and long-distance shipping still need to step up their decarbonisation efforts.

Results

CA A1 – Systems and Components for E-Mobility

Leader CA A1
Prof. Dr. Andrea Vezzini, BHF

E-mobility based on renewable energy will play an important role in future mobility. However, there are still a number of challenges and hurdles that need to be overcome. In addition to the provision and distribution of renewable energy, battery storage is a particular challenge that many research centers around the world are dealing with.

Objectives

Storage has so far been the main obstacle to the introduction of electric propulsion and auxiliary units in automotive applications. This is especially true for vehicles that have to meet special performance requirements and therefore require large volumes of energy, for example in relation to their tractive power. With this in mind, the objective of CA A1's research was to improve battery performance, reliability, charging time and technology, lifetime, and costs.

The effective and efficient combination of these factors is key to bringing workable "large-scale" automotive applications to market. As market conditions and infrastructure vary strongly from country to country, it was decided that research should be limited to storage solutions in Switzerland. However, it can be assumed that solutions which first become visible and prove their performance in Switzerland could serve as the basis for development in other countries and also be taken up by industry.

What was achieved

Research and development concentrated on electric storage solutions for locomotives, buses, construction, agricultural and municipal utility vehicles. The infrastructure for CA A1's research was provided by the newly established Swiss Battery Research Platform, with battery testing facilities at BFH, ETHZ, Empa and OST. This platform, distributed across various universities, provides important infrastructure for testing and characterising battery cells and systems and the necessary research infrastructure for the development of battery systems for specialised vehicles.

HIGHLIGHT

SWISSTROLLEY PLUS

The special and new performance of SwissTrolley plus is achieved by combining proven catenary technology with state-of-the-art battery technology. The novel, high-performance traction battery permits emission-free journeys without a catenary, making it easier to extend lines and eliminating the need for complex catenary technology at traffic hubs. The battery design supports the flattening of peak-time energy demand, considerably relieving the load on the power supply system and reducing transmission losses. Unlike in conventional trolleybuses, the SwissTrolley plus traction battery allows the trolleybus to capture and reuse almost all its regenerative braking energy. As a result, SwissTrolley plus requires up to 15% less energy than a conventional catenary bus. Sophisticated software has been developed to plan and control the battery charge level. It takes a combined view of the energy flows of the drive system and the air conditioning system in the passenger compartment, thus maximising energy efficiency.

Also supported by the SFOE, Carosserie Hess AG
and Verkehrsbetriebe Zürich

The CA also built and developed competences and guidelines for testing and novel algorithms for managing the electrical and thermal behaviour of battery systems. ETHZ and OST also investigated the power electronics required for the integration of battery systems in applications and for the charging infrastructure. They were able to demonstrate efficient and compact systems for connecting batteries to the high-voltage systems of locomotives and wireless charging systems.

The Swiss Battery Research Platform examines the key topics of thermal management, safety and reliability, power electronics and advanced charging technologies, and develops testing and characterisation methods. All this takes place in the context of small, highly specialised application areas. The findings of these key research tasks were applied in Swiss-specific demonstration projects and thus fulfilled the programme objective to achieve a high TRL extending right through to implementation. Another advantage of applications in specific niches is future economic implementation in Switzerland to complement applications in mass production areas as targeted by large companies.

The Smart Mobility Data Platform also developed a complete data acquisition platform, consisting of cost-effective data acquisition hardware, the data transmission network, data storage and visualisation. As a result, a toolchain was established for long-term data acquisition to stimulate customer and research partnerships for vehicle monitoring and understand data privacy regulations in connection with vehicle monitoring.

HIGHLIGHT

eDUMPER

The eDumper, which is used in a quarry in the Canton of Bern, was converted from a diesel vehicle into the world's largest electric vehicle. It has an empty weight of 58 tonnes and a payload of 65 tonnes. The eDumper is powered by batteries and was converted from a Komatsu HD 605-7 diesel truck. It is equipped with a high-performance lithium-based storage system that can be charged and discharged several thousand times. The system was developed to provide a safe and reliable battery technology with the highest-possible energy density and longest-possible service life. The green eDumper is fully integrated into the quarry's dumper family. The project is financially supported by the SFOE through its pilot and demonstration programme. The implementation partners are Kuhn Schweiz AG, eMining Switzerland and Lithium Storage. Over the next ten years, the eDumper is expected to produce around 1,300 tonnes less CO_2 annually than the diesel version.

Also supported by the SFOE and Kuhn Schweiz AG, emining Switzerland and Lithium Storage

Contribution to the SCCER's objectives

One core asset of the research into electric storage solutions was the Swiss Battery Research Platform, which was newly established and massively boosted by CA A1's research activities. It also offered interfaces to other SCCERs, in particular the SCCER HaE and the SCCER-FURIES. The platform is equipped with battery testing facilities at BFH, ETHZ, Empa, and OST. Distributed across various universities, it provides extensive infrastructure for testing and characterising battery cells and systems and the necessary research infrastructure for the development of battery systems for specialised vehicles.

The CA also built and developed competences and guidelines for testing and novel algorithms for the management of the electrical and thermal behaviour of battery systems. ETHZ and OST also investigated the power electronics required for the integration of battery systems in applications and for the charging infrastructure. They were able to demonstrate efficient and compact systems for connecting batteries to the high-voltage systems of locomotives and wireless charging systems.

A very fruitful interaction was established across all cooperation activities, not only between disciplines and specialised competences but also between different kinds of research institutions, creating perspectives for long-term collaboration. This will make a significant contribution to the Energy Strategy 2050, which relies not only on the achievement of goals but also on the availability of highly skilled staff.

Assessment of the achievements

Nearly all activities went well and in line with the original work plan. This applies to both the achievement of milestones and the provision of deliverables as planned.

Given Switzerland's research capacity and resources in this area and the extreme scope of the challenges, the A1 research team succeeded very well in focusing on the essential topics. Swiss-specific demonstration projects such as the eDumper and the Swiss Trolley Bus should enable the research results to be translated well into future Swiss products and services. It was also an excellent way to achieve international visibility.

The level of research stands up very well in an international comparison, particularly in the fields of lifecycle modelling and battery management.

CA A2 – Chemical Energy Converters

Leader CA A2
Christian Bach, Empa

CA A2 concentrated on the efficient and economic conversion of renewable chemical energy into electrical or mechanical power for vehicle propulsion, with the aim of creating efficient and fossil fuel-free road traffic. Long-distance road transport was a particular area of focus.

Objectives

- Hydrogen is a promising energy carrier for the carbon-free or carbon-reduced mobility system of the future. It also seems particularly suitable for long-range applications due to its high energy density. The fuel cell usually used still presents major challenges, however, one of the most important being cost-competitiveness. The main objective of CA A2 was therefore to research cost-effective solutions for fuel cell systems.

- The primary aim of the "combustion-based systems" sub-topic was to further optimise gas engines based on existing highly optimised fossil diesel and fossil petrol internal combustion engine technologies. Increasing the energy efficiency of these engines is also intended to counter developments whereby conventional petrol or diesel engines are often simply "converted" to run on renewable fuels such as biogas or biodiesel, without the engine having originally been designed with the properties of these fuels in mind. This can lead to a loss of efficiency and often also means that the combustion advantages of renewable fuels do not come into play.

What was achieved

By exploring the development of an evaporation cooling system for fuel cells, CA A2 addressed a key problem associated with the use of fuel cells. The solution it investigated uses the phase transition of water, injected directly into electrochemical cells, as a cooling principle. A material-based concept was pursued in which modified porous materials permitted the evaporation of the coolant water directly in the electrochemical cell. The first step was to develop these modified porous materials. The fundamental work on the evaporation process in porous materials was carried out by PSI researchers together with a group at EPFL. ZHAW contributed cell-level modelling, a principle that was proven to work experimentally at PSI.

HIGHLIGHT

FUEL CELLS WITH EVAPORATIVE COOLING

A novel cooling concept based on the evaporation of water was developed. The concept uses modified gas diffusion layer materials including hydrophilic lines, part of the hydrophobic porous structure, filled with water. The advantage of this solution is that it does not require separate cooling channels, thus reducing the volume, complexity and cost of the fuel cell system by up to 30%. The water also evaporates near the membrane, contributing to better humidification and thus to higher ionic conductivity and allowing higher operating temperatures without the need for external humidification. Function was demonstration via a short stack prototype.

Although new propulsion systems are being developed at a rapid pace, internal combustion technology could continue to be relevant in some areas of transport if it succeeds in achieving low CO_2 emissions. As a basis for improvements in internal combustion systems, the low reactivity of methane gas was investigated at ETHZ's Aerothermochemistry and Combustion Systems Laboratory. A diesel pilot fuel injection concept was developed together with a combustion control concept by the ETH Institute for Dynamic Systems and Control.

The European Horizon 2020 GasOn project led by Volkswagen Group Research built on these experiences to develop a novel combustion concept for passenger car engines. By improving the design of the pre-chamber and its combustion control, an efficiency of 45% for passenger car engines was achieved.

To gain a better insight into exhaust gas pollutants produced by the novel combustion concept, a follow-up project was initiated with support from the SFOE involving a shift from air-diluted to stoichiometric exhaust (inert) gas-diluted combustion, which allows the application of a three-way catalytic converter system. It also addressed the increased challenge posed by ignition by using a novel nanosecond-pulsed ignition technology. The main achievements were the availability of a numeric approach to the design of pre-chamber ignition systems and the knowledge necessary for their technical realisation.

In parallel to the ignition research, Empa and ETHZ developed a hybrid solution in the form of an electrohydraulic-actuated, fully variable valve train. Up to now, power control in conventional Otto-cycled engines has been carried out by throttling the intake air, resulting in significant efficiency losses with low and part loads in particular. The newly developed valve train prevented those losses by varying the lift and opening duration of the gas exchange valves. Having succeeded with a demonstrator system, integration into a full passenger car engine began. One main research question dealt with the use of such a system in hybrid electric propulsion systems. Initial results indicated that an electric engine and battery can be designed to be smaller (and cheaper) if the internal combustion system is operated with a variable valve actuation system.

HIGHLIGHT

GasOn

Pre-processed biogas or synthetic methane (e-gas) have very low CO_2 emissions and a significantly higher knock resistance than fossil fuels. To investigate the potential of natural gas-dedicated vehicles, researchers developed a novel turbocharged pre-chamber gas engine concept with a high compression ratio optimised for lean operation. This included the setup, operation and control of the engine and the design of the pre-chamber using experimental equipment and numerical simulations, the results of which were then incorporated into the experimental validation of the engine combustion concept. A flexible motor-control system allowed the new combustion process to be implemented on the test engine.

Also supported by Horizon 2020, European automobile manufacturers and automotive suppliers

Another main research field for CA A2 was the use of new oxygen-containing liquid fuels such as dimethyl ether (DME) or polyoxymethylene dimethyl ethers (OMEs) that form fewer or almost no particles during combustion and therefore permit more efficient combustion concepts for diesel engines. DME and OMEs can be produced from hydrogen and CO_2 in a catalytic process. To carry out the research, a novel research instrument was developed to improve understanding of the injection, inflammation, and combustion of these new fuels. To this end, researchers from FHNW and ETHZ equipped the head of one cylinder of a multi-cylinder engine with optical access.

The approach and the results of this project were included in a separate project conducted with FPT Motorenforschung in Arbon. The efficiency of a heavy-duty diesel engine was increased by almost 50% through the implementation of a new exhaust gas recirculation (EGR) concept, and the engine was then converted for DME operation.

HIGHLIGHT

AUTOMATED DRIVING SENSOR TESTING – DIGITALISATION

The Automated Driving (AD) Sensor Testing Vehicle project focused on the sensors that are crucial for AD systems, how they behave in laboratory environments and in real driving conditions, and the sensor data flow. The main outputs of the project were the vehicle with all AD sensors and drive-by-wire system installed, and a small test track setup at Empa. The vehicle and test facilities remain available for future projects and to start new collaborations.

Also supported by the Federal Roads Office (FEDRO), Federal Institute of Metrology METAS, auto schweiz, IRIS, Touring Club Schweiz, Embotech, Axa and Lexus

Contribution to the SCCER's objectives

In the future, defossilisation based on the use of renewable energy will have to take place in various ways. In all probability, the overall objective for transport cannot be met with technology such as battery electric drives. For example, the limited storage density of batteries limits their use in construction equipment and especially long-distance passenger and freight transport such as rail, air and shipping. A technology-neutral approach is therefore essential, focusing on the efficient and economic conversion of renewable chemical energy into electrical or mechanical power for the propulsion of efficient and fossil-free mobility devices. It is in this area that CA A2 made several important contributions.

Hydrogen and renewable gaseous or liquid fuels as energy carriers and fuel cells and combustion engines as energy converters will play a very important role in meeting these challenges. The research results achieved are important with respect not only to the general development of low-CO_2 powertrains but also to the provision of relevant research results for Swiss industrial partners in this field such as FPT Fiat Powertrain in Arbon, Liebherr in Bulle, WinGD (formerly Sulzer) in Winterthur or Swiss automotive suppliers.

During the course of the digitalisation programme, another important task was carried out that will have an impact on the use and consequences of mobility systems. An experimental vehicle was equipped with testing sensors for ADAS (Advanced Driver Assistance Systems). Initial tests were carried out, and laboratory and on-road results delivered on a test track at Empa.

Particular added value was created through multiple collaborations between academic test facilities (ETHZ, Empa, BFH and OST), which included intensive interaction with key industrial players in Switzerland that will last far beyond the lifetime of the SCCER Mobility. This type of collaboration creates excellent cohesion and cross-fertilisation between research and practice.

Assessment of the achievements

The targets set were achieved, results helped boost knowledge and improve designs. The output is reflected in publications in valued international journals, in White Papers on selected topics, and in particular in cooperation with industry. The intensive cooperation with and support from industry partners demonstrate the industry relevance and maturity of the research field. The high level of appreciation, both domestically and internationally, is evident from the cooperation with well-known companies outside Switzerland.

Over the long term, all CA A2 projects will contribute to CO_2 reduction in long-distance road vehicles in particular.

The approaches adopted in areas such as fuel cell cooling and in the development of processes and controls for internal combustion engines using defossilised fuels were also at a high level and innovative by international standards. These are smart approaches and are remarkable in a field where there are now so many active participants.

CA A2's automated driving sensor testing activities do not seem as innovative. International research in this area is already very intensive and wide-ranging, but these activities do form the basis for further testing of entire systems in the future.

CA A3 – Minimization of Vehicular Energy Demand

Leader CA A3
Prof. Dr. Paolo Ermanni, ETH

CA A3's activities were geared to reducing the energy intensity of road travel, independent of vehicle propulsion systems. Research focused in particular on the properties and production of lightweight materials and structures. As a rule of thumb, a 10% reduction in weight results in a 6–7% reduction in CO_2 emissions per kilometre during operation.

Objectives

- CA A3 aimed to find pathways towards a significant reduction in the energy demand of road vehicles by developing and testing new materials/ lightweight components for vehicle production, paying particular attention to production cost, materials performance and environmental impact.

- Its other goal was to develop and apply models to map future vehicular energy demand and identify strategies for optimising them, along with options for integrating alternative propulsion technologies and novel lightweight materials into vehicle systems.

What was achieved

A semi-empirical model was developed to determine the energy demand for operating any car under real-world road conditions. When combined with fleet cohort models and scenarios for market and technology development, these models enabled researchers to predict the future energy demand for the fleet. Based on the identification of options to reduce the energy required to operate the vehicle mass, novel lightweight materials for car construction were explored.

HIGHLIGHT

RESEARCH AND ESTABLISHMENT OF STARTUPS

Several fields of research within the SCCER Mobility achieved a high TRL with promising results, making it possible to establish startup companies in order to exploit these results commercially:

- industrial 3D printing solution based on the automated, additive deposition of material according to a digital blueprint to build fibre-reinforced thermoplastic (FRTP) composite components for new lightweight constructions (ETH spin-off 9T Labs, www.9tlabs.com)
- technology based on (recyclable) preform materials made from glass fibres to reduce the cycle time of large-scale part production while improving material quality (ETHZ spin-off Antefil Composite Tech, www.antefil.com)
- new healable composite solutions, i.e. technology for in-situ repair solutions that lengthen the lifespan of composite structures (EPFL spin-off CompPair Technologies SA, www.comppair.ch)

Also supported by the SNSF

While the reduction potential refers to the key energy demand during vehicle operation, energy demand may also be relevant for vehicle production. To provide a realistic assessment of the reduction in energy consumption through lightweight materials, a cost analysis and LCA was carried out. Emphasis was placed on the circularity and LCA of the new processing approaches to sustainable production.

Lightweight vehicular components were developed based on recyclable thermoplastic composite technologies for mass production. New material systems for complex shaped parts, carbon-fibre composite and bioinspired materials with high resistance were investigated. As a guideline for the design of lightweight composite materials, novel materials for increasing crash resistance were essential.

To successfully employ thermoplastics in the automotive market, fast production processes had to be developed that are competitive with existing market solutions. To achieve this, researchers concentrated on expanding the manufacturing and mechanical possibilities of thermoplastic composites by improving impregnation, fibre-matrix adhesion and compatibility with several polymeric matrix materials. To date, compression resin transfer moulding (RTM) has emerged as one of the most promising approaches.

Another research focus was on high-fluidity thermoplastic polymers, in particular polyamide, developed by Solvay, an industry partner of the SCCER Mobility. A dry textile fabric was impregnated with molten polyamide. Two strategies were validated: (1) a very-high-permeability non-crimp textile fabric; and (2) more conventional glass or carbon textiles. The second strategy, for which a patent was filed, offers improved flexural stiffness of the finished part. Scaling up with industry partners was underway by the end of the SCCER period.

HIGHLIGHT

COST AND LIFECYCLE INVENTORY OF PROCESSING ROUTES

CA A3 developed various impregnation strategies with recyclable thermoplastic composites to reduce vehicle mass and minimise vehicular energy demand: compression RTM process (FHNW), melt RTM process (EPFL), continuous fibre impregnation process (ETHZ). These approaches underwent LCAs to identify their potential compared with the conventional metal process for producing a bonnet. The total energy input for the production of a fibre-reinforced plastic bonnet can be lower than for the production of a conventional metal bonnet, if the amount of recycled metal is below a certain value and further welding and assembly operations are avoided thanks to a one-shot production.

To simplify the development of complex parts, CA A3 developed new manufacturing strategies in the form of hybrid bicomponent fibres (BCFs) – e-glass monofilaments clad in polycarbonate sheaths. The fast processing in the development of fully impregnated products, coupled with the flexibility of unconsolidated preforms, makes thermoplastic composites significantly more attractive to high-volume production markets, including those for automotive parts and the development of complex parts.

To evaluate the potential of the three newly developed thermoplastic production processes, each underwent an LCA and was compared with the conventional production process for a metal bonnet. Researchers found that the energy required to replace the metal bonnet of a car with a plastic one is balanced out after around 100,000 kilometres, after which energy savings start. This figure may differ depending on the metal used (recycled or not), or the choice of fibres.

The potential of nacre (mother-of-pearl), which displays an exceptional combination of strength and non-catastrophic fracture behaviour, was investigated as a novel material for increasing vehicular crash resistance. Nacre-inspired composites currently offer the best combination of high stiffness, strength and toughness for this class of materials, with properties rivalling traditional, energy-intensive carbon-fibre composite materials. These findings open up an enticing pathway towards the manufacture of high-performance composites using more sustainable and environmentally friendly building blocks.

HIGHLIGHT

BIOINSPIRED COMPOSITES

A printing technique was developed that combines bottom-up self-assembly with top-down shaping from a 3D printer to produce scalable bioinspired hierarchical materials from thermotropic liquid crystal polymers (LCPs). The 3D-printed high-performance polymer objects are lightweight and show mechanical properties typically only found in fibre-reinforced polymers or metals, while also being fully recyclable and less energy-intensive. The ETH spin-off NematX AG, founded in 2020, is developing this technology to market maturity. Their work is inspired by two natural materials – spider silk and wood. A patent application for this NematX technology has already been filed.

Contribution to the SCCER's objectives

While the immediate contribution of lightweight materials to reducing energy demand in the transport sector is difficult to assess, there is no doubt that CA A3's role in the Energy Strategy 2050 has to be considered across different areas, i.e. not only with reference to the transport sector. In short, CA A3 significantly increased the TRL of several specific lightweight materials technologies, giving rise to future-oriented, recyclable and sustainable thermoplastic composite technologies. Although the technologies investigated do not all have the same TRL, results are already finding practical applications in companies such as Bcomp or startups including 9T Labs, NematX and CompPair.

The startups in particular were guided and inspired by CA A3's industry partners, who also provided technical expertise for the research projects. This pioneering collaboration with industry also revealed the challenges facing researchers looking to meet the short-term needs of Switzerland's OEM and supplier network.

In contrast to other SCCER Mobility sub-projects, where research results were often generated through direct collaboration, CA A3 had more of a cluster structure in which each participant was highly specialised, with the results obtained on the basis of their specialisation then shared with the other partners in the cluster. Even under this structure, the value of subject-specific complementarity is shown by the fact that the research subject can be approached from a broad perspective.

Assessment of the achievements

All the proposed milestones were achieved – most of them within the planned timeframe – and documented either by specific reports or by journal or conference publications. The number of publications is satisfying given the number of researchers involved. It would have been pleasing if CA A3's research partners had also been able to produce a publication, possibly a White Paper, that summarised the state of the art, options and future outlook for the lightweight materials field from both a scientific and economic point of view.

There was intensive and productive cooperation with industry. It goes without saying that there was good cross-fertilisation of research and industry for several topics.
With regard to the production processes for composite parts especially, the activities are of international interest and represent the state of the art in terms of research. The spin-offs already established offer hopes and expectations that the innovative processes can also be implemented economically in an internationally competitive field, at least in niche areas.

CA B1 – Design, Demonstration and Dissemination of Systems for Sustainable Mobility

Leader CA B1
Prof. Dr. Martin Raubal, ETH

CA B1 addressed three areas in which usability and the use of new mobility options and user behaviour are of particular importance: infrastructures for mobility based on renewable energy carriers, efficiency gains through ICT and communication, and spatial planning and environmental impact.

Objectives

- CA B1 examined not only technical but to a large extent also behavioural and social issues. Overall, CA B1 applied a systemic perspective to solutions – technologies and services – that have the general potential to increase energy efficiency in the mobility sector.
- CA B1 investigated the degree to which the potential of new technologies and services – for different travel modes – could be or even already has been implemented, along with the interactions between users, technology and infrastructure.
- To clarify and quantify this potential, new methods and models had to be developed and implemented as prototypes.

What was achieved

CA B1 focused on "soft" results like data, models and methods. New research methods were developed and new insights gained, partly enabled by new ICT functionality relating to the availability, collection and processing of data. The mobility sector stakeholders addressed by CA B1 differed from those targeted by the other CAs. Software prototypes were developed that will hopefully be adopted and further improved by industry partners, particularly with regard to future MaaS applications.

Research in CA B1 focused on the insight that for a challenge to be mastered, every technological solution also needs to be accepted, implemented correctly and used accordingly. Its work was grouped into three research areas: infrastructure, ICT and urban planning. Existing survey data on mobility behaviour was first analysed in detail, then the spatiotemporal behaviour of humans was monitored and simulated in several research projects. The resulting mobility patterns were linked to environmental data and in the end to urban planning, providing a consistent and complete set of (simulated, measurement-based) data to support decisions that enable the mobility sector to improve at a systemic level and hence be more energy-efficient.

HIGHLIGHT

GoEco!

The GoEco! smartphone application was created to investigate whether and how information feedback and social interactions can be effective in fostering changes in personal mobility choices. Testing was carried out with around 400 users in the Canton of Ticino and the city of Zurich. GoEco! did bring about some change in individual mobility patterns, reducing both average energy consumption and average CO_2 emissions per kilometre. However, significant behavioural changes were only recorded for Ticino. In a city like Zurich where the level of public transport use is already high, behavioural change towards lower energy consumption is more difficult to achieve (www.goeco-project.ch).

Also supported by the SNSF

One line of research targeted increased energy efficiency and infrastructure usage for railway operations, both passenger and freight. On-board monitoring data was collected and railway simulation models validated and calibrated. These models then allowed the estimation of energy-efficient strategies in railway operation, especially with regard to autonomous driving in mixed traffic (InterRegio trains and faster InterCity trains) on the national rail network.

Another line of research concentrated on road-based mobility, considering which types of energy carrier are optimal for which purposes, the corresponding composition of the total fleet of passenger cars, and what this means for energy infrastructures. To map the different purposes, researchers analysed the Swiss mobility micro-census in depth and derived different electric car charging patterns from it. This enabled them to derive the optimal composition of the fleet of passenger cars based on the carbon intensity of the electricity used.

In a third line of research, CA B1 investigated how e-mobility, i.e. the charging of electric cars, is integrated into and coordinated with electricity distribution grids. The resulting charging load from electric cars was simulated for the topology of representative distribution grids (the Basel area) and its impact on local distribution grids assessed. Optimal charging strategies and the (beneficial) impact on distribution grids were outlined for a scenario with an increasingly electrified Swiss fleet. Assumptions about and scenarios for the growth of local PV production were also used to derive the strategies.

HIGHLIGHT

THE ENVIRONMENTAL IMPACT OF HOUSEHOLDS

In Switzerland, the largest share of the total carbon footprint of household consumption is attributable to mobility requirements. These are influenced by place of residence and thus by distance travelled to both the workplace and service infrastructure. To explore this connection more closely, researchers from ETHZ developed a regionalised, large-scale, bottom-up model to predict realistic consumption and environmental profiles for individual households in Switzerland. Certain general macro trends were observed in the 2018 data, namely that higher incomes lead to higher mobility emissions, smaller households use cars more often than larger households, and mobility effects decrease as household members get older. Rural households tend to travel further by car than urban households but use air travel and taxis less.

The fourth area of focus was the standards for and development of an algorithm for the optimal mix of different transport modes to ensure that transport demands are satisfied in an energy-efficient manner. This was then used to develop a prototype for a spatiotemporally resolved expert system to recommend the optimal mode of transport (including cycling or ride-sharing) for a given trip or transport purpose.

The fifth task was to quantitatively model the environmental impacts of mobility and other consumption areas for all Swiss households. Once again, this involved a spatio-temporally highly resolved model that can be used to support political decisions on policy scenarios. In particular, the model exhibits causal relationships and trade-offs between mobility and other consumption areas. This model was then combined with the Multi-Agent Transport Simulation (MATsim) micro-simulation traffic model from another ETHZ research group. In combination, this permitted an ex-ante evaluation of the possible effects of measures/incentive systems on the mobility impacts of individual households in future scenarios.

HIGHLIGHT

EFFECTS OF CHARGING ELECTRIC CARS ON THE ELECTRICITY DISTRIBUTION NETWORK

An important issue for both transport and infrastructure planning is the way in which charging electric cars impacts the electricity distribution network. B1 carried out research that addressed this question in detail and made an essential contribution to knowledge in this area. The intensely measured low-voltage distribution grid area of the city of Basel was mapped into a model and thus made accessible to experimental approaches, in particular the investigation of likely grid impacts given increasing deployment of electric vehicles. A transferable methodology was then developed to model the interaction between electric vehicles and charging infrastructure at any scale, from local case studies to national applications. A comprehensive overview paper on charging impacts was published in July 2020.

Contribution to the SCCER's objectives

Research in CA B1 confirmed – as expected – the need for integrated research into technologies and user behaviour. The experiments and analyses carried out by the research group revealed that users may be willing and able to change their behaviour within certain parameters in terms of infrastructure, technologies and access to information. At the same time, however, it became obvious that scalable behavioural change is difficult to achieve, particularly when larger proportions of the population already apply sustainable forms of mobility behaviour.

While technology will need to continue to improve, people will also need to change their behaviour. A joint effort will be required to solve the most challenging problems regarding supply and demand in the mobility sector.

Transferring these results into practice only affects marketable technologies or software-based services to a very limited extent. Rather, the results are relevant for urban and transport planning and for transport policy, although this could make a considerable contribution to achieving the objectives of the Energy Strategy 2050.

The project generated useful synergies between empirical and modelling-based approaches in the mobility research sector, thus supporting enhancement on both sides: empirical research creates the ability to build quantitative scenarios, while modelling is enriched by in-depth empirical data that helps bring modelling results closer to behavioural realities.

Assessment of the achievements

The research work gained in importance throughout the funding period and finally achieved a high status within the overall concept of the SCCER. The capabilities of the research groups increased, not least thanks to a constant improvement in interdisciplinary exchange. This also led to innovative and fresh research questions and valuable results that produced a high degree of added value.

One particular outcome of the research carried out in CA B1 is the disclosure of the gap between the fundamental potential that exists and the implementation of technologies and services that form the basis for this potential. CA B1 also showed that it is not just about acceptance and use per se, but that the time dimension must also be taken into account when it comes to reducing GHGs in the mobility sector.

CA B1's contributions to improving energy efficiency in Switzerland will be predominantly indirect. This is inherent to the research field and was also laid out in the proposal for phase 2.

CA B2 – Integrated Assessment of Mobility Systems

Leader CA B2
Dr. Stefan Hirschberg, PSI

The integrated assessment of transport systems aimed to understand mobility from different perspectives – technologies, energy availability and consumption, technology users, everyday needs and specific needs – and develop an integrated view of the transport system and how it can be made more sustainable.

Objectives

- The overall goal of CA B2 was to provide a comprehensive, primarily quantitative, long-term assessment of the Swiss transport sector as part of the wider energy system embedded in the socio-economic environment. The analytical work was to include all major modes of mobility (personal and freight) and explore long-term transition scenarios in the context of the entire Swiss energy system. The aim was to promote an understanding of the role of new and emerging technologies in reducing CO_2 emissions and energy demand.

- The overall goal was subdivided into a range of sub-goals, with methods to be developed to systematically consider and deal with interdependencies between different socio-economic developments, regional levels and stakeholder groups as they affect the dynamic of the transformation process. Living lab experiments were to be conducted with a view to understanding whether a shift towards less car-dependent lifestyles could be fostered by smartphone apps. New functionalities of the GoEco! app were to be developed and tested, and finally the main drivers for investor and consumer acceptance of e-mobility were to be investigated in cooperation with the SCCER CREST.

What was achieved

To obtain a holistic assessment of current and future mobility technologies, a broad range of quantitative analyses were carried out based on state-of-the-art modelling approaches such as LCA, impact pathway approach (IPA), risk assessment, internal cost assessment (ICA), external cost assessment (ECA), total cost assessment (TCA) and multicriteria decision analysis (MCDA).

HIGHLIGHT

"BELLIDEA" – TRANSFORMING MOBILITY IN SWITZERLAND

To better understand the limitations of and motivations for using appbased programmes to change people's mobility behaviour, 40 citizens from Bellinzona were invited to codesign a smartphone app intended to promote more sustainable mobility. The results were encouraging, with even "mainstream car drivers" changing their behaviour. The development process also strengthened mutual trust between citizens and policymakers, revealing opportunities for participatory governance practices in future decision-making processes (www.bellidea.ch).

Also supported by the EU's Smarterlabs programme and the city of Bellinzona

Databases that provided inputs to the models were updated and extended to assess the performance of a wide range of drivetrains and fuels in terms of the environmental, economic and social dimensions of sustainability.

HIGHLIGHT

LIFE CYCLE ASSESSMENT (LCA) OF PASSENGER CARS

The Carculator web tool was developed as a decision support for car buyers and decision-makers and can be used to compare the environmental performance of passenger cars over their entire lifecycle. Users selects various parameters such as the type of powertrain, vehicle size or emission standards, and the Carculator then estimates the environmental burden of current and future vehicles. Users can also add their country-specific electricity mix for battery electric cars. The Carculator also allows professionals to install and use the tool as a Python library, enabling them to view the source code and underlying calculations (carculator.psi.ch).

Also supported by the European ELEGANCY project, the Mercator Research Institute on Global Commons and Climate Change, the Potsdam Institute for Climate Impact Research and with the contribution of the SCCER HaE and the SCCER-SoE

The socio-economic part of CA B2 focused on different approaches to changing the present mobility paradigm. For example, smartphone applications were developed and tested to investigate opportunities for the transition to energy-efficient and environmentally friendly mobility behaviour. These applications allowed researcBELLIDEA hers to track mobility patterns and test how effective nudging interventions are in initiating behavioural change (extension of the functions of the GoEco! app). Behavioural aspects were also investigated by analysing consumer preferences for electric vehicles and the integration of these vehicles into the electricity grid, and by exploring the potential of MaaS for fostering changes in mobility behaviour.

These projects underlined the ongoing changes in the mobility sector with regard to electrification, the use of digitalisation and alternative mobility concepts.

HIGHLIGHT

EXPLORING SCENARIOS FOR CLIMATE-FRIENDLY AND EFFICIENT MOBILITY

Scenarios were explored together with the associated JAs by modelling the transport sector as part of the Swiss energy system. The scenarios covered different levels of ambition: (1) an "ambitious" CO_2 reduction scenario of 80% by 2050 compared with 1990; and (2) netzero CO_2 emissions by 2050 (excluding emissions from international aviation, land use and forestry). The scenarios were assessed using the Swiss TIMES Energy Systems Model (STEM), which generates costoptimal solutions and considers the multiple interdependencies between technologies and actors. The modelling showed the following: that the number of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) will increase if purchase costs are reduced while fossil fuel prices continue to rise, that largescale use of electric trucks will only happen in connection with ambitious climate policy measures such as strict emission targets or high taxes on fossil fuels, with lightduty vehicles and urban buses then becoming extensively electrified, and that to meet the goal of netzero CO_2 emissions by 2050, hydrogen will need to account for 20% of the transport sector, which would in turn help promote the production of biomass-based hydrogen.

Looking at CA B1 and CA B2 together shows that the holistic assessment of national long-term climate goals was successful, as there are clear interdependencies between climate change mitigation actions across different sectors of the economy. Cross-sector coordination is required to achieve the national climate goals. Sector-specific potential and the costs of emission mitigation have a major impact on the design of sectoral policies. For example, the use of mature mitigation options (e.g. electric passenger cars, heat pumps) and disruptive end-user innovations (e.g. car sharing, smart homes) should be prioritised and supported, followed by appropriate incentives to increase the TRL of CCS technologies in electricity and hydrogen production in order to achieve cost-efficient netzero emissions by 2050.

Contribution to the SCCER's objectives

The results and tools elaborated in CA B2 primarily facilitated the development and testing of policy strategies and interventions and thus had a largely indirect impact on business. As such, TRLs cannot be assigned to them.

CA B2 identified the strengths and weaknesses of the various options for reducing energy consumption and examined how these options might or might not contribute to policy goals.

One important element in the realisation of the overall approach was the extension of the Swiss energy model by

- implementing a much more detailed representation of mobility technologies;
- expanding other demand sectors;
- adding a number of supply and storage technologies that will play an increasing role in a more decentralised energy system.

Using a global model, researchers were also able to account for environmental burdens within energy supply chains outside Switzerland.

Another contribution that could help reduce energy consumption was a deepened and improved understanding of factors that could increase or hinder acceptance of MaaS. This knowledge will help cities, public transport operators and commercial service providers design and implement services that contribute to more sustainable mobility.

The interplay of rational and affective factors in the decision-making process regarding the purchase of an electric vehicle was also examined. CA B2 identified touchpoints that would permit more effective promotion of electric vehicles in the future.

Researchers involved in CA B2 started to work together across CA B2 projects, not only with respect to the variety of disciplines involved but also with respect to the type of research institution to which researchers belonged – particularly the ETH Domain, universities of applied sciences and universities.

Particular synergies were generated between the very different modelling approaches used. For example, the data used and analysed in the Carculator tool also enriched the impact assessment carried out in CO_2 emissions scenarios.

Assessment of the achievements

Most deliverables were delivered in due time. The “report on total costs of mobility” (deliverable B2.2.2-D1) and the “final sustainability assessment report” (deliverable B2.2.2-D2) are not yet available. The SCCER’s final report does not specify a completion date, but simply states that the results will be published in various publications.

CA B2 achieved state-of-the-art results that attracted major international attention. The scientific efforts were both worthwhile and challenging. The complexity and extraordinarily high data intensity required for the different assessment approaches and scenarios presented a very special challenge. Although the search for a practicable netzero CO_2 emissions scenario was extremely difficult, the CA B2 researchers ultimately succeeded in finding a solution.

The LCA tool is widely used in the research community and its developers received a lot of positive feedback.

Socio-economic activities were carried out in close cooperation with local and regional stakeholders and may contribute to changes in mobility behaviour in the future.

Over the lifetime of the SCCER Mobility, CA B2 managed to become strongly involved in topics relating to the EU research and innovation agenda.

Finances and capacity of the SCCER

The SCCER Mobility's activities, and in particular the development of research capacity, had total financing of CHF 100.7m between 2014[30] and 2020. Innosuisse support was CHF 26.4m, while the participating HEIs contributed CHF 29.1m and the remaining CHF 45.2m came from competitive federal funds (CHF 28.4m) and from contributions by industry partners and international projects (CHF 16.8m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period. Funding from own sources and competitive federal funds clearly exceeded that requirement.

Research Capacity + Operating Expenses + Other direct costs

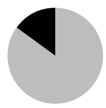
Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**26'373'763**	**29'105'953**	**28'370'249**	**16'857'601**	**100'707'566**
Share in percentage	26%	29%	28%	17%	**100%**
Ratio (Innosuisse = 100%)	100%	110%	108%	64%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	3.7	23	16%
Assistant Professor / Lecturer	0.4	2	18%
Senior Researcher	26.2	53	49%
Post Doc	17.4	21	83%
Technician	5.6	14	40%
PhD student / Research Assistant	79.6	119	67%
Other	2.6	5	52%
Total	**135.5**	**237**	**57%**

Gender ratio

15% female | **85%** male



As at the end of 2020, 237 researchers were involved in the SCCER Mobility. This corresponds to 135.5 FTEs. 59% of the active researchers within this SCCER were PhD students or research assistants. 15% of the researchers were female.

[30] Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

Conclusion and outlook

The SCCER Mobility can rightly be described as a kind of "experiment" – one whose aim was to merge engineering and social science knowledge in terms of content and methods and thus generate new knowledge, but also to foster a broader understanding among the researchers involved of how their respective contributions are embedded in the overall sum of knowledge about the transport system. As was to be expected, the experiment was not equally successful across all parts of the SCCER Mobility, due in particular to differences in the level of receptiveness to topics from "other" disciplines. There were certainly personal and professional discussions across disciplinary boundaries, however, and their impact will certainly extend well beyond the duration of the SCCER Mobility.

One important element in the exchange of ideas was the common desire to make a significant contribution to a sustainable transport system that, in particular, enables Switzerland to achieve its energy and climate goals. A number of concrete measures and events ensured that mutual learning about the different aspects of mobility research actually took place:

- close cooperation between CA coordinators within Executive Committee meetings
- annual conference, which played a key role in building the community
- different workshops and thematic seminars, including the webinar dedicated to the newest science.

The exchange of ideas also highlighted the particular challenges posed by politics and administrations due to Switzerland's specific governance structures with its different and distinct spatial levels. At the same time, however, the SCCER Mobility also took advantage of these structures, for example when it came to establishing participation and bottom-up acceptance on a small scale.

Against this background, it is not surprising that the outlook presented by the SCCER rightly focused on the need for both technical developments and behavioural changes. The potential of existing and new energy-efficient technologies can only be optimally exploited by incorporating the user perspective. The SCCER Mobility made important contributions with regard to individual mobility patterns; the task of future research will be to position these findings within the three classical paradigms of transport planning (avoidance of transport needs, modal shift towards public transport, and more efficient vehicles). It is postulated that developing technologies for autonomous mobility have the potential to make the entire mobility system more efficient.

Future research will need to broaden the scope to include the risks of rebound effects and an increase in traffic due to autonomous vehicles. Digitalisation, real-time connection of vehicles and the availability of data will permit customised and efficient mobility services, including smart trip and traffic planning. Establishing a better link with the user perspective, not only in terms of immediate needs but also with a view to users' rational and emotional attitudes, will enable new technologies to make a greater contribution to the achievement of energy and climate goals.

The challenges that this presents for the Innovation roadmap relate once again to the fruitful combination of technological and social science research:

Which technologies and which services will contribute to the achievement of energy and climate goals? What is the best and comparatively quick way to implement these technologies and services? Which political interventions are needed to accompany this? How should these interventions be designed? How and at what point is user integration essential?

Research at the interface of technology and social science should continue to provide an essential hub in the future, as already carried out in CA B2 in particular. Ideally, this will be supported even more strongly by qualitative work that also addresses technical aspects of the transformation of mobility.

As the combination of technological and social science research requires communication and exchange platforms as a basis, the role played by the SCCER Mobility Management Office throughout both phases as a common contact point for all scientific disciplines was key to most of the successes achieved by the SCCER Mobility. The establishment of some sort of continuation by the host institution, ETHZ, would secure and maintain this basis for interdisciplinary and thus fruitful research.

ETHZ has established the Master of Advanced Studies (MAS) "Mobility of the Future" programme, comprising the three Certificates of Advanced Studies (CAS) "Systemic Aspects", "Technological Potential" and "New Business Models". This is a further achievement of the SCCER Mobility that will hopefully be successful and further evolve as a standalone institution.

Further Information

LITERATURE

Bauer C. (2020): The environmental burdens of passenger cars: today and tomorrow. EnergieSchweiz, factsheet (available in English, German, French and Italian).

Cox B. and Bauer C. (2018): The environmental burdens of passenger cars: today and tomorrow. Background report.

Dehdarian A. (2020): The Key Performance Indicators of the Swiss Mobility System – A systemic approach to research activities within the SCCER Mobility network.

Raubal M., Jonietz D., Ciari F., Boulouchos K., Küng L., Georges G., Hirschberg S., Schenler W., Cox B., Kannan R., Rudel R., Cellina F., Kovacs N., Hoppe M., Michl T., Bach C., Büchi F., Onder C. and Vezzini A. (2017): Towards an Energy Efficient and Climate Compatible Future Swiss Transportation System (2017), SCCER Mobility Working Paper.

SCCER Mobility (2019): Important topics for transport research in Switzerland post 2020: SCCER Mobility Mission Report.

SCCER Mobility (2020): SCCER Mobility Synthesis: Book.

Schlaefly S. (2018): Mobilität in Bewegung. Bulletin.ch.

Vogel B. (2020): Alternative Antriebe auf dem Prüfstand. eco2friendly-Magazin.

WHITE PAPERS

Boulouchos K., Cellina F., Ciari F., Cox B., Georges G., Hirschberg S., Hoppe M., Jonietz D., Kannan R., Kovacs N., Küng L., Michl T., Raubal M., Rudel R. and Schenler W. (2017): Auf dem Weg zu einem energieeffizienten und klimafreundlichen Schweizer Mobilitätssystem SCCER Mobility White Paper 1.

Bach C., Bauer C., Boulouchos K., Bucher D., Cerruti D., Dehdarian A., Filippini M., Held M., Hirschberg S., Kannan R., Kober T., Sugrañes A.M., De Martinis V., Michaud V., Oswald K., Raubal M., Seymour K. and Vezzini A. (2021): Pathways to a net zero CO_2 Swiss mobility system SCCER Mobility White Paper 2.

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CREST

Competence Center for Research in Energy, Society and Transition

Action Area
Economy, environment, law, behaviour

Leading House
University of Basel (UNIBAS)

Participating Institutions
Swiss Federal Institute of Technology Lausanne (EPFL)
Swiss Federal Institute of Technology Zurich (ETHZ)
University of Applied Sciences and Arts Western Switzerland (HES-SO)
University of Geneva (UNIGE)
University of Lucerne (UniLu)
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SCCER CREST

Synthesis

Understanding what people in Switzerland use energy for and how they use it is a prerequisite for planning and steering the energy transition. This transition also requires a level of investment that tends to exceed what the market alone will provide under current framework conditions, which necessitates improvement on both the demand and the supply side.

Challenges in the "Economy, environment, law, behaviour" action area

The transformation of the Swiss energy system requires not only technical solutions but also an economic, legal and societal environment that facilitates their fast implementation. The action plan[31] therefore attached great importance to socio-economic research. It also recognised the need for a research community at the interface of technology and socio-economic sciences to address the topic over the longer term. Accordingly, a large number of research areas were identified as requiring more intensive investigation. The Federal Council's dispatch[32] placed the focus on regulatory issues and market conditions, the analysis of individual and group behaviour and general trends, as well as incentive systems and the role of sufficiency.

Transformation also requires a good understanding of the nature and scale of energy demand for different purposes in different sectors of the economy as a prerequisite for developing both social and technical solutions.

On the supply side, it is becoming apparent that photovoltaics and hydropower will be the key technologies for electricity production by 2035[33]. Given the fluctuating nature of photovoltaics, the importance of digitising the entire energy value chain is increasing. As such, sluggish or inadequate regulation can become a major barrier to the successful realisation of innovative business models.

No country has so far been able to successfully synchronise the transition to renewable energy sources, digitisation while preserving national data sovereignty, and an approach to energy governance that promotes the creation of new business models. Switzerland could play a pioneering role in this task.

[31] Kaiser T., Hotz-Hart B. and Wokaun A. (2012): Aktionsplan Koordinierte Energieforschung Schweiz. Report commissioned by the Interdepartmental Working Group on Energy (EDI – EVD – UVEK).

[32] Federal Council (2012): Dispatch on the "Coordinated Energy Research in Switzerland" action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

[33] VSE (2020): Energiewelten 2020. Das VSE-Denkmodell für die Schweizer Energieversorgung der Zukunft. Aktualisierung des VSE Trends 2035.

Vision and objectives of the SCCER CREST

The Energy Strategy 2050 calls for nuclear power and fossil fuels to be replaced by renewable energy sources, which will require major investments in electricity generation and transmission and large-scale electrification. The electricity system will need to accommodate a much larger share of intermittent supply. Existing energy companies will need to realign their activities, and new business solutions will emerge to facilitate the transition. Consumers are also expected to change their habits, particularly as the plan involves decreasing per capita energy consumption by 40%. All this will require new or strengthened energy policies and market designs.

To address these issues with scientific evidence, the SCCER CREST built up or strengthened 15 research groups across 9 HEIs, with skills in areas including economics, management, law, sociology, psychology, political sciences and energy systems. These groups worked closely with research groups of the technical SCCER, national and local authorities, and many existing and new companies in the energy sector. This collaboration was intended to ensure the realism and practical relevance of the research and accelerate the implementation of its results. Indeed, the goal of the SCCER CREST was to deliver recommendations for policies and business strategies that will induce the transformation of the energy system, and policies that will steer supply and demand in the direction set by the Energy Strategy 2050.

Specifically, the SCCER CREST was set up to provide answers to the following four overarching questions:

1. Which policies, institutions and firm strategies will facilitate the integration of a larger share of "new" renewables into the Swiss energy system?

2. Which options are available for reducing household energy consumption?

3. Which regional and company-level strategies support the diffusion of novel solutions such as distributed generation, local storage or e-mobility?

4. Which transition pathways of the Swiss energy system are consistent with planned policies and expected market trends?

What was achieved

The SCCER CREST achieved almost all of its targets and exceeded many of them. Research capacity was expanded as planned, with all new groups set up and existing groups strengthened. Due to the successes achieved by many of the young researchers, a substantial number of research positions had to be refilled in the second phase of the SCCER CREST as many researchers gained senior positions in industry, public administration or research institutions. The funding provided by Innosuisse was almost quadrupled through own contributions from the institutions and the acquisition of other public and private funding. In particular, the SCCER CREST acquired CHF 13m in competitive research funding, part of which stemmed from applied projects funded by federal offices.

The modelling and simulation capacity was expanded. A large annual survey of the population was implemented and repeated five times, providing a vast dataset on households' energy-related behaviour. Eleven White Papers were published, gathering the best scientific evidence on core issues relating to the energy transition and conveying its results in an effective and accessible manner. Several White Papers led to invitations to make presentations to parliamentary groups or industry groups, enabling a detailed discussion of the recommendations with key stakeholders. Some of these recommendations have also been taken up in recent legislation such as the revision of the Federal Electricity Supply Act or the revision of the CO_2 Act, although this may be coincidental.

Contribution to Energy Research and to the Energy Strategy 2050

Given the non-technical nature of the SCCER CREST, it was not expected to deliver specific results in terms of energy savings or additional renewable generation capacity, but rather to shed light on the workings of the energy system, its suppliers and consumers and their interactions, and the role and potential of energy policy. In addition, the SCCER CREST successfully built up and strengthened a non-technical but multidisciplinary energy research community at Switzerland HEIs. New groups were built up in fields where research capacity was previously missing (e.g. psychology, political sciences, consumer behaviour related to energy) and existing groups were motivated to move their research into energy topics (e.g. legal sciences, economics, management). Most importantly, these groups were connected across institutions and across disciplines, contributing to a strong scientific output from SCCER CREST. Between 2014 and 2020, SCCER CREST researchers published more than 200 papers, several hundred of which were presented at international conferences. More than 60 PhD students finished their studies as part of the SCCER CREST, and many new courses were set up at BA and MSc level.

The large number of publications in highly ranked international journals and participation in Horizon 2020 projects are testament to the international excellence of SCCER CREST research.

To complement the scientific progress made, the SCCER CREST also delivered a great deal of output that was directly relevant for the Swiss energy transition. SCCER CREST White Papers have informed the political discourse on key topics such as the promotion of renewables, grid tariffs, instruments for climate policy and policy measures to reduce household energy consumption.

Recommendations

based on the SCCER CRESTS's research findings

- Transition policies need to work both on innovation, by pushing low-carbon alternatives, and on reduction, by putting pressure on existing but unwanted technologies and business models. Different policies are required for different phases of the transition and for different sectors. These need to be sequenced and ratcheted up in accordance with the development of technology in order to build broad acceptance.

- Initiatives, instruments and campaigns aimed at reducing energy consumption should be based on continued research into the nature and scale of demand from different activities and sub-groups. Indeed, they need to be geared to the wide variety of consumers and pay more attention to "outliers", especially those people and practices that are likely to provide the greatest assistance to the energy transition. They should combine monetary incentives with non-monetary measures including salience, increasing energy literacy or equality and gender considerations.

- There is also a diverse set of actors on the supply side of the energy system, who must be induced through a variety of measures to implement technical and nontechnical innovations with stronger links between heat, mobility and electricity. Energy policy and governance structures at all levels should enable these actors to test ideas, business models and new patterns of collaboration, and should support the diffusion of successful new concepts and products across Switzerland.

- Energy sector startups have different needs to startups in other sectors and require specific support. Established companies outside the traditional energy sector could make a more significant contribution.

- Market designs need to be found that make investments in renewables profitable at market prices, that also make investments in backup capacities and grid extensions profitable, and that provide sufficient incentives to produce electricity when it has the highest value. Flexible electrification technologies can be supported through carbon pricing and measures to reduce curtailment; the latter can be achieved through incentives for flexibility services and new business models, saving on grid expansion costs.

Results

WP 1 – Energy, Innovation, Management

Co-Leader WP 1
Prof. Dr. Maximilian Palmié, HSG
Dr. Jochen Markard, ETHZ

Research in WP 1 focused on technology and innovation strategies for companies in the context of the Swiss energy transition. The political and legal framework conditions are crucially important for the success of new business models in the energy sector.

Objectives

- How do actors in the energy sector address systemic challenges, particularly via new capabilities, collaboration strategies and business models? Previous research showed that it is the decisions of a large number of heterogeneous actors (e.g. startups, utilities, technology providers, companies from adjacent sectors, public authorities and universities) and their ability to collaborate that determine which technologies and business models will be developed and diffused in the future.

- How can these actors address systemic implementation challenges associated with the Swiss energy transition? The increasingly distributed nature of electricity production multiplies the number of interfaces and the complexity of energy systems. These changes at both actor and technology level influence the way in which companies and regions innovate and adopt new technologies.

- How can the Swiss energy transition leverage the potential of smart city initiatives? Smart cities can certainly be conceptualised to comprise multiple service areas that combine human, social, cultural, economic, environmental and technological aspects.

What was achieved

SCCER CREST researchers successfully developed a tailored methodological framework for assessing the prospects of innovative business and collaboration models under high uncertainty and applied it to a real case in the energy sector. They supported Arbon Energy with its investment in a large-scale battery and its development of a flexibility business model around it. The SCCER White Paper 9 synthesised research from WP 1 to provide case evidence and a framework for capturing technological and market innovation through various types of collaboration. The results were especially interesting for (Swiss) utilities.

HIGHLIGHT

POWER ALLIANCE PROJECT

The project is seen as a highlight because it led to a roadmap with actor-specific recommendations for implementing a new business model. Policymakers need to analyse leverage points such as tax reform to reduce cost barriers, while customers need information and a realistic perception in order to analyse their benefits and risks. Utilities and their technology partners should also intensify their search for innovative business models.

Also supported by the SFOE

The Swiss Environment & Energy Innovation Monitor and the annual Energy Startup Day have become an integral part of the energy entrepreneurship landscape in Switzerland. They foster collaboration with various partners and funding sources to continue linking different actors and give insights into the development of the Swiss energy and cleantech startup landscape. The newly developed startup guide section of the Swiss Environment & Energy Innovation Monitor provides specific support for new ventures in this sector.

25 distinct business model archetypes were identified in the electricity sector, helping to promote a better understanding of the competitive landscape in this sector. The business models adopted by startups and incumbents were compared to highlight their respective contributions to the disruptive transformation of the electrical power sector. Furthermore, a quantitative study conducted among Swiss SMEs entering the renewable energy or energy-efficiency sector revealed that the different prominent ways in which organisational leaders make decisions have substantial implications for the extent to which SMEs pursue these new business opportunities.

SCCER CREST researchers analysed how Swiss utilities use energy scenarios in their decision-making, in particular to steer and adapt to changes related to the Swiss energy transition. This research provides a typology illustrating the importance of user-adapted communication and the limitations of complex modelling results in helping develop policies.

A large proportion of the research dealt with renewable electricity integration, complementarities and new transition challenges. A wide range of solution technologies for facilitating renewable energy integration were characterised. Researchers studied the effects of renewable energy deployment policies on innovation in distributed storage, and the collaborative innovation of incumbent utilities and startups. They identified new policy challenges for the acceleration of transitions and studied industry decline processes.

HIGHLIGHT

QUARTIERSTROM PROJECT

This project is seen as a highlight because it shows a real-world application of a digital blockchain-based platform for a local P2P energy market that uses a bottom-up electricity tariff. The platform is based on Tendermint technology (combining a blockchain consensus engine and a generic application interface) and was implemented as a consortium blockchain. The Quartierstrom project could provide significant impetus for utilities and their technology partners, and regulations for scaling blockchain application in the energy sector.

Also supported by the SFOE and several companies

SCCER CREST researchers used many case studies, in particular to shed light on alternative power resource orchestration strategies and associated business model design choices, which allow virtual power plants to go beyond a "one size fits all" solution and adapt their business model to their specific situation.

HIGHLIGHT

SMART CITY MANAGEMENT MODEL

This book was designed as a standard, practical reference for executing smart city transformations. Smart city initiatives can provide pathways toward sustainable urban development in which technological solutions facilitate the achievement of the goals set. Pioneering the Smart City Management Model, the book provides tools, processes, checklists, tips and general experiences to support the implementation and execution of smart city projects. It has been published in German and English.

The evolution towards smart cities was analysed in a comparative case study of pioneer smart city initiatives, and a smart mobility platform developed and tested. A comprehensive book was published describing the topic of smart cities as an important application area for digital technologies such as the Internet of Things (IoT). This book (see more under Highlights) can be used as a practical reference for smart city projects. Following the example of the work on smart cities, further research could focus on expanding the elements discussed, integrating them into an overall picture for technology and innovation strategies in the changing energy sector, and gathering more in-depth findings in concrete implementation programmes. Experiences in other countries regarding the various aspects of the influence of digital technologies should be considered.

Contribution to the SCCER's objectives

The WP played a major role in creating better links between actors. This is best illustrated via the following two activities:

- The Swiss Environment & Energy Innovation Monitor provides information on active startups, innovative projects and companies in the environment and energy business sectors. It is a continuously updated database, in use since 2014 and online since 2018. The monitor aims to make projects and startups visible and accessible to a wider audience, especially startups, investors, collaboration partners, researchers and startup ecosystem supporters, who can search the list of companies and obtain information about support opportunities, networking events and research results. The startups can create their own profile on the website and enter data in the monitor, which is then checked and transferred by the innovation monitor team.

- The Energy Startup Day, organised in collaboration with a number of utilities, is an annual event that supports collaboration between Swiss energy incumbents and energy startups and promotes joint technology development.

The WP also made a significant contribution to the transformation of business in the energy sector. This is best illustrated via the following two activities:

- Researchers sought to understand how past and traditional business models will change in the future and how different actors in the energy sector (e.g. utilities, startups, policymakers) can adapt their business models in order to profit from the energy transition. The factors analysed included the role of information and communication technologies in innovative business models.

- The methodology used to virtually experiment with and evaluate innovative business models reached a new scientific level. The methodology was applied to the group of business models for the economic integration of flexibilities. Its insights were translated into concrete recommendations and visualised in a roadmap.

Assessment of the achievements

WP 1 intensified its research on the acceleration phase of the energy transition, which is a very important topic. It focused on policies to drive system change. It acknowledged the inadequacy of standard economic framings of the problem and potential solutions, and the need for a systems approach, a focus on effectiveness rather than efficiency, transformative innovation rather than a reliance on carbon pricing, context-sensitive policies and a pragmatic approach to political realities.

It would appear that more work is necessary on the topic of "acceleration" in order to differentiate between a local, national, European and global perspective. Which patterns of acceleration in different parts of the world are relevant for Switzerland? What is the impact of actors (disruptors) from outside the traditional energy sector? How fragile are relatively small Swiss utilities? What is the role of IoT and AI platform partners/competitors?

WP 2 – Change of Behaviour

Leader WP 2
Prof. Dr. Paul Burger, UNIBAS

WP 2 identified options for reducing household energy consumption. It provided scientific contributions to help understand its determinants and assess the efficacy of instruments for changing behaviour. Besides psychological mechanisms, it also revealed the importance of structural factors that shape individual behaviour.

Objectives

- What are the socio-economic, psychological and societal determinants of individual and household energy consumption, and what are the drivers of change of behaviour? Research on these questions has too often been divided along disciplinary lines.

- Which policy instruments and civil society measures can help to overcome the efficiency gap in household energy consumption and bring about a substantial reduction in this consumption? Basic assumptions underlying households' behaviour need to be questioned, such as the usefulness of rational choice approaches and the notion of an "average consumer" as a recipient of information and incentives.

- Which policy instruments are effective and efficient at the aggregate level? Previous energy-saving initiatives in households have been rather unsuccessful, so it is to be assumed that greater success can only be achieved with adequately designed programmes.

What was achieved

One major achievement of WP 2 was to improve understanding of the interplay between monetary and non-monetary policy instruments. Financial incentives only lead to changed behaviour if individuals understand their logic and perceive them as salient. Based on the findings of its Swiss Household Energy Demand Survey (SHEDS), the WP showed that these requirements are often not met, e.g. with respect to the CO_2 levy or energy-savings and substitution subsidies, which might explain their only moderate impact.

HIGHLIGHT

INEFFECTIVE POLICY MEASURES

Energy-saving measures that work on paper may not work in reality if individuals do not understand them or if the measures are not salient, i.e. sufficiently visible and present in individuals' daily routines. These requirements are often not met, meaning that typical monetary policy instruments such as taxes or subsidies often fail to bring about the expected energy savings. These insights are important, as they highlight the importance of public information/discussion and challenge conventional policymaking.

A second achievement was to gain a better understanding of the role played by daily routines, which lead to inertia in terms of household behaviour that – as research conducted in this WP documented – is very difficult to change with cognitive or financial instruments alone. However, windows of opportunity for facilitating change or new routines can emerge in conjunction with life events (e.g. a change of workplace) or can be created by new products (e.g. e-cars that induce a different type of transport behaviour), or new ownership structures (e.g. energy communities that impose new behavioural rules). Nudge theory has also been shown to be a useful instrument in changing behaviour.

A third achievement was the finding that structural aspects are important predictors of behaviour and in particular of routines. Changes to structural aspects, whether at an aggregate level or at local level (e.g. the existence of car parks in cities) can foster behavioural changes. Research activities in WP 2 also showed that a lack of structural adaptation (e.g. in relation to charging stations or cycling infrastructure) can hinder intended behavioural changes towards lower energy use. These findings were summarised in a White Paper.

In addition to these insights, one of the WP's most important contributions was to establish an interdisciplinary perspective on the above questions. This relates not only to the collaboration between different disciplinary teams but also to the development of an interdisciplinary framework and the joint survey project.

HIGHLIGHT

THE "AVERAGE CONSUMER" DOES NOT EXIST

There are major differences between households in terms of the structural factors that determine energy use, daily routines, level of information, etc. These differences need to be considered when developing policy programmes, as tailored measures are more effective. Energy-saving activities also need to become much more holistic, for example by combining mobility, heat and electricity or by combining structural (access to slow mobility modes) and individual (improved wellbeing) aspects.

Contribution to the SCCER's objectives

WP 2 addressed energy consumption by individuals or households, the reduction of which is an indispensable component of a zero-carbon strategy. As far as the vision and objectives of the SCCER CREST are concerned, WP 2 played the key role in identifying options for reducing household energy consumption. Its recommendations extend further than the state of the art that existed prior to the establishment of the SCCER CREST. WP 2 showed that a holistic (integrative) perspective is essential in helping to predict the effectiveness of energy-saving measures and programmes.

One of the main contributions of WP 2, in addition to its substantial research findings, was the development of fertile interdisciplinary collaboration across economics, psychology, sociology, business and consumer science, and political science. Important successful outputs of this endeavour were a joint framework paper on determinants of behaviour and dimensions of behavioural change, with contributions from all of the above fields[34], representing all the partner institutions in WP 2) and the jointly designed SHEDS (first wave in 2016), which provided a shared database for collaboration and many insights from more than a dozen choice experiments included in waves 2 to 5.

WP 2 also contributed to cooperation with implementation partners. This transdisciplinary cooperation led to the co-creation of knowledge with cities for engagement in energy-saving activities, with cities and civil society actors for engagement in sufficiency-oriented activities or to carry out energy counselling for households, and with local utilities to develop new business models targeted at households.

[34] Burger P., Bezençon V., Bornemann B., Brosch T., Carabias-Hütter V., Farsi M., Hille S. L., Moser C., Ramseier C., Samuel R., Sander D., Schmidt S., Sohre A. and Volland B. (2015): Advances in understanding energy consumption behavior and the governance of its change – outline of an integrated framework. Frontiers in Energy Research, 3(29).

Assessment of the achievements

The achievements of WP 2 provided important contributions to the original objectives of the SCCER CREST, including the creation of an interdisciplinary research network/framework and data collections. Research within the WP produced a large number of relevant scientific results, reflected in numerous scientific publications. Some of the results were also novel and led to different views on energy-saving practices and effective policy measures compared with the pre-SCCER period.

There is a conflict between "scientific rigour" and a more open-ended evaluative approach based on "learning by doing"; WP 2 focused on the former. While this produced useful data and publications in disciplinary journals, one weakness was that most of the results related to basic research but were not transferred into concrete, practical recommendations that can be implemented right away. The recommendations remain at a rather generic level and it is not clear how policy programmes should be designed and targeted. Overall, the WP mostly provided information on what does not work; it was less strong on insights into how to do things better. More dialogue with implementing bodies might have helped – and could still do so.

WP 3 – Energy Policy, Markets and Regulation

Leader WP 3
Prof. Dr. Hannes Weigt, UNIBAS

WP 3 focused on modelling national energy markets, with a view to assessing existing policies and market structures and providing recommendations for new policies and market designs. WP 3 also sought to provide a more comprehensive, system-wide perspective on the future development of the Swiss energy system.

Objectives

- How are existing energy policies and market structures performing, and how could they be improved with new policies and market designs? The Swiss energy system will certainly have to accommodate a larger share of new renewables on its transition path. Planned policies and expected market trends need to be compared against these developments.

- How can we obtain a more comprehensive, system-wide perspective on the future development of the Swiss energy system? This question is linked to JASM, but has the potential to enrich it with behavioural changes and market innovations. The interplay between mobility and electricity and between heating and electricity is of particular interest.

What was achieved

Many novel results were obtained in this WP regarding market and policy design, and sectoral modelling was consolidated and improved considerably. The focus on integrating individual behaviour into energy models, based on collaboration with WP 2, was particularly commendable. A significant number of papers were published in leading journals. WP 3 teams contributed to the research challenges of National Research Programmes 70 and 71 (NRP 70 and NRP 71). They held the lead of four project clusters and contributed to the joint cluster on future electricity markets, conducting numerous studies with utilities and energy companies in Switzerland. The WP's contribution thus extends from linking technical and economic assessments to performing an aggregated macroeconomic policy evaluation, and from pushing scientific frontiers in energy research to providing first-hand recommendations to Swiss decision-makers.

HIGHLIGHT

ELECTRICITY MARKET DESIGN

The fifth SCCER CREST White Paper highlighted the challenges presented by the transition from today's electricity system towards a portfolio dominated by renewables, namely the altered income structure for power plants in the system, the impact of renewables on supply security along different timescales, the role of imports and exports, the emergence of new actors and the role of the demand side. The White Paper's main conclusion was that the requirements for future design options will depend largely on political and societal priorities, and that future systems will need to coordinate a large number of heterogeneous actors and different timescales to ensure a reliable energy supply.

Also supported by the SNSF

Particular mention should be made of the White Papers for which WP 3 had the lead. The first SCCER CREST White Paper examined the design of support measures for Swiss hydropower and showed (1) that a more flexible framework was needed for operators to be able to run them at a profit; and (2) that coordination with the EU needed to be advanced. The second White Paper examined the renewable power support scheme (feed-in tariff). It showed that cross-subsidisation of PV users by other network users was less of a problem than the conflict of interest between adding more renewable capacity and developing an efficient power grid. This calls for new support (and guidance) mechanisms, which could first be tested at local level. The third White Paper extended the analysis of the feed-in tariff and the plan to gradually phase it out. The paper showed that renewable energies would no longer be sufficiently supported, even though there are still good reasons to do so, especially if the objectives of the Energy Strategy 2050 are to be achieved. It also proposed new instruments for achieving them.

The WP also coordinated the fifth SCCER CREST White Paper, which dealt with the transformation of our electricity supply from a highly regulated system based on

HIGHLIGHT

SWISS ENERGY MODELLING PLATFORM (SEMP)

The SEMP was set up to model and assess energy and climate strategies for Switzerland using an ensemble of models. Under its umbrella, five modelling teams helped assess the economic and technological consequences of deep decarbonisation up to 2050. The results were published in a special issue of the Swiss Journal of Economics and Statistics and provide a reference for the ongoing debate regarding the Energy Strategy 2050.

hydro and nuclear power to a decentralised, market-driven system with a high proportion of intermittent renewables. This transformation calls for a new energy market design that provides sufficient incentives for investments to ensure grid stability while also accommodating a growing number of prosumers. It cannot be drafted without including developments from Switzerland's interactions with the EU. The sixth White Paper, also led by this WP, scrutinised the proposed third CO_2 Act, particularly with regard to carbon pricing. It recommended taking existing taxes on fossil energy into account and introducing a form of mobility pricing for cars and a surcharge on emissions trading system certificates "imported" by Swiss emitters.

HIGHLIGHT

LINKING HEAT AND ELECTRICITY

Through collaboration between different research teams, a link was established between heating and electricity modelling at a detailed household level and local and national model assessments. This new framework allowed a theoretical first best solution derived from overall system optimisation to be compared with the interlinked market result of different actors (households and energy companies). As these actors can be subject to different incentive structures, the main questions are which policies and tariff designs could ensure a reliable and cost-efficient transition to greater electrification of the Swiss heating system and how could this be achieved. By incorporating the wide range of Swiss household structures into a consistent modelling framework for more than 300,000 building specifications, the model allowed researchers to carry out in-depth assessments of different heating and storage options (due to be completed in 2021). This will also provide a link to more detailed analysis in research relating to households, storage, efficiency and buildings.

Also supported by the SNSF

WP 3 researchers therefore authored five of the eleven SCCER CREST White Papers. Each White Paper was signed by between 6 and 14 authors from several institutions, demonstrating the intensity of the collaboration.

Contribution to the SCCER's objectives

WP 3 influenced the development of energy and climate policy in Switzerland through its White Papers and other publications and through its frequent exchanges with the community of energy stakeholders, particularly with regard to the future of hydropower and support for this energy source, the future development of the electricity market, supply security given the growing share of intermittent electricity production, the design of support instruments and incentive prices, and energy and climate policy overall. Two synthesis reports on electricity and efficiency aspects provided well-condensed insights and recommendations for the next steps in the Swiss energy transition. A Swiss version of Germany's electricity market meetings was established, bringing together experts from academia, administration and business to discuss relevant energy and electricity topics. Through this channel and those mentioned above, WP 3's different teams and research projects supplied essential scientific insights for the ongoing discussions.

Most of its output, in particular the White Papers, was realised by between 6 and 12 junior and senior researchers from several HEIs and different disciplines (mostly law and economics), ensuring both robustness and credibility. The WP also reinforced existing research networks and created new ones.

Assessment of the achievements

WP 3 was able to strengthen an already strong and internationally well-established energy modelling community. Its members leveraged their SCCER resources to ensure strong participation in other national (NRP 70 and NRP 71) and international research programmes. WP 3 also achieved its main objective of providing salient input for the Swiss energy policy debate. The established network structure not only within the SCCER CREST but also across all SCCERs meant that Swiss energy stakeholders were able to call on a coordinated structure and obtain a more extensive assessment of pressing questions than an uncoordinated set of individual groups could have provided. WP 3 members also played central roles in other SCCER macroeconomic modelling exercises, in particular JASM and JA Mobility. The shared modelling platform SEMP did not deliver all the simulations expected, however, and its future is not assured.

WP 4 – Energy Governance

Leader WP 4
Prof. Dr. Peter Hettich, HSG

Transforming an entire industry involves overcoming legal, political and behavioural obstacles. Energy governance for the energy transition therefore calls for the development of a regulatory framework and possibly also a change in the roles of the actors for an area that is in continuous development.

Objectives

- What legal, political, investor-related and voter-related obstacles stand in the way of the transformation of the energy sector? To analyse these obstacles to good governance, researchers must consider both the heterogeneous preferences of actors and their multi-level nature.

- What governance framework would facilitate the Swiss energy transition? This is the key question, as the governance framework connects different actors such as companies and customers as well as political and legal institutions. One difficulty is that the available technologies and specific goals of the Energy Strategy 2050 keep changing. As such, deciding on the focus and form of regulation in the medium term within the framework of energy governance at the level of companies, cooperations, and political and legal institutions is like aiming at a moving target. This difficulty is compounded by the fact that energy governance has to consider a large number of national and regional peculiarities.

What was achieved

In the first stage of identifying obstacles to the energy transition, a broad set of actors were integrated into a comprehensive – legal, political and economic – analysis framework with a view to investigating not only formal procedures such as political and democratic processes but also market behaviour, societal practices and public discourse.

HIGHLIGHT

HANDBOOK ON SWISS ENERGY GOVERNANCE

This book has the potential to be a highlight, because it brings together the different perspectives and findings of the different groups within WP 4, proposing a common understanding of the term "governance" and its varying facets. The book addresses the interactions between Swiss and European energy systems and policies and considers the Swiss system of multi-level governance. Against the backdrop of these and other framework conditions, it takes a closer look at the state and non-state actors that drive (or are affected by) the energy transition, thereby making use of catalysts or facing up to obstacles. The roles of these actors are analysed on the basis of their observed behaviour, in particular how they manage their specific policy and acceptance risks.

This framework was based in part on agent-based models that put decision-making by utilities and the socio-political implications of energy policies center stage. WP 4 also conducted research into the following: technology and policy risks for investors in renewable energies; stakeholder engagement, along with their characteristics and influence on Swiss energy policies; the Europeanisation of the Swiss energy system and the international level of governance and its influence on Swiss energy policy, in particular Swiss climate policy; smart grids (digitalisation), the convergence of energy grids and storage.

HIGHLIGHT

ENERGY TRANSITION PREPAREDNESS INDEX

This index quantifies business actors' response to the large-scale energy transition. It is a tool for comparing the transformation of the energy sector in different countries. It may also provide both business actors and policymakers with information on innovation in respect of business models and policies. The findings imply that the progress of the energy transition has so far been measured in a superficial and extremely limited way.

In the last year of the Energy Funding Programme, the WP was mostly working on a joint book on Swiss energy governance that was still under peer review with Springer when this Final Report was published.

Another important result was the Energy Transition Preparedness Index, which quantifies business actors' response to the large-scale energy transition. It is a helpful tool for redesigning energy governance with a view to enabling incumbents to reconfigure their business models and stimulating business model innovation among startups and new entrants in new energy systems.

HIGHLIGHT

ALIUNID

Founded in 2018, this startup brings together energy providers, hydropower producers and IoT developers to create an innovative business ecosystem. At the core of the digital business model is its own Swiss Internet of Things (SIoT) platform. The vision is a breathing energy system that adapts flexibly to fluctuations in supply and demand and is controlled by aliunid from the bottom up. The white label solution proposed by aliunid provides smart home and smart business services for households and SMEs. For utilities, aliunid analyses energy flows in households, boroughs, municipalities and larger regions. Drawing on real-time data, aliunid helps to optimise local and regional energy supply and consumption, thereby saving grid costs and electricity for balancing. The aliunid business model was field tested in 2019 and 2020. Solutions for end-customers (HOME) and grid operators (GRID) are scheduled to be launched in 2021.

Also supported by the SFOE

Another core element of the WP's work was the aliunid field test. The aliunid business model was compared with current electricity market regulation. On the governance side, one of the main findings was that there are no legal impediments to operating a smart grid, nor are there any legal norms to facilitate it. The focus of current electricity market design is on breaking up vertically integrated monopoly structures with strict unbundling rules. However, this unbundling gives rise to transaction costs (cost of regulation and enforcement, cost of lost synergies, etc.). Unbundling electricity markets requires procedures for coordinating the build-up of grid and generation capacity to replace internal coordination within the integrated energy supplier. New instruments and procedures for adjudication and dispute settlement are needed but are not within reach. Moreover, many of the regulatory principles that govern the energy and electricity markets were developed for situations that are no longer relevant in the context of today's energy transition. As a result, some of the old instruments are now hindering the transformation of the energy industry.

Contribution to the SCCER's objectives

The handbook on Swiss energy governance has brought together the diverse research findings of WP 4 and thus laid important foundations for further work. It has become clear that new business models also call for innovations in terms of governance. The challenges for the future are to concretise these results. It is currently impossible to predict with any certainty when and how such concretisation can be achieved.

One promising path for the future could be further cooperation with aliunid. On the scientific side, this would require an interdisciplinary team in which, in addition to SCCER CREST competences, skills in other areas such as AI and the IoT are bundled in order to achieve results in the area of digital governance.

The big opportunity is to use existing financial support to develop a successful model for the entire country that strikes an appropriate balance between agile, decentralised customer solutions and a central platform with a suitable digital architecture.

The model of aliunid's SIoT platform is quite similar to Europe's Gaia-X initiative, in that both approaches seek to reduce dependence on cloud providers outside Europe. Such a path could also lead to an independent Swiss/European energy governance model.

Assessment of the achievements

WP 4 produced a number of interesting research results that clearly advanced the academic state of the art. This is also borne out by the papers published in highly regarded scientific journals. It summarised its scientific results in a handbook and sought to help foster links between the four SCCER CREST WPs and other researchers.

The potential for interdisciplinary collaboration may have been exploited to a lesser extent in this WP, partly because it was only put together at the beginning of the second phase. Its policy recommendations are also rather abstract and superficial. While they offer important general perspectives on good governance, there are not many concrete recommendations on how exactly to achieve this unless these are to be provided in the handbook.

One option, the potential of which was unfortunately not fully exploited, would have been to use aliunid's innovative business model as a common focus of analysis for all SCCER CREST WPs and relevant technical SCCERs and help scale it up beyond Switzerland's borders. There would also have been an opportunity to link this work with corresponding European initiatives. Europe's Gaia-X project, for example, is looking for an independent path to the energy transition and energy governance.

Finances and capacity of the SCCER

The SCCER CREST's activities, and in particular the development of research capacity, had total financing of CHF 105.1m between 2014[35] and 2021[36] . Innosuisse support was CHF 27.6m, while the participating HEIs contributed CHF 45.7m and the remaining CHF 31.8m came from competitive federal funds (CHF 13.6m) and from contributions by industry partners and international projects (CHF 18.2m). The SCCER fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20/21 period. Funding from own sources clearly exceeded that requirement.

Research Capacity + Operating Expenses + Other direct costs

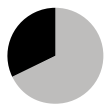
Financial reports 2014–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**27'609'659**	**45'664'644**	**13'548'805**	**18'242'856**	**105'065'965**
Share in percentage	28%	44%	13%	17%	**100%**
Ratio (Innosuisse = 100%)	100%	165%	49%	66%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**SCCER-related average activity rate** in %
Professor	9.7	30	32%
Assistant Professor / Lecturer	12.8	17	75%
Senior Researcher	7.6	12	63%
Post Doc	22.0	33	67%
Technician	1.1	3	37%
PhD student / Research Assistant	47.2	77	61%
Other	0.4	1	42%
Total	**100.8**	**173**	**58%**

Gender ratio

32% female | **68%** male



As at the end of 2020, 212 researchers were involved in the SCCER CREST. This corresponds to 132.3 FTEs. 54% of the active researchers within this SCCER were PhD students or research assistants. 18% of the researchers were female.

[35] Although the Energy Funding Programme issued its request for proposals in 2013, the SCCERs started their activities in 2014 and only used the funding from that year on.

[36] Due to the Covid-19 pandemic Innosuisse allowed the SCCERs and JAs to use Innosuisse funds also from January to March 2021. Not all SCCERs and JAs made use of this possibility.

Conclusion and outlook

In a critical appraisal, the following positive aspects can be cited. First of all, the SCCER CREST delivered a large amount of high-quality scientific collaboration and output. There was also a great deal of interdisciplinary cooperation between "non-technical" energy research groups. This emerged smoothly and rapidly, leading to the creation of a strong interdisciplinary research community focusing on non-technical aspects of the energy transition. A further positive aspect was the growing willingness of most groups to convert research insights into strategy and policy recommendations using the SCCER CREST White Papers as an effective and successful communication tool. Last but not least, the SCCER CREST built up a shared infrastructure including joint data collection of the successive waves of SHEDS surveys and of the modelling groups federated in the Simulation Lab and put into action in the context of the JASM.

However, improvements and more work appear to be required in the following areas. It proved difficult to move from small pilot projects or field experiments to larger transition programmes together with businesses and policymakers. It also proved difficult to align the mindset and competences of researchers with those of advisors or consultants with a view to achieving an impact in both the short and long term. The SCCER CREST struggled to overcome the outdated model of an energy transition with two only loosely connected silos of technical and non-technical knowledge.

There are also still a large number of unknowns regarding households' energy behaviour (in relation to mobility, electricity or heating) and the possible ways in which this can be changed. The challenge remains to better understand the nature and scale of demand for energy services in all sectors of the economy – not just households – and develop a national database of energy consumption for different purposes at different times of the day and year. This will be vital for planning in relation to efficiency/demand reduction, storage and supply policy.

There is also still scope for new market designs and corresponding regulations, particularly those that facilitate sector coupling. Similarly, a larger corpus of more concrete information is still required on how to implement such desirable regulatory and policy contexts at a political level.

There are still a large number of uncertainties regarding the relationship between Swiss and EU policies and regulations, the cooperation options that would have public support in Switzerland, the mutual benefits of cooperation for Switzerland and the EU, and how this cooperation could be governed. Finally, there are still questions with regard to the implications for the energy sector of new connective management, which combines different management and leadership building blocks. Innovative business models at the strategic level are being complemented by the emergence of digital AI-based architectures at the operational level, leading to new organisational forms such as resource platforms with agile teams.

Any outlook for possible future developments should consider that the energy sector has fundamentally changed since the start of the SCCER CREST project. Economic, innovation, digital and sustainability policy are converging at the political level. New issues such as data sovereignty have gained in importance, resulting in new requirements for energy governance. All industries are confronted with the increasing importance of a sustainability-driven purpose, and this is also changing the behaviour of investors.

Further Information

LITERATURE

Burger P., Hess A-K., Parlow S, Schubert I and Sohre A. (2020): Suffizienz im Alltag. Vielversprechende Schritte auf dem Weg zur Erreichung einer CO_2-armen Gesellschaft. University of Basel.

Burger P., Schubert I., Van Dijk J., Puntiroli M., Volland B., Weber S. and Farsi M. (2018): Energieverbrauch der Haushalte in der Schweiz (German version)/Consommation d'énérgie des ménages en Suisse (French version). SCCER CREST report.

Farsi M., Péclat M., Weber S., Burger P., Schubert I. and Sohre A. (2020): Datenanalyse der «Swiss Household Energy Demand Survey» (SHEDS) für die Stadt Zürich, Energieforschung Stadt Zürich. Report No. 61, Research Project FP-1.22.

Frauendorfer K., Gutsche R., Haarbrücker G., Liebenberger C. and Schürle M. (2020): Spannungsfeld: Stromversorgung vs. Stromhandel: Herausforderungen für das Management, White Paper. University of St.Gallen.

Gassmann O., Böhm J. and Palmié M. (2019): Smart City – Innovationen für die vernetzte Stadt – Geschäftsmodelle und Management.Hanser-Verlag.

Landis F. (2020): Wie gerecht ist die CO_2-Abgabe? In: Die Volkswirtschaft. Ed. State Secretariat for Economic Affairs SECO.

Schleiniger R. (2020): Klimaziele der Schweiz: Reicht das CO_2-Budget? In: Die Volkswirtschaft. Ed. State Secretariat for Economic Affairs SECO.

Schleiniger R. (2021): Den Strassenverkehr effizient bepreisen. In: Die Volkswirtschaft. Ed. State Secretariat for Economic Affairs SECO.

Weigt H. (2018): Strommarktdesign: Die Politik bestimmt die Richtung. In: Die Volkswirtschaft. Ed. State Secretariat for Economic Affairs SECO.

Weigt H. (2020): Ungewisse Zukunft der Schweizer Wasserkraft. Bulletin.ch.

SCCER CREST End Communication 2014–2020.

WHITE PAPERS

Betz R., Cludius J., Filippini M., Frauendorfer K., Geissmann T., Hettich P. and Weigt H. (2016): Wasserkraft: Wiederherstellung der Wettbewerbsfähigkeit. SCCER CREST White Paper 1.

Ulli-Beer S., Hettich P., Kratz B., Krause T., Kubli M., Walther S. and Kobe C. (2016): Netznutzungstarife im Zielkonflikt: Anreize für den Ausbau erneuerbarer Energien versus Verursachergerechtigkeit. SCCER CREST White Paper 2.

Abrell J., Betz R., Bretschger L., Camenisch L., Cludius J., Heselhaus S., Hettich P., Hoffmann V., Krysiak F., Rausch S., Schleiniger R., Walther S., Weigt H. and Wüstenhagen R. (2017): Was kommt nach der kostendeckenden Einspeisevergütung (KEV): Fördern, Lenken, Abwarten? SCCER CREST White Paper 3.

Burger P., Bezençon V., Brosch T., Carabias-Hütter V., Farsi M., Hahnel U., Hille S., Lanz B., Lemarie L., Moser C., Puntiroli M., Schubert I., Sohre A. and Volland B. (2018): Reduktion der Energienachfrage von Haushalten – erfolgversprechende Schritte auf einem langen Weg. SCCER CREST White Paper 4.

Weigt H., Abrell J., Betz R., Frauendorfer K., Krysiak F., Roux C., Schlecht I., Schleiniger R., Walther T. and Winzer C. (2018): Strommarktdesign: In welche Richtung soll es gehen? SCCER CREST White Paper 5.

Abrell J., Betz R., Kosch M., Piana V., Schleiniger R. and Stünzi A. (2018): Zur schweizerischen Klimapolitik: Wie effizient ist die Bepreisung des fossilen Energieverbrauchs? SCCER CREST White Paper 6.

Thaler P., Hofmann B., Abegg A., Bornemann B., Braunreiter L., Burger P., Dörig L., Ejderyan O., Heselhaus S., Opitz C., Petrovich B., Rinscheid A., Schillig I., Schreiber M. and Sohre A. (2019): Schweizer Energiepolitik zwischen Bund, Kantonen und Gemeinden: Zentralisieren, dezentralisieren oder koordinieren? SCCER CREST White Paper 7.

Filippini M., Burger P., Cerruti D., Gamma K., Haufler F., Lanz B., Patel M., Schubert I. and Sohre A. (2019): Politische Maßnahmen zur Reduzierung der Energieeffizienzlücke. SCCER CREST White Paper 8.

Bencsik B., Kubli M., Markard J., Palmié M., Wemyss D. and Zobel A.-K. (2020): Erfolg durch Partnerschaft: Neue Kollaborationsmodelle für einen Energiemarkt im Wandel.
SCCER CREST White Paper 9.

Patel M., Broc J.-S., Cabrera D., Cho H., Eberle A., Federici A., Freyre A., Jeanneret C., Krysiak F., Narula K., Oikonomou V. and Yilmaz S. (2021): Energieeffizienzprogramme – Lehren aus und für die Schweiz. SCCER CREST White Paper 10.

Krysiak F., Burger P, Blumer Y., Braunreiter L., Cometta C., Emmenegger R, Lordan-Perret R., Marcucci A., Roux C. and Sohre A. (2021): Von Modellen zu Visionen: Ansätze zur Ergänzung von quantitativen Energieszenarien.
SCCER CREST White Paper 11.

Joint Activities

Joining forces for a systemic perspective

During the first phase of the Energy Funding Programme, a large number of results, models and demonstrators were created in the various action areas of the SCCERs. Since networks emerged not only within but also between SCCERs, it soon became evident that many activities and results address similar challenges from different angles. The need therefore arose to exploit the potential of collaboration across action areas and address systemic research questions that are at the interface of two or more energy areas.

This development was in line with the objectives set by the Federal Council[37] to support the transformation of the Swiss energy system and optimise the structure of Swiss energy research by promoting collaboration and coordination between research institutions. In the re-application process for the second funding period, the SCCERs proposed six JAs involving between two and all eight SCCERs (see overview on page 247).

Innosuisse decided to promote all six JAs with total funding of CHF 7.7m. All JAs started their work in 2017 and by the end of the Energy Funding Programme had achieved most of their objectives, some of which were very ambitious given the novel nature of the project format. The identification of common definitions for interdisciplinary variables or analysis methods proved to be challenging and time-intensive. This was also true for JA CEDA, which was created to develop a common basis for the energy-systemic assessment of six demonstrators (see page 267).

Thanks to the enthusiasm and motivation of the partners involved, both JA CEDA and all the other JAs overcame these initial challenges and achieved remarkable results. JASM, for instance, created a cross-SCCER modelling framework (see page 248) that went beyond the models used in the individual SCCERs and thus exemplified the added value generated by combining the efforts of different research areas to analyse the entire system.

Although the mainly technical SCCERs also considered economic, social, political and/or legal aspects, it was widely accepted that these factors are and will be of the utmost importance for the introduction of new technologies and services. As a result, most JAs not only included but also specifically worked on questions at the interfaces of technical and non-technical areas. For example, JA Mobility modelled mobility behaviour based on extensive empirical information and identified aspects that promote or hinder the achievement of energy and climate goals (see page 280).

In the opinion of the experts that evaluated the JAs, these activities involving different energy research areas and disciplines are and will become more important as the realisation of the Energy Strategy 2050 advances.

[37] Federal Council (2012): Dispatch on the"Coordinated Energy Research in Switzerland"action plan – measures for the years 2013–2016. Bundesblatt 47, 9017–9064.

6 Joint Activities

Scenarios and Modeling (JASM)

Participating SCCERs:

FEEB&D / EIP / SoE / BIOSWEET /FURIES / HaE Storage / Mobility / CREST

▶ p. 248–253

The evolution of mobility: A socio-economic analysis (Mobility)

Participating SCCERs:

CREST / Mobility

▶ p. 280–286

Integrated development processes for hydropower and deep geothermal projects (IDEA-HDG)

Participating SCCERs:

CREST / SoE

▶ p. 254–259

White Paper on the Perspectives of Power-to-Product (P2X) Technology in Switzerland

Participating SCCERs:

FURIES / HaE Storage / CREST / Mobility / BIOSWEET

▶ p. 273–279

Socio-economic and technical planning of multi-energy systems (RED)

Participating SCCERs:

FEEB&D / FURIES / CREST

▶ p. 260–266

Coherent Energy Demonstrator Assessment (CEDA)

Participating SCCERs:

FEEB&D / HaE Storage / Mobility / BIOSWEET

▶ p. 267–272

More about the SCCER
▶ p. 18–244

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Joint Activity

Scenarios and Modelling (JASM)

Participating SCCERs
FEEB&D / EIP / SoE / BIOSWEET / FURIES / HaE Storage / Mobility / CREST

Contact
Dr. Gianfranco Guidati
ETHZ (2017–2020)

There is strong demand from industry, science and public administration for robust and authoritative scenarios regarding the development of the Swiss energy system over the next few decades. To meet this demand, JASM combined the modelling capabilities of all eight SCCERs to develop such scenarios.

Objectives

The main objective of JASM was to build a cross-SCCER modelling framework with a common data infrastructure, coherent basic assumptions regarding exogenous variables and the ability to harness the joint power of different modelling approaches, platforms and codes. This joint modelling framework was and will continue to be used for the following tasks:

- to define representative scenarios to be modelled at different spatial levels and timescales, involving key stakeholders from industry and from federal and cantonal offices;
- to benchmark and validate modelling approaches and results, with the option of also testing those produced by industry and private consultants;
- to issue periodic reports, authoritative evaluations and policy recommendations, including future updates of the outlook for national energy.

What was achieved

The modelling framework was established, combining complementary and distinct models with a view to simulating energy transition pathways for Switzerland. This framework allows researchers to expand on the modelling developed and used in each SCCER while still preserving the specificity of the individual approaches. It was able to harness the joint power of different modelling approaches, incorporating both system-wide and sectoral perspectives. At its core are the energy system models, which represent the whole system and in particular the interdependencies between energy supply and demand. These are fed by a series of sectoral models for building stock, industry, transport, electricity generation and transmission, etc.

> This framework has the potential to facilitate future joint research and ensure a higher degree of coherence in energy simulation and forecasting.

The modelling framework is based on a shared data infrastructure that includes both historical data and assumptions about future paths for a set of common drivers of energy demand and supply, such as macroeconomic parameters and resource and technology characteristics. These common assumptions were defined through intensive collaboration. Both the modelling framework and the data infrastructure are well documented and offer great potential for use in future work and by other modellers. JASM researchers defined interesting energy transition scenarios with the SFOE and modelled them using – and thus proving the effectiveness of – the new framework.

Contribution to the Energy Strategy 2050 and the network of research institutions

The joint modelling framework developed by JASM was used to simulate a set of energy transition scenarios based on different assumptions about future climate policy, the availability of technology and degrees of energy markets integration with the EU. These simulations provided guidance on what can be achieved with current and planned policies and the additional measures that would be needed to achieve the ambitious goals of Swiss energy and climate policy. In particular, they showed which technologies, investments and policies are needed. The pathways are realistic in terms of the availability of resources and technology and the necessary infrastructure (e.g. system adequacy). Close cooperation with the SFOE guaranteed that these results would feed into policymaking alongside official energy perspectives.

The exchange of information and ideas on models, technologies, scenarios and data that took place in JASM helped everyone improve their own modelling, strengthening the entire community and enriching modelling for everyone.

Assessment of the achievements

JASM managed to bring together the pieces it needed to draft three possible futures for the Swiss energy system. Researchers learned to exchange information and ideas on their macroeconomic and sectoral models across disciplines, share data and agree on scenario assumptions. This framework has the potential to facilitate future joint research and ensure a higher degree of coherence in energy simulation and forecasting.

However, these models are admittedly limited in terms of their capacity to simulate the effects of policies. They can show what the future might look like, and which technologies and investments are needed, but not how to get there. Nor are they particularly suitable for estimating the costs and benefits of energy transition outside of direct investment and operating costs.

Recommendations

- **Need for carbon capture and negative emissions**
  To achieve net-zero emissions in 2050, at least 9 Mt/a of CO_2 needs to be captured and stored. These emissions include unavoidable emissions from waste incineration and cement plants. Switzerland's CO_2 storage potential is likely to be insufficient, however, meaning that it will need to link up with foreign storage sites.

- **Hydrogen needs to be promoted**
  To achieve net-zero emissions in 2050, an annual net contribution of 10–20 TWh/a of hydrogen is needed, mainly for the indirect electrification of mobility, especially for freight transport, CHP and industrial heat. This hydrogen will be produced through a mix of electrolysis, gas reforming and biomass gasification.

Finances and capacity of the JA

JASM's activities, and in particular the development of research capacity, had total financing of CHF 5.6m between 2017 and 2020. The Innosuisse support was CHF 2m. JASM did not wholly fulfil the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period. The targets were achieved over the entire Energy Funding Programme, however.

Research Capacity + Operating Expenses + Other direct costs

Financial reports 2017–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**2'000'000**	**2'079'511**	**643'124**	**922'314**	**5'644'949**
Share in percentage	35%	37%	12%	16%	**100%**
Ratio (Innosuisse = 100%)	100%	104%	32%	46%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcounts financial report 2020**	**JA-related average activity rate** in %
Professor	1.5	4	38%
Assistant Professor / Lecturer	0.0	0	0%
Senior Researcher	1.7	7	25%
Post Doc	3.8	5	76%
Technician	0.2	1	15%
PhD Student / Research Assistant	4.0	8	50%
Other	0.2	3	8%
Total	**11.4**	**28**	**41%**

As at the end of 2020, 28 researchers were involved in JASM. This corresponds to 11.4 FTEs.

Conclusion and outlook

JASM was established as a Joint Activity between all the SCCERs to respond to the strong demand from industry, science and public administration for robust and authoritative scenarios regarding the development of the Swiss energy system. Based on a common data infrastructure, coherent basic assumptions and close interdisciplinary cooperation, it aimed to use different modelling approaches, platforms and codes to identify ways of decarbonising the Swiss energy system and analyse variants. Researchers from a wide range of disciplines combined their sectoral perspectives to create a single overall picture. The new Swiss-Energyscope (ETHZ) and the improved Swiss-Energyscope (EPFL) are now strong models that can be used to describe possible pathways and simulate new variants. The simulations show which technologies, investments and policies are needed. Concrete recommendations for policy measures and actions can be formulated on the basis of sound modelling.

Even though the JASM joint framework was unable to obtain funding for structured future cooperation, it seems obvious that after years of collaboration the models will continue to contribute to the development of the energy transition roadmap. What is not clear, however, is how the teams operating these models will obtain updates of the sectoral scenarios that they integrated so well into a single system picture.

Further Information

LITERATURE

Bollinger A. (2020): Energy Supply System Optimization Baden Nord. JASM final report.

Guidati G., Marcucci A., Damartzis T., Burg V., Schildhauer T., Giardini D. and Kröcher O. (2021): Biomass and Waste Potentials and Conversion Pathways for Energy Use, JASM-BIOSWEET paper. JASM final report.

Guidati G., Marcucci A. and Giardini D. (2021): Probabilistic Assessment of the Swiss Energy Strategy – Scenario Analysis with the SES-ETH Model. JASM final report.

Gupta R.K., Sossan F. and Paolone M. (2020): PV Generation Hosting Capacity of Medium Voltage Distribution Grids of Switzerland. JASM final report.

Li X., Damartzis T. and Maréchal F. (2020): Decarbonization of Swiss energy systems in 2050: Integrated scenario analysis with the SES-EPFL model. JASM final report.

Marcucci A., Panos E., Guidati G., Lordan-Perret R., Schlecht I. and Giardini D. (2021): JASM Framework and Drivers Definition. JASM final report.

Marcucci A., Guidati G. and Giardini D. (2021): Documentation of the Swiss Energy Scope – ETH model. JASM final report.

Panos E., Kober T., Kannan R. and Hirschberg S. (2020): Long-term energy transformation pathways – Integrated scenario analysis with the Swiss TIMES energy systems model. JASM final report.

Schlecht I. and Weigt H. (2020): JASM transmission adequacy assessment. JASM final report.

Streicher K., Allan J., Murray P. and Bollinger A. (2020): Energy Efficiency from Buildings Retrofitting. JASM final report.

Yilmaz S., Murray P., Bollinger A. and Guidati G. (2020): Hourly Demand Profiles for Space Heating and Electricity. JASM final report.

Zuberi J., Li X., Wallerand S.A., Maréchal F. and Patel M. (2020): Energy efficiency in the Industry Sector. JASM final report.

WHITE PAPER

Marcucci A., Guidati G., Panos E., Kober T., Ramachandran K., Hirschberg S., Bauer C., Schildhauer T., Streicher K.N., Yilmaz S., Zuberi J., Patel M., Schlecht I., Lordan-Perret R., Weigt H., Li X., Gupta R., Damartzis T., Maréchal F., Paolone M., Bolliger A., Murray P., Berger B., Sanchez D.C., Burg V. and Giardini D. (2020): Net-zero greenhouse gas emissions for Switzerland – Results from the Joint Activity Scenarios & Modelling. ETHZ.

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Joint Activity

Integrated development processes for hydropower and deep geothermal projects: regulatory, political and participatory perspectives (IDEA-HDG)

Participating SCCERs
CREST / SoE

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Hydropower (HP) and DGE have a crucial role to play in the Swiss energy transition due to their controllable productions levels and large potential. However, these projects often encounter difficulties during the planning and authorisation phases due to complex authorisation procedures and objections from local communities, NGOs or the general public.

Objectives

- The objective of JA IDEA-HDG was to provide recommendations on how project development processes (public engagement), the legislative framework and governance structures could be enhanced to resolve conflicts between stakeholders and thus increase investment in HP and DGE projects.

- Research was conducted in two workstreams (WSs) WS 1 focused on stakeholders and governance structures (cantonal and national legislation and non-legal governance structures). The aim was to identify typical conflicts of interest and ways of addressing them under current governance structures through pathway analysis and modelling.

- WS 2 sought to provide information on how socio-political barriers can be identified at an early stage of projects and how public engagement procedures can be used to prevent unnecessary friction.

What was achieved

One early finding was that the two technologies have different key actors in terms of social acceptance and are affected by very different economic and technical issues. In the case of DGE the main issues are public support and acceptance, whereas the decisive actors for HP are operators, environmental NGOs and cantons. With regard to the latter, conflicts are mainly reported in the event of interference with nature conservation. Within DGE, there is an important difference between DGE for heating, which is well accepted because it causes hardly any seismicity, and DGE for electricity production, which faces strong political and societal resistance. As for stakeholders, most municipalities are in favour of promoting DGE heating, while only very specialised undertakings are interested in promoting DGE electricity. These insights influenced subsequent research activities.

A survey of public opinion on DGE revealed that the key predictors for the risk perception of an earthquake are information-processing factors such as having heard of an earthquake or having experienced an earthquake caused by DGE. Technology benefit perception also proved to be a more important predictor of acceptability than risk perception.

JA IDEA-HDG focused on in-depth studies of knowledge and the role of information levels. One core finding was that while a portion of the population had a relatively good objective knowledge of both DGE and HP, a substantial number of people were completely misinformed, revealing knowledge deficits. Whether or not people are willing to take in new pieces of information is not objective knowledge but self-assessed knowledge, i.e. the feeling that they can understand further information. Based on these findings, JA IDEA-HDG developed policy recommendations on how to address citizens and steer the policy debate.

Research activities also focused on the cantonal perspective and stakeholder involvement. The HP study not only identified the conflict between energy production and environmental regulation as a major challenge, but also showed that the main problem is a lack of clarity on hydropower issues in federal regulations. As for DGE, researchers proposed a platform for better coordination of the different actors involved in DGE production.

Contribution to the Energy Strategy 2050 and the network of research institutions

JA IDEA-HDG mainly emphasised and demonstrated that social acceptance and clear operational and regulative structures are decisive for the realisation of further HP and DGE projects in Switzerland. It identified a number of factors and approaches for improving the current situation. The most important of these could be improved communication between and integration of relevant stakeholders (which could differ between renewable energy sources).

However, the findings also highlighted challenges that appear difficult to solve in the short and medium term. In this vein, JA IDEA-HDG can be seen as the starting point for future research activities that focus even more closely on the interface between legal and social sciences with a view to successfully launching new HP and DGE projects.

> Social acceptance and clear operational and regulative structures are decisive for the realisation of further HP and DGE projects in Switzerland.

From the outset, JA IDEA-HDG recognised the need for interdisciplinary research activities. The successful collaboration between ETHZ and the Universities of Lucerne and Basel demonstrated the potential of a coordinated research approach. Highlighting this topic at national and international conferences also helped boost its visibility. The comparison with the Netherlands is a good example of fostering research networks beyond Switzerland's borders.

Assessment of the achievements

The most important achievement might be the recognition that including social context is a crucial step in all HP and DGE projects. There were also other clear outcomes such as the recommendations to enhance coordination between federal and subnational levels and improve people's knowledge by providing clear and independent information.

The increased visibility of this kind of research activity and the improved collaboration between experts within Switzerland can also be described as a major achievement.

Overall, JA IDEA-HDG thus provided a series of rather novel scientific findings on the role of social discourse in the context of HP and DGE projects.

Recommendations

- When developing DGE projects, companies should pay more attention to their framing. This development process should enable companies to become embedded in a local social context. This means connecting with existing discourses about the wishes of the community, its development plans and political orientation.

- Given that the political debate on DGE is still nascent, great caution is necessary when guiding people's (and parties') discourse in relation to this issue. The fact that subjective knowledge and effective objective knowledge are not always congruent has to be taken into account when designing communication and engagement strategies for DGE projects. Further instruments are needed to encourage people who are especially uninformed about the topic to engage with more information.

- Stronger coordination between federal offices (and other actors) would facilitate the work of the cantons. Administrative and economic actors are particularly relevant for HP projects.

Finances and capacity of the JA

JA IDEA-HDG's activities, in particular the development of research capacity, had total financing of CHF 2.6m between 2017 and 2021[38]. Innosuisse support was CHF 989,580. JA IDEA-HDG did not wholly fulfil the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20/21 period. The targets were achieved over the entire Energy Funding Programme, however.

Research Capacity + Operating Expenses + Other direct costs

Financial reports 2014–2021	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**989'580**	**877'952**	**298'909**	**444'945**	**2'611'386**
Share in percentage	38%	34%	11%	17%	**100%**
Ratio (Innosuisse = 100%)	100%	89%	30%	45%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcounts financial report 2020**	**JA-related average activity rate** in %
Professor	0.2	3	7%
Assistant Professor / Lecturer	0.3	2	16%
Senior Researcher	0.0	0	0%
Post Doc	2.2	8	28%
Technician	0.0	0	0%
PhD Student / Research Assistant	1.4	5	28%
Other	0.0	0	0%
Total	**4.1**	**18**	**23%**

As at the end of 2020, 18 researchers were involved in JA IDEA-HDG. This corresponds to 4.1 FTEs.

[38] Due to the Covid-19 pandemic Innosuisse allowed the SCCERs and JAs to use Innosuisse funds also from January to March 2021. Not all SCCERs and JAs made use of this possibility.

Conclusion and outlook

JA IDEA-HDG was undoubtedly a very important activity, highlighting the problems in governmental regulatory strategies and in planning and licensing procedures for hydropower and DGE. Researchers analysed the difference between proceedings and legal remedies and how these can be used in practice for different purposes.

It is very obvious that security and acceptance are crucial for both technologies, which are intended to make a significant contribution to the realisation of the Energy Strategy 2050. The interdisciplinary approach adopted within JA IDEA-HDG was needed in order to successfully analyse these barriers in HP and DGE projects. Research in this field is now much more coherent among Swiss energy experts. Some outcomes still appear to be at a preliminary stage. Further research into social and legal sciences, more project activities like JA IDEA-HDG, and thus more funding, are necessary in this important field.

Further Information

LITERATURE

"Geothermie-Kommunikation ist Knochenarbeit". Geothermie-Schweiz Newsletter, 30.01.2019.

"Développement de la géothermie: Etat fédéral, cantons, municipalités, qui donne le ton?". Geothermie-Schweiz-Newsletter, 19.12.2019.

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Joint Activity

Socio-economic and technical planning of multi-energy systems (RED)

Participating SCCERs
FFEEB&D / FURIES / CREST

Contact
Prof. Dr. François Maréchal
EPFL (2017–2020)

JA RED explored the coupling of the electrical grid with heat and gas systems and addressed the socio-economic aspects of the multi-energy systems and smart grid solutions developed by SCCER-FURIES in its Romande Energie and Arbon demonstrators.

Objectives

- The aim of this multidisciplinary activity was to combine competences from three different SCCERs, adding value to the two demonstrators and resulting in a turnkey solution for DSOs.
- Research in WP 1 focused on technical aspects relating to the planning of multi-energy systems at building, district and community level.
- Research in WP 2 focused on socio-economic aspects relating to multi-energy systems and other smart grid solutions and the search for new business models to promote them.
- The results were to be validated in real-world scenarios centered around the existing Romande Energie demonstrator and to some extent the Arbon demonstrator, then generalised to make them applicable to other DSOs.

What was achieved

WP 1 created guidelines for the planning of future multi-energy systems, including an analysis of energy demand at building level and integration into district models taking grid restrictions into account. Academic partners collaborated with local authorities on a step-by-step basis in the following activities: an analysis of the potential of renewables and waste heat in the communities of Rolle and Mont-sur-Rolle, allowing first conclusions to be drawn in respect of Rolle's energy plan; the creation of scenarios for future energy demand based on refurbishment rates, planned demolition and planned construction; and the development of future energy system designs to maximise the use of renewable energy resources. The analysis methods used were integrated into planning tools that can be applied to other regions.

A deployment plan was defined for Rolle and Mont-sur-Rolle, possible regulations and incentives that would support implementation were identified in collaboration with the cantonal energy office, and an action plan was derived. The recommended actions were clearly structured in terms of thematic areas and short to long-term focus, but remained at a systemic level (e.g. "encourage more efficient investment in distributed energy systems" or "understand the synergies between electricity and heat systems and networks"). It was not made clear who should address them.

In WP 2, a platform for validating business models for the implementation of renewable energy resources at regional level (TREES) was applied to three different decentralised flexibility business models: battery swarm, district battery and multi-energy flexibility. A user interface enabled the project partners to perform business model evaluations easily for these scenarios, applying a wide variety of assumptions such as technology learning curves, incentive models and percentage of battery capacity made available by the owner. The project partner Romande Energie directly financed the integration of the third business model (multi-energy flexibility) and a scenario analysis based on this model. A comparative analysis of the regions of Romande Energie and Arbon Energie was also conducted to study the expected dynamics of diffusion of solar prosumers and home storage solutions and provide a comparison with the district battery business case. The results highlighted the impact of local tariffs on the attractiveness of prosumer concepts. A GIS-based energy planning tool for identifying the best solution for meeting energy needs was developed for Romande Energie. It will be used to address the needs of real estate promoters for greener buildings that valorise local energy resources.

Contribution to the Energy Strategy 2050 and the network of research institutions

JA RED provided tools and methods for addressing business, planning and regulatory issues. It carried out prototypical planning for real-world examples of renewables integration, creating methods that can be applied to other regions. It supported local, cantonal and federal authorities in planning the transformation of regions towards the goals of the Energy Strategy 2050 and identified regulatory barriers or effective incentives.

The work on business model evaluation was also valuable for companies facing the challenge of entering new business fields and needing to assess the opportunities and risks, since they often lack expertise in the area of renewable energies.

A tool for urban energy planning led to the creation of a spin-off company that commercialises part of this solution for energy label communities.

A tool for urban energy planning led to the creation of a spin-off company that commercialises part of this solution for energy label communities, ZHAW is now also using the interactive TREES platform for other utilities, and a GIS-based energy planning tool was developed for Romande Energie. While the intended focus was on the Romande Energie demonstrator and use cases, the next step should be to transfer the findings to other DSOs.

JA RED increased collaboration between partners at various levels, including the sharing of data and methods, the use of complementary expertise in Joint Activities, and joint meetings with authorities. JA RED's partners are aware of the benefit of interdisciplinary exchanges and of access to the experiences and results of other partners.

Assessment of the achievements

JA RED's activities were in line with the original work plan. They were enhanced by additional validation activities carried out on the basis of the collaboration established with implementation partners after the project was approved.

The research groups involved in JA RED were aware of international research in their respective areas, and the results presented advanced the state of the art. Given the large number of researchers involved, however, JA RED's scientific output was low in terms of peer-reviewed publications. JA RED's activities were focused on extending the ongoing activities of its participating SCCER partners towards implementation rather than on driving substantially new research.

Recommendations

- **Refine the role and responsibilities of local, cantonal and federal authorities in the implementation of the Energy Strategy 2050**
  Authorities can play a catalytic role in the implementation of the Energy Strategy 2050 by improving the conditions for the implementation of multi-energy grid solutions via energy plans, support measures and revisions of energy law.

- **Develop a decentralised production and flexibility market**
  Decentralised production and a flexibility market could make a significant contribution to the Energy Strategy 2050. Decentralised concepts require flexibility, but without a market for the latter investor uncertainty will remain an obstacle to implementation.

- **Create a database for energy planning purposes**
  A significant amount of data is available that could be used for precise energy planning and is not subject to privacy issues. However, a large portion of this data is only discoverable by experts. A central, publicly accessible database needs to be created in order to collect data for energy planning uses.

Finances and capacity of the JA

JA RED's activities, and in particular the development of research capacity, had total financing of CHF 3.6m between 2017 and 2020. The Innosuisse support was CHF 894,183. JA RED fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period. Funding from own sources and competitive federal funds clearly exceeded the requirement.

Research Capacity + Operating Expenses + Other direct costs

Financial reports 2017–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**894'183**	**994'232**	**1'183'617**	**554'863**	**3'626'895**
Share in percentage	25%	27%	33%	15%	**100%**
Ratio (Innosuisse = 100%)	100%	111%	132%	62%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcounts financial report 2020**	**JA-related average activity rate** in %
Professor	0.2	3	8%
Assistant Professor / Lecturer	0.0	0	0%
Senior Researcher	1.5	8	19%
Post Doc	0.2	1	20%
Technician	0.3	2	15%
PhD Student / Research Assistant	4.2	12	35%
Other	0.1	1	5%
Total	**6.5**	**27**	**24%**

As at the end of 2020, 27 researchers were involved in JA RED. This corresponds to 6.5 FTEs.

Conclusion and outlook

JA RED research led to some initial practical results and also to new research questions that the partner institutions have decided to continue working on. These questions concern a number of fields:

1. identifying methods for rolling out the planning, assessment, continuous adaptation and evaluation of regional, renewable energy systems to municipalities and communities in Switzerland

2. finding the best solution for the future between the extremes of a fully centralised and a fully decentralised energy system, taking into account all stakeholders from building owners to network operators and utilities

3. finding viable combinations of technical multi-energy hub solutions and corresponding business models that link efficient technology with economically realistic implementation options

4. addressing barriers relating to regulatory issues or customer acceptance

In conclusion, JA RED enabled teams from Empa, HSLU, ZHAW and EPFL to collaborate on multi-energy systems, grid integration and business models with the strategic industry partner Romande Energie and the cantonal and local authorities in Rolle and Mont-sur-Rolle. The participation of the industry partner and public stakeholders allowed the researchers to validate the proposed approaches in specific relevant cases and is a first important step towards overcoming the barriers to implementation caused by uncertainties regarding the interplay of technical options, new business models, incentives and regulations. The development of a market for service providers utilising the methodologies and tools should be supported by the authorities.

Task sharing was a key factor in the generation of these results, and collaboration should be stepped up in this key cross-disciplinary field of implementation-oriented research.

Further Information

LITERATURE

Kubli, M. and Canzi, P. (2021): Business strategies for flexibility aggregators to steer clear of being "too small to bid". Renewable and Sustainable Energy Reviews 143, 110908.

Middelhauve L., Baldi F., Stadler P. and Maréchal F. (2021): Grid-Aware Layout of Photovoltaic Panels in Sustainable Building Energy Systems. Frontiers in Energy Research 8, 573290.

Stadler P., Girardin L., Ashouri A. and Maréchal F. (2018): Contribution of Model Predictive Control in the Integration of Renewable Energy Sources within the Built Environment. Frontiers in Energy Research 6, 22.

PRESENTATIONS

Comment rendre une ville autonome en énérgie. Presentation by François Maréchal at TEDxGeneva.

Comment la Suisse est devenue indépendante et neutre. Presentation by François Maréchal at TEDxMartigny.

Authors
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Joint Activity

Coherent Energy Demonstrator Assessment (CEDA)

Participating SCCERs
FEEB&D / HaE Storage / Mobility / BIOSWEET

Contact
Dr. Gil Georges
ETHZ (2017–2020)

In the course of their work, the SCCERs established a large number of demonstrator platforms and systems. JA CEDA was initiated to create a data exchange and communication platform with the aim of creating cross-links between the various projects.

Objectives

The four SCCERs participating in JA CEDA brought together six (multi-)energy demonstrators. While there were major differences in the specific objectives of these demonstrators, their shared goal was to explore novel energy technologies in the context of the Energy Strategy 2050. With this in mind, the goal of JA CEDA was to provide a common basis for the energy-systemic assessment of the different conversion and storage technologies investigated.

This was achieved by examining a set of demand profiles (over time) to derive plausible usage profiles that future energy devices might encounter, while at the same time defining and cataloguing mutually consistent operational characteristics of the devices studied.

What was achieved

JA CEDA's work was organised in three WPs: generation of comparable performance characteristics for the technologies investigated (WP 1); provision of relevant demand data for the technologies and devices investigated (WP 2); and integration of data for energy-systemic case studies (WP 3). The main challenges encountered by JA CEDA were aligning measurement procedures between the different demonstrator platforms based on their comparability, and adequately addressing the data needs of energy modellers based on the case studies carried out, which were ultimately expected to lead to new insights at a systemic level.

> The CEDA database is a repository of energy flow models that describe the converters and storage devices investigated in any of the participating demonstrators.

Data from the six energy demonstrator platforms grouped under JA CEDA – High Efficiency Power-to-Gas Pilot (OST), ESI Platform (PSI), Move (Empa), NEST (Empa), Ehub (Empa) and Grid to Mobility Demonstrator (EPFL) – was used to establish a database comprising 27 different energy technologies. CEDA archetypes were then defined for each technology. From a technical perspective, an archetype is a standardised specification sheet that defines the technology modelled, describing the device it has been based upon and the extent to which this model may be used to represent similar devices.

The core deliverable of JA CEDA was the CEDA database, a repository of energy flow models that described the converters and storage devices investigated in any of the participating demonstrators. The models were designed to fit the modelling paradigm of most energy system modelling frameworks.

Establishing the CEDA database and generating appropriate data proved to be a challenging and time-consuming task. The full set of archetypes and associated data were due to be available by the end of the overall project. An initial selection of case studies were carried out, such as a hydrogen distribution study (from production sites to fuel stations) or power-to-gas implementation on a national scale.

Further promising results can be expected if the CEDA database is made accessible via open access publication, for specific projects such as the ReMaP platform (ETHZ) or as a tool for exploring new business cases.

Contribution to the Energy Strategy 2050 and the network of research institutions

JA CEDA's activities touched on a highly relevant aspect of the Energy Strategy 2050 when it comes to bringing together the various new energy technologies and finding optimised approaches at a systemic level for different dimensions such as the technical integration of the different technologies, their economic optimisation and/or other aspects such as geographical, spatial and resource/potential-related issues. The complex nature of the different solutions and their dependence on a wide range of technological, local, economic and environmental parameters mean that case studies are the most appropriate form of tangible results. JA CEDA therefore made more of an indirect rather than a direct contribution to the Energy Strategy 2050 by connecting real-life experience from the demonstrators and modelling assumptions at a systemic level.

One immediate outcome of JA CEDA was closer cooperation between the different energy demonstrators and their respective research groups and a stronger link with the world of the energy modellers. Given the methodological challenges involved in bringing all these different elements together, it is debatable whether the database can and will be used for future assessments of this kind, particularly as the data collection process will need to be continuously updated in line with technological progress and expected developments in respect of investment costs due to global market expansion.

Assessment of the achievements

The work plan was successfully completed within the project lifetime. A number of methodological challenges were encountered when bringing together the different energy demonstrators, which address different energy markets and technologies and are at varying stages of development and differing scales. This was also true when it came to harmonising the various technological concepts and their respective research groups and tackling the different worlds of experimental researchers and energy system modellers. A great deal of work was therefore necessary to identify a sound and acceptable design for the CEDA database.

Recommendations

JA CEDA showed the importance and necessity of an interdisciplinary exchange of ideas between the experimental and modelling community. Such an exercise calls for effort from both sides, and the resources required to overcome the gap between the different mindsets are not necessarily available.

The recommendations are that:

- modellers should use the CEDA archetype concept as a template for structuring and streamlining the debate, and extend the existing database;
- experimental researchers should feed their data into the CEDA database in order to continuously improve this valuable database;
- the CEDA database should continue to be developed and updated;
- companies and governmental organisations should use case studies based on the database as a feasible simulation tool for exploring new business cases that support the energy transition.

Finances and capacity of the JA

JA CEDA's activities, and in particular the development of research capacity, had total financing of CHF 5.3m between 2017 and 2020. Innosuisse support was CHF 1,645,135.
JA CEDA fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period.

Research Capacity + Operating Expenses + Other direct costs

Financial reports 2017–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**1'645'135**	**1'276'512**	**1'479'017**	**900'843**	**5'301'507**
Share in percentage	31%	24%	28%	17%	**100%**
Ratio (Innosuisse = 100%)	100%	78%	90%	55%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcounts financial report 2020**	**JA-related average activity rate** in %
Professor	0.0	1	3%
Assistant Professor / Lecturer	0.0	0	0%
Senior Researcher	2.1	12	18%
Post Doc	1.5	7	22%
Technician	3.0	14	22%
PhD Student / Research Assistant	2.3	3	75%
Other	0.3	2	16%
Total	**9.3**	**39**	**24%**

As at the end of 2020, 39 researchers were involved in JA CEDA. This corresponds to 9.3 FTEs.

Conclusion and outlook

JA CEDA undertook the challenging task of bringing together the most important results from a number of recent (multi-)energy demonstrator projects realised in Switzerland over the past few years and fostering closer links between their research teams by building a common, easy-to-use and well-organised platform to support data exchange, communication and coordination. The concrete deliverable was the CEDA database, comprising archetypes of 27 different energy technologies and associated data provided by the various demonstrators and processed to make them more generic. The challenge was not only to define appropriate archetypes in order to make the various demonstrators more comparable, but also to provide a useful dataset that can be used by energy modellers to study specific case studies at a systemic and more general level. It took a great deal of time and effort to build the database, which was due to be complete by the end of the project.

Initial case studies were carried out to demonstrate the benefits of this approach. In an ideal scenario, future modelling work will make increasing use of the CEDA database as a data source, provided that it yields the expected added value in respect of previous practice and is continuously updated as the different technologies develop and new results are generated from the ongoing operation of the various demonstrators. Maintaining and updating the database in ongoing and future projects will therefore be crucial if the tool is to be used more systematically.

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Joint Activity

White Paper on the Perspectives of Power-to-Product (P2X) Technology in Switzerland

Participating SCCERs
FURIES / HaE Storage / CREST / Mobility / BIOSWEET

Contact
Dr. Tom Kober
PSI (2017–2020)

Power-to-X (P2X) refers to technologies that convert (green) electricity into gases, liquids or heat that can be stored on a long-term basis and used as feedstock for many kinds of energy use or for the production of chemicals. "X" often stands for hydrogen, synthetic gases such as methane, or synthetic fuels such as diesel, gasoline or kerosene).

Objectives

Long-term (days, months) storage is particularly important for energy systems that are heavily reliant on intermittent renewable energy sources such as photovoltaics and wind power. Such sources sometimes produce much more and sometimes much less electricity than is needed at any given moment, but electricity cannot be stored.

Many experts consider P2X technologies to be very promising, as they offer CO_2-free energy carriers such as hydrogen for future mobility, industrial processes and electricity production in dark and/or calm weather conditions. Other experts doubt that P2X can make a significant contribution due to its low conversion efficiency and hence high costs.

However, the arguments depend strongly on the particular energy system in question and its framework, meaning that careful analysis is required for each specific energy landscape. This is what the White Paper on P2X provides[39].

[39] Kober T., Bauer C., Bach C., Beuse M., Georges G., Held M., Heselhaus S., Korba P., Küng L., Malhotra A., Moebus S., Parra D., Roth J., Rüdisüli M., Schildhauer T., Schmidt T.J., Schmidt T.S., Schreiber M., Segundo Sevilla F.R., Steffen B. and Teske S.L. (2019a): Perspectives of Power-to-X technologies in Switzerland – A White Paper. PSI, Villigen (available in German, French and English).

What was achieved

The White Paper provides a candid and thorough review of the perspectives of P2X in Switzerland. First, it sets out what P2X actually means and which aspects of P2X are discussed and which not (e.g. power-to-heat). It also briefly explains chemical processes like electrolysis and the various methods of producing "X" (power-to-power, power-to-methane, power-to-liquids), including some remarks about their technology readiness. Second, the White Paper shows why P2X may be important for Switzerland, in particular because it considerably enhances the flexibility of the energy system. This may be required to meet the challenges of future trends, especially given that (intermittent) renewable energies may come to dominate Swiss energy supply. Third, it includes a detailed cost analysis of the various P2X pathways based on current regulatory and economic conditions. Fourth, the paper discusses the embedding of P2X into energy markets, broken down into an analysis of the available sources of carbon/CO_2, the aspects for integrating P2X into the power system and into gas markets, and its potential contribution to various clean mobility solutions and industrial processes. Finally, the White Paper also examines innovation aspects and discusses the legal framework based on existing laws that affect P2X in potentially relevant markets.

At first glance, the White Paper appears to be rather long (40 pages) and does not provide the clear-cut conclusions that might be desired by decision-makers. As things stand, however, this is a suitable approach for P2X, because it is a rather complex topic and dependent on future technological, regulatory and economic conditions.

The White Paper is complemented by a Supplementary Report[40] (over 80 pages), which is actually a longer version of the White Paper containing more material and deeper insights into various aspects. It goes into more detail, performs more comprehensive analysis and provides more references. As such it is closer to a scientific publication and is therefore more useful for experts and readers who like more information.

Contribution to the Energy Strategy 2050 and the network of research institutions

The Energy Strategy 2050 is heavily reliant on the implementation of renewable energies to meet ambitious CO_2 reduction targets. Since most renewable electricity sources are strongly dependent on weather conditions, electricity needs to be stored in sufficient quantities and at acceptable prices. An important set of electricity storage options is summarised under P2X. These have both advantages (e.g. flexibility)

[40] Kober T., Bauer C., Bach C., Beuse M., Georges G., Held M., Heselhaus S., Korba P., Küng L., Malhotra A., Moebus S., Obrist M., Parra D., Roth J., Rüdisüli M., Schildhauer T., Schmidt T.J., Schmidt T.S., Schreiber M., Segundo Sevilla F.R., Steffen B. and Teske S.L. (2019b): Perspectives of Power-to-X technologies in Switzerland – Supplementary Report to the White Paper. PSI, Villigen.

and disadvantages (e.g. costs) and fit future needs in different ways. A careful and complete analysis of the various P2X options is therefore required, and this is provided by the White Paper.

As some P2X options are at an early stage of development while others have already reached a high TRL, a complete overview of the entire field is needed, in particular as a means of determining where R&D ought to be strengthened and which options ought to be pushed. The White Paper summarises the present state of knowledge and shows that for some decisions (e.g. a new hydrogen strategy), much more knowledge is required.

The White Paper provides a careful and complete analysis of the various P2X options.

The White Paper profited substantially from the intensive cooperation between various academic institutions in Switzerland (ETH Domain, cantonal universities, universities of applied sciences) and industry partners. This cooperation in energy research has been triggered to a large extent by the Energy Funding Programme programme and by the implementation of JAs. This is particularly true in the case of P2X, which can only be successfully addressed through a holistic approach based on cooperation between institutions and different sub-fields of energy research and development.

Assessment of the achievements

The White Paper and Supplementary Report review a host of P2X options together with their advantages and implications for the future energy system, including detailed cost analyses based on the current legal framework, TRLs and market conditions. This is an important prerequisite for future decision-making, in particular long-term decisions on new concepts (battery vs. fuel cell vehicles) and infrastructure investments.

The White Paper and Supplementary Report cover all aspects of the initial work plan. They reflect the international state of the art and reference many relevant publications in the field. Such projections onto the Swiss energy system are unique and therefore make an important contribution to the energy discussion.

The projections ought to be extended beyond the near future, to a point when intermittent renewable sources dominate electricity production and all neighbouring countries are also heavily reliant on intermittent sources.

Recommendations

- **Strengthen the systemic view**
  The flexibility of the Swiss energy system needs to be adapted to the requirements of intermittent renewable sources, namely that long-term (seasonal) storage of electricity will play a more important role than it does today. Decisions about future transport and heating concepts also need to be prepared and made.

- **Further develop the technology**
  Several processes need to become more mature (higher efficiency, greater stability, lower costs) before they can be implemented in the energy system. This will require timely research and development.

- **Adapt the market and legal framework**
  The implementation of greater flexibility and the introduction of new technologies like P2X into the market require significant changes to the legal framework before these technologies can become competitive. A long-term perspective will stimulate development but requires immediate action.

Finances and capacity of the JA

JA P2X's activities, and in particular the development of research capacity, had total financing of CHF 373,984 between 2017 and 2018. Innosuisse support was CHF 115,416. JA P2X did not fully fulfil the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–18 period. The targets were achieved over the entire Energy Funding Programme, however.

Research Capacity + Operating Expenses + Other direct costs

Financial reports 2017–2018	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**115'416**	**143'721**	**97'497**	**17'350**	**373'984**
Share in percentage	31%	38%	26%	5%	**100%**
Ratio (Innosuisse = 100%)	100%	125%	84%	15%	

FTEs by type of position as at 31 December 2018

	FTEs financial report 2020	**Headcounts financial report 2020**	**JA-related average activity rate** in %
Professor	0.4	5	7%
Assistant Professor / Lecturer	0.1	1	8%
Senior Researcher	0.6	6	10%
Post Doc	0.1	1	7%
Technician	0.0	0	0%
PhD Student / Research Assistant	0.3	3	10%
Other	0.1	1	9%
Total	**1.5**	**17**	**9%**

As at the end of 2018, 17 researchers were involved in JA P2X. This corresponds to 1.5 FTEs.

Conclusion and outlook

The White Paper gives a thorough and comprehensive review of the perspectives of P2X technologies in Switzerland. It provides enough explanation to understand the chemical processes and also looks at the industrial challenges, including costs and potential revenues. It shows how P2X production processes could be integrated into the Swiss electricity and gas markets, and possible uses of its products in transport and industry as well as energy storage. It also addresses legal aspects and possible public support (innovation policy). The White Paper and Supplementary Report reflect the international state of knowledge, adhere to high international scientific standards and concentrate on projecting all aspects of the Swiss-specific situation.

P2X may play a very important role in the future of the Swiss energy system in 20–30 years' time. However, many developments and decisions need to take place much earlier, in fact as soon as possible. If the various challenges mentioned in the White Paper and Supplementary Report are not met in time, the energy system may become unstable and/or more expensive, or not sufficiently successful on its way to a low-carbon future. However, the costs of P2X pathways are currently still too high due to insufficiently developed technologies and an inappropriate framework, preventing significant autonomous implementation of P2X. Immediate action is therefore recommended in view of the long timescales needed. The White Paper may serve as a compass for identifying the next steps in energy and energy research policy.

Further Information

LITERATURE

Kober T., Bauer C., Bach C., Beuse M., Georges G., Held M., Heselhaus S., Korba P., Küng L., Malhotra A., Moebus S., Parra D., Roth J., Rüdisüli M., Schildhauer T., Schmidt T.J., Schmidt T.S., Schreiber M., Segundo Sevilla F.R., Steffen B. and Teske S.L. (2019): Perspectives of Power-to-X technologies in Switzerland – A White Paper. PSI, Villigen (available in German, French and English).

Kober T., Bauer C., Bach C., Beuse M., Georges G., Held M., Heselhaus S., Korba P., Küng L., Malhotra A., Moebus S., Obrist M., Parra D., Roth J., Rüdisüli M., Schildhauer T., Schmidt T.J., Schmidt T.S., Schreiber M., Segundo Sevilla F.R., Steffen B. and Teske S.L. (2019b): Perspectives of Power-to-X technologies in Switzerland – Supplementary Report to the White Paper. PSI, Villigen.

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Joint Activity

The evolution of mobility: A socio-economic analysis (Mobility)

Participating SCCERs
CREST / Mobility

Contact
Prof. Dr. René Schumann
HESO-SO (2017–2020)

At the core of JA Mobility was detailed scientific analysis and forecasting of individual and household behaviour in view of the development and introduction of new technologies and services relevant to energy consumption in the transport sector.

Objectives

JA Mobility defined the following goals in its original proposal:

- To develop approaches for reducing mobility-related household energy demand, incorporating conventional incentive-based approaches such as taxes, social determinants and information-based measures.

- To develop coherent scenarios for a future Swiss mobility system, including an assessment of the energy and CO_2 impact of mobility scenarios along with information on which policy measures would be required to make different scenarios more likely.

- To conduct one or two field experiments to test the impact of programmes that use “soft measures”, such as information regarding lifetime costs, policy measures or environmental impacts.

The work was organised into three workstreams.

What was achieved

JA Mobility focused on studying the role of behavioural aspects in the mobility sector. Various methodological approaches were chosen (1) to obtain a consistent picture of the population's mobility behaviour and mobility-related energy consumption; and (2) to identify measures for reducing mobility-related energy consumption or convert it from fossil to "green".

Empirical knowledge was acquired on several fundamental aspects that determine mobility-related energy consumption: transport choices for different trip types (UniNe), sustainable travel choices (UniBas), use of autonomous vehicles (UniBas), use of electric cars, charging behaviour and its effect on local grids (ETHZ), pro-environmental choices, and push-and-pull strategies (UniBas). The data enabled researchers to improve modelling to produce better, more realistic representations of individual behaviour. In particular, they were able to show how and to what extent mobility pricing can motivate people to change their behaviour, but also which areas of policy intervention have non-monetary aspects that can trigger behavioural change.

The model-based work was integrated into overall SCCER activity by docking with the Energy Policy (EPOL) and the Net-Zero (CLI) future energy scenarios that were defined from an economic-technical perspective (cost-minimising technology mix) in JASM. Options were investigated relating to how behavioural changes can be brought about not only through price-based measures. Households were represented in broad areas of behaviour relevant to energy consumption, such as homeworking, car ownership, ride-sharing or online shopping. The results provided a clear understanding of which combinations of household behaviour patterns can promote or hinder the achievement of energy or climate goals, and which levers must be set in motion at either local or national level.

This work was supplemented by a large-scale field test, which not only revealed that price measures affect mobility behaviour but also showed how they work with regard to the time of travel and choice of travel mode. Only information-based measures did not seem to have significant effects.

Overall, the interconnected JA Mobility workstreams created a comprehensive and coherent picture of the mobility behaviour of population groups, its importance for energy consumption and how it can be controlled, thereby providing direct starting points for political action and the concrete design of behaviour-influencing measures.

Finally, and obviously not something that was foreseen in the work plan, the Covid-19 pandemic and the strong mobility measures taken in spring 2020 provided a unique set of conditions for a large-scale real-world experiment and associated extended data collection.

JA Mobility's results were substantiated in an impressive list of scientific publications and reports.

Contribution to the Energy Strategy 2050 and the network of research institutions

JA Mobility did not deliver a contribution to be used immediately for the introduction of products or services – that was never its aim. The direct contribution that its results can nevertheless make lies in the targeted, tailored development of measures and interventions designed to influence the behaviour of people and households specifically in the area of mobility itself or in activities linked to mobility. The measures considered in JA Mobility ranged from the implementation of new technologies such as electric vehicles or the flexibilisation of charging processes in the context of vehicle-to-grid to the expansion of public transport with additional or alternative services or the redesign of the working world via homeworking. This means that the insights and results obtained in JA Mobility are relevant not only in the context of future support for policymaking and planning but also for economic decisions intended to fulfil energy and climate goals.

Insights and results obtained in JA Mobility are relevant not only in the context of future support for policymaking and planning but also for economic decisions intended to fulfil energy and climate goals.

One major contribution from a scientific and also research policy perspective came from the coupling of energy and mobility research, permitting innovative approaches to cross-sectoral analysis. This contribution was important because sector coupling is usually considered from a purely technical and economic perspective. In this case, however, it was supplemented and expanded by the user component, making forecasts and scenarios more realistic.

JA Mobility was also successful in building stronger ties with relevant stakeholders related to the mobility sector, such as federal offices (Federal Roads Office FEDRO, Federal Office for Spatial Development ARE or the SFOE), railway companies (SBB Swiss Federal Railways) and selected utilities.

Assessment of the achievements

JA Mobility performed excellently in terms of achieving the goals set. This applies both to the content developed and to the insights and results further developed on the basis of existing approaches. As outlined above, particularly innovative elements were the integrated perspective on energy consumption and mobility behaviour and the integration of energy and transport models, enabling both forecasts and an evaluation of the impact of measures for reducing energy use in the mobility sector and beyond. This also means that the institutions involved are among the leading international institutions in this field.

It should also be emphasised that these results were only achieved through interdisciplinary collaboration. JA Mobility thus fulfilled its particularly relevant purpose of connecting researchers from different backgrounds in order to perform joint competitive research. Overall, JA Mobility can be considered to have been a big success.

Recommendations

- **Consider behaviour as a relevant factor and focus on effective behaviour types in further studies and interventions.**
  The mobility behaviour of individuals and households is a relevant variable that should be considered as an active element in achieving the emissions and energy goals of the mobility sector. JA Mobility demonstrated how mobility behaviour is influenceable. Based on the results achieved so far, an in-depth analysis is now required to determine how the relevant types of behaviour can actually be brought about.

- **Use the full portfolio of governance options for the mobility sector.**
  Further work should investigate which mix of interventions has the most promising effects. This applies not least to the mix of national and local interventions.

Finances and capacity of the JA

JA Mobility's activities, and in particular the development of research capacity, had total financing of CHF 6.4m between 2017 and 2021[41]. Innosuisse support was CHF 1,961,055. JA Mobility did not wholly fulfil the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20/21 period. The targets were achieved over the entire Energy Funding Programme, however.

Research Capacity + Operating Expenses + Other direct costs

Financial reports 2017–2020	Innosuisse	Own	Competitive federal funds	Industry and others	**Total**
Total Funding in CHF	**1'961'055**	**2'243'726**	**1'764'784**	**459'784**	**6'429'349**
Share in percentage	31%	35%	27%	7%	**100%**
Ratio (Innosuisse = 100%)	100%	114%	90%	23%	

FTEs by type of position as at 31 December 2020

	FTEs financial report 2020	**Headcount financial report 2020**	**JA-related average activity rate** in %
Professor	1.0	5	21%
Assistant Professor / Lecturer	1.0	2	50%
Senior Researcher	1.3	6	22%
Post Doc	0.6	2	28%
Technician	0.5	1	50%
PhD student / Research Assistant	6.1	13	47%
Other	0.0	0	0%
Total	**10.5**	**29**	**36%**

As at the end of 2020, 29 researchers were involved in JA Mobility This corresponds to 10.5 FTEs.

[41] Due to the Covid-19 pandemic Innosuisse allowed the SCCERs and JAs to use Innosuisse funds also from January to March 2021. Not all SCCERs and JAs made use of this possibility.

Conclusion and outlook

Achieving the energy and climate targets that Switzerland has set for 2050 will require not only the development and implementation of new technologies and services but also knowledge about the behaviour of individuals and households. This is particularly true for mobility, which accounts for around 40% of GHG emissions in Switzerland. With this in mind, JA Mobility focused on investigating how households' mobility behaviour can be influenced and the impact of measures and interventions in different scenarios. JA Mobility has thus created an important basis for evaluating technologies and measures.

JA Mobility has paved the way for integrated energy and mobility research in Switzerland. The joint acquisition of projects shows that the JA Mobility partnership built on methodological issues and collaborations between researchers. It was able to build long-term bridges between research communities that were previously largely separate. JA Mobility demonstrated that multidisciplinary research – bringing together perspectives from a range of experts such as modellers, economists, engineers and social scientists – is not only fruitful but is in fact imperative when it comes to obtaining the required new insights into complex systems.

JA Mobility was by design a highly interdisciplinary research project. As such, it faced the challenges common to all such projects, namely integrating different points of view, methods and domain/discipline-specific wording. JA Mobility actively tackled these challenges, enabling it to deliver valuable insights and establish collaborations that did not exist beforehand. In that sense, JA Mobility endorsed the expectation that interdisciplinary and multidisciplinary projects, while demanding, offer a great deal of potential for important and relevant results. Achieving the energy and climate targets seems almost impossible without projects of this type. The interdisciplinary approaches developed in JA Mobility should definitely be continued.

Further Information

LITERATURE

Klinger N. (2020): Autos können Teil der Lösung sein, aber nicht der wichtigste. VBZ Online.

Schreiber M. (2020): Förderung der Elektromobilität im Strassenverkehrsrecht, Center for Law and Sustainability (CLS), Working Papers Series, Working Paper No. 9.

Schreiber M. and Zumoberhaus M. (2020): Ladeinfrastruktur für Elektrofahrzeuge. Rechtliche Instrumente zur Förderung des Aufbaus privater und öffentlicher Ladepunkte. Center for Law and Sustainability (CLS), Working Papers Series, Working Paper No. 7.

Zumoberhaus M. (2020): CO_2-Reduktion durch emissionsfreie Fahrzeuge. Center for Law and Sustainability (CLS), Working Papers Series, Working Paper No. 8.

Financial overview of the Energy Funding Programme

The activities of the SCCERs and JAs, and in particular the development of research capacity, had total financing of CHF 724.6m between 2014 and 2021[42]. Innosuisse support was CHF 193.8m[43], while the participating HEIs contributed CHF 251.2m and the remaining CHF 279.6m came from competitive federal funds (CHF 149.4m) and from contributions by industry partners and international projects (CHF 130.2m). The Energy Funding Programme fulfilled the financial criterion set by the government and parliament, which required the financial contribution from each of the other sources to be at least 50% of Innosuisse funding for the overall 2014–20 period. For example, the participating HEIs contributed CHF 251.2m of their own funds, which corresponds to 130% of the Innosuisse contribution and is thus above the target value of 50% (see ratios in the table below).

Funding of SCCER activities 2014–21
Research Capacity + Operating Expenses + Other direct costs

Financial reports 2014–2020	Innosuisse	Competitive federal funds	Own	Industry and others	**Total**
Total Funding in CHF	**193'752'651**	**149'447'410**	**251'164'770**	**130'227'539**	**724'592'370**
Share in percent	47%		35%	18%	**100%**
Ratio (Innosuisse = 100%)*	100%	77%	130%	67%	

*Other funding sources needed to be at least 50% of Innosuisse funding for the overall 2017–20 funding period.

As at the end of 2020, 1,356 researchers were involved in the SCCERs, corresponding to 832.5 FTEs. Academics at all levels were involved in the SCCERs, ranging from professors (42.2 FTEs) to senior researchers/postdocs (285.2 FTEs) and PhD students/research assistants (429.2 FTEs). PhD students & research assistants accounted for approximately half of the positions.

[42] Due to the Covid-19 pandemic Innosuisse allowed the SCCERs and JAs to use Innosuisse funds also from January to March 2021. Not all SCCERs and JAs made use of this possibility.

[43] This figure also includes the CHF 3m received by the SCCERs FURIES and Mobility in the context of the Digitalisation action plan (for more information see the webpage of the State Secretariat for Education, Research and Innovation).

Development of research capacity in FTEs

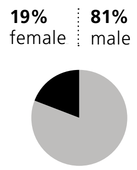
FTEs Financial report **2020**	FEEB&D	EIP	SoE	BIOSWEET	FURIES	HaE	Mobility	CREST	Joint Activities	Total
Professor	2.4	4.9	6.1	3.1	5.5	3.8	3.7	9.7	**3.0**	**42.2**
Assistant Professor / Lecturer	1.3	2.7	4.2	2.5	0.3	5.0	0.4	12.8	**1.3**	**30.4**
Senior Researcher	19.8	6.1	22.3	14.7	22.5	15.6	26.2	7.6	**6.7**	**141.4**
Postdoc	10.3	3.9	29.2	7.6	19.2	25.9	17.4	22.0	**8.3**	**143.9**
Technician	1.1	1.2	3.2	8.8	1.7	7.4	5.6	1.1	**4.0**	**34.0**
PhD student / Resarch Assistant	21.1	25.0	41.1	33.6	91.9	71.8	79.6	47.2	**17.9**	**429.2**
Other	3.3	–	1.2	0.5	0.1	2.8	2.6	0.4	**0.6**	**11.4**
Total	59.3	43.8	107.3	70.8	141.0	132.3	135.5	100.8	**41.8**	**832.5**
2019										
Professor	2.4	3.5	5.2	3.5	4.4	4.4	4.0	9.4	**3.8**	**40.7**
Assistant Professor / Lecturer	1.3	1.2	5.9	3.3	0.1	2.4	0.1	13.2	**2.6**	**30.1**
Senior Researcher	21.1	5.7	30.2	14.4	22.0	22.8	25.0	10.3	**8.8**	**160.2**
Postdoc	13.8	6.2	28.5	12.2	21.7	28.9	22.8	28.6	**6.7**	**169.5**
Technician	1.3	0.7	2.4	11.0	4.7	6.7	5.0	1.1	**3.4**	**36.3**
PhD student / Resarch Assistant	27.9	34.1	53.1	43.4	89.0	78.8	68.3	49.2	**21.7**	**465.5**
Other	3.3	0.1	0.7	0.5	0.1	3.0	1.3	2.6	**1.0**	**12.4**
Total	71.1	51.4	125.9	88.3	141.9	147.0	126.5	114.4	**48.0**	**914.5**
2018										
Total	65.5	53.4	151.6	80.8	123.8	130.2	115.9	114.5	**52.6**	**888.1**
2017										
Total	71.0	49.5	161.0	72.7	126.4	131.8	123.8	127.0	**48.6**	**911.9**
2016										
Total	64.9	40.4	173.0	65.5	108.5	103.3	109.9	119.9	**–**	**785.2**
2015										
Total	69.6	40.8	160.5	57.5	94.1	92.6	91.1	121.6	**–**	**727.9**
2014										
Total	66.4	27.0	121.4	58.9	69.9	87.1	61.1	81.6	**–**	**573.4**

Although the Energy Funding Programme ended on 31 December 2020, more than 1,300 researchers were still working in the SCCERs and JAs on this date. In general, the number of research staff built up over the funding period was always above the planned figures.

FTEs by type of position and funding source
as at 31 December 2020

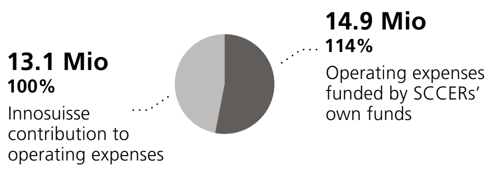
	Innosuisse		Own	Competitive federal funds	Industry and others
	Financial Report	Proposal	Financial Report	Financial Report	Financial Report
Professor	3.8	2.0	31.9	4.1	2.3
Assistant Professor / Lecturer	8.3	11.8	18.0	1.9	2.3
Senior Researcher	50.9	49.8	39.6	31.0	19.9
Post Doc	48.3	98.9	29.1	34.9	31.5
Technician	7.2	7.3	16.6	6.8	3.4
PhD student / Resarch Assistant	104.7	69.2	99.1	140.8	84.7
Other	2.9	1.7	5.4	0.6	2.5
Total	**226.1**	**240.6**	**239.8**	**220.2**	**146.5**
Proposal 2020			**223.4**	**199.7**	

Gender ratio



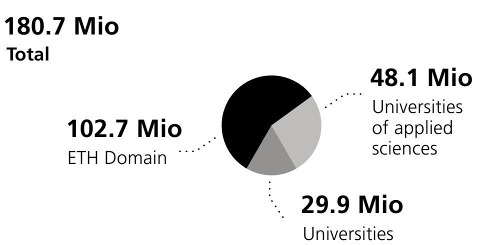
Between 2014 and 2020, an average of 20% of the active researchers involved in the SCCERs were female. 280 female researchers (19% of research capacity) were active in 2020.

Funding ratio
contribution to SCCERs' operating expenses 2014–2020 (in CHF)



The HEIs involved in the SCCERs covered more than 50% of the operating expenses.

Innosuisse funding (research capacity)
by type of HEI 2014–2020 (in CHF)



Universities of applied sciences and universities also played a major role within the SCCERs in addition to the ETH Domain.

Conclusion and outlook

The most important conclusions to be drawn from the activities carried out within the Energy Funding Programme can be summarised as follows. Alongside further innovations in technology, industry, society and policy, one key success factor for the Energy Strategy 2050 will be a new generation of well-trained energy professionals in all relevant disciplines (technical, economic, social and political sciences). In terms of research, the various SCCERs built up more capacity than planned and engaged in intensive collaboration between research groups of different disciplines, including collaboration with industrial partners. The established network comprising the research institutions of the ETH Domain, cantonal universities and universities of applied sciences proved to function very well. The SCCERs also created important new training material for the continuous education of energy professionals, which will be an essential prerequisite for ensuring that innovative solutions are put into practice. Well-conceived KTT concepts were another success factor, closing the gap between the academic and industrial worlds and thus leading to the implementation of innovative concepts. This includes access to laboratories and large-scale demonstrators.

Switzerland's energy and climate goals can only be achieved if the fruitful combination of technological and social science research is not simply maintained but actually reinforced. It will also be increasingly vital to show which particular challenges are posed by both politics and administrations. This is all the more important given Switzerland's specific governance structures with its different and distinct spatial levels.

Key questions – both cross-sector and relating to connecting sectors – can already be formulated today. Which technologies and services contribute and are scalable? What is a good and direct way to implement them? Which political interventions are needed, and at what level should they start? How must interventions be designed to generate the intended effects? How can user participation be made particularly fruitful? In other words, research at the interface of technological and social sciences should continue and play an essential role in the future.

One key success factor for the Energy Strategy 2050 will be a new generation of well-trained energy professionals in all relevant disciplines (technical, economic, social and political sciences).

Looking at the results of the individual SCCERs, the various scientific findings of the **SCCER FEEB&D** clearly showed that the transformation of our energy system away from fossil and nuclear energy and towards net-zero CO_2 emissions cannot be realised through technical innovations alone, but will also require adequate regulations and substantial changes in human behaviour. This applies in particular to the Swiss building stock, which over its whole lifespan generates about 40% of energy demand and roughly 30% of CO_2 emissions, without considering grey energy and embodied CO_2.

Starting with technical aspects at building level, there are a lot of components and systems that need to be installed by building owners. Such investments will usually be made if there is a reasonable return on investment, either due to financial savings or due to higher income from rents. However, users must also contribute, e.g. through increased flexibility on the demand side. Looking at building clusters such as villages, districts or communities, the SCCER FEEB&D's research results showed that decentralised multi-energy systems are technically feasible and economically competitive, particularly in settlements with low density and relatively high solar radiation. In dense urban areas, heat demand can be covered by low temperature networks fed by medium and deep geothermal energy.

Another problem in dense urban centers – heat island effects – were also analysed by the SCCER FEEB&D. The corresponding studies showed that extreme temperature in city centers can be considerably reduced either by arranging and sizing buildings and street corridors appropriately and/or by applying porous outdoor floor surfaces to be wetted periodically, combined with intensive planting. Though the solutions are ready, practical applications are still rather rare, partly because architects, engineers and contractors aren't yet familiar with these new technologies, and partly because building and energy regulations need to be adapted to these concepts.

Although the manifold research results delivered by the SCCER FEEB&D can be expected to make relevant contributions to the transformation of our energy system, one central challenge remains. How can we double the renovation rate of the existing building stock, and who will pay for it? The current rate is 1.0–1.5% per year, meaning that it will take 50 to 70 years to upgrade all existing buildings. Even taking into account the fact that buildings realised during the last two decades will not need an energy-related upgrade until 2050, the targets of the Energy Strategy 2050 will never be achieved at the current renovation rate. The costs of such upgrades are also considerable, mainly due to the relatively high construction costs in Switzerland. As a result, the market alone will not be able to deal with this problem. One possible solution is a combination of an adequate CO_2 levy and substantial government subsidies for homeowners. Neither measure will be easy to implement in a direct democracy like Switzerland.

Turning to increasing energy efficiency in industry, the topic covered by the **SCCER EIP**, the starting point was that domestic industry accounts for about 18% of Switzerland's total final energy consumption and the current policy scenario will not be sufficient to achieve the goals of the Energy Strategy 2050 or even carbon neutrality. The models, methodologies and technologies developed by the SCCER EIP and their consequent implementation will therefore be essential in taking a significant step forward towards carbon-neutral industry.

Comprehensive analyses of several industry sectors produced advice on potential measures. Existing methodological approaches were effectively extended and software tools developed to identify and implement energy-efficiency measures and renewable energies in industrial processes. Initial contacts were made with implementation partners with a view to further rollout.

Significant progress was made on increasing energy efficiency in thermal applications, especially in the field of advanced surfaces for heat transfer, high temperature heat pumps and turbo machinery. The technologies developed are mainly located at demonstrator and prototype level.

Besides energy efficiency, CO_2 capture is also crucial for limiting global warming. While the SCCER EIP's research on adsorption processes and direct air capture was at a basic level, the process developed for embedding CO_2 in recycled concrete is one example of the outstanding applied technological results achieved by the SCCER EIP.

The SCCER EIP made a large number of relevant contributions to increasing industrial energy efficiency and reducing CO_2 emissions. The results of its models showed that current market conditions and political frameworks do not offer sufficient support for the implementation of existing technologies. Regulation therefore needs to be adapted to lower the economic hurdles facing energy-efficient technologies. Further research should also reflect flexible energy consumption, approaches based on the circular economy and applications of less energy-intensive materials in industry. It will be important to further develop these technologies and establish an effective political framework to foster broad implementation.

Switzerland's energy and climate goals can only be achieved if the fruitful combination of technological and social science research is not simply maintained but actually reinforced.

The **SCCER-SoE**'s research focused on two main areas, namely geo-energy and hydropower. In the case of geo-energy, the SCCER-SoE's work helped Switzerland become one of the most important countries for geothermal research, especially in the area of hydraulic stimulation testing. Mastering these methods and developing new schemes will have a large impact on future stimulation. The SCCER-SoE thus had a major impact on the worldwide scientific reputation of geothermal research in Switzerland.

Despite achieving scientifically excellent results in newly established underground laboratories, the research showed that in practice, significant and economically viable contributions to power generation are still a long way off. The expectations for geothermal power generation need to be lowered, but the prospects for geothermal heat are promising. Hydropower will continue to be a central pillar of the Swiss electricity generation portfolio in the future. It became clear that this will only be possible under the best possible conditions: climatic changes and increased environmental requirements will necessitate the construction of new large-scale power plants along with consideration of extensions and renewals. The potential of small hydropower must also be fully exploited. Further hydropower potential is limited and faces considerable obstacles that will not be easy to overcome. The SCCER-SoE helped answer a large number of questions and led to a much better understanding of many aspects. With climate change continuing, and the markets influenced by technological progress, global strategies and governmental decisions, many questions remain unanswered and a number of new questions have come to light. In summary, there is now a deep level of knowledge about the perspectives of further hydropower development, in particular the role of hydropower in the flexible energy market of tomorrow. The role of pumped storage power plants in a scenario involving extensive use of solar and wind energy was clarified.

In terms of contributions to Switzerland's energy goals, in the case of deep geothermal energy there seems to be a need to focus on thermal solutions, which are important for heat supply in urban areas in particular. As for deep geothermal energy electricity, there is now an excellent basis for further research that could open up significant opportunities for new approaches in the future. Strategies for possible underground CO_2 storage also need to be discussed further.

In the case of hydropower, there is a clear need for continued research. The best way to achieve this is if the coherence of the research carried out under the SCCER-SoE approach can be maintained or even developed further. Interdisciplinary approaches that go beyond technology could also be the appropriate way to enable new projects relating to the refurbishment of existing hydropower plants and the realisation of new ones.

The **SCCER BIOSWEET** delivered a significant number of results covering the full range of possibilities for converting organic matter into (bio)energy. Within the area of biogas production based on anaerobic digestion processes, innovative concepts were further developed, promising sound implementation under Swiss conditions. The hydrothermal gasification process was also improved from a TRL of 4 to 7; in the case of low-value biomass (e.g. sewage sludge) in particular, this option can now contribute to corresponding energy-efficient treatment by providing a valuable energy carrier in parallel. The thermochemical methanation process was further developed, enabling the conversion of gasified solid biomass (e.g. demolition wood) into methane as a "green" substitute for natural gas; this also included extensive sulfur analysis.

In addition to the transformation of biomass into a substitute for natural gas, the combustion of solid biomass is another important conversion pathway. Successful research work made existing conversion concepts more environmentally sound, more robust in relation to less-promising solid biofuels, and more efficient in relation to a specific use case.

Very successful work was carried out on biomass depolymerisation and on an improved combination of biological and chemical upgrading processes. The respective utilisation pathways were developed from very low TRLs to a point where a company was founded to bring these results into the markets for raw materials (i.e. fine and bulk chemicals) and potentially for transport fuels.

In addition to tackling different options within the portfolio of biomass to energy, the various research activities extensively investigated the role of bioenergy within the overall energy system and showed that – despite limited resources – bioenergy could play an increasingly important role within the Swiss energy system.

Bioenergy is becoming increasingly important as a key pillar of the Swiss energy system in the context of ongoing defossilisation (reduction of carbon from fossil resources). Biomass resources are limited, however, and are also in demand from the food sector and as raw materials. Biomass is a sustainable source of carbon and thus could provide the carbon needed for industry in a future defossilised world. This implies a need to improve carbon usage efficiency, for example in combination with electricity-based processes. Corresponding research work should be clearly accelerated. Less favourable biomass streams need to be unlocked in the future, including the development of better-adapted technologies and an improved understanding of the given constraints. As the use of selected biomass streams will often be too expensive for exclusive energy provision, combined use as a raw material (e.g. fine chemicals) and as an energy carrier within integrated biorefineries needs to be further developed.

The **SCCER-FURIES** addressed key questions relating to future power grid technologies that could enable a seamless and sustainable power supply based on traditional and new renewable energy resources. The SCCER-FURIES realised a variety of new concepts, components and system solutions for efficiently accommodating and managing large amounts of variable power generation. Successful realisation of grid innovations will require private and industrial end-customers to be included in the discussions. Unless the future strategy can show a win-win situation for all stakeholders, any key changes are likely to encounter opposition. Future work should focus on projects that will enable researchers to show win-win scenarios for implementation and attract the attention of policy-makers. As part of the continental European synchronous system, Switzerland's opportunities to operate networks and implement the Energy Strategy 2050 also depend on developments in Europe. Future scenarios should be tackled jointly with other European transmission system operators to avoid conflicting market solutions in the EU and Switzerland.

The SCCER-FURIES's work on digitalisation should serve as a basis for intensified work in the future, as the issues relating to the digitalisation of energy supply, including security, are key to the transformation of the energy system.

The SCCER-FURIES has developed concrete topics for further research that go beyond the scope of future grids: i) the transition to renewable energy requires further development of the market design; ii) the present scenarios for energy demand in 2050 must be enhanced to reflect, for example, e-mobility, environmental control, energy demand by future communication systems, etc.; iii) a complete study on the limits of PV and wind energy plants in Switzerland should be carried out, considering all barriers such as minimum distances between wind energy plants and houses; iv) the future work on DC should focus more on systems, e.g. reference designs would be more of a research question than operating equipment.

The **SCCER HaE** focused its research on a range of energy storage technologies, covering electricity, heat and fuels (including hydrogen). If fossil energy carriers are to be eliminated in order to meet the climate protection goals, solutions for short and long-term (seasonal) energy storage are required to compensate for the intermittent nature of renewable sources. Short-term storage technologies are available or almost ready for the market. Seasonal storage concepts have only passed the proof of principle or been successful in small-scale demonstration projects, however, and hence still have a lot of room for further improvement.
The Energy Strategy 2050 roadmap provides for the development of seasonal storage concepts for market readiness. More advanced concepts (TRL 6–9), e.g. at demonstrator level, require up-scaling know-how, manufacturing and durability experience, and economic assessments. Such development projects require strong consortia of industry partner(s), who will take the risk of further exploring this technology on a larger scale, and academia to support the process, contributing improvements, innovations and alternatives.
The SCCER HaE's broad industrial network is a sound basis for such ventures. The demonstrators, currently on the kW scale – such as the ESI platform, the many heat storage concepts and the more advanced hydrogen production and storage technologies – belong in the category of advanced concepts. The assessment of energy storage is also one of the most advanced subjects. Although the demonstrators are still in the academic research domain, they are paving the way for future public and private activities.

The transformation of our energy system away from fossil and nuclear energy and towards net-zero CO_2 emissions cannot be realised through technical innovations alone, but will also require adequate regulations and substantial changes in human behaviour.

The more fundamental approaches at TRL 5 and below have to tackle questions relating to materials – an area for universities and large research institutions. Here, the collaborative work that started in the SCCER HaE must continue, e.g. in the NCCR Catalysis. The competences accessible via the SCCER HaE network are of great interest to the R&D departments of large industrial companies.

Nevertheless, support for fundamental research through public funding is still needed. All topics pursued by the SCCER HaE are relevant for the Energy Strategy 2050 and should be targeted for further progress. Seasonal storage and material research in particular are long-term challenges that need to be addressed.

This led to critical progress for individual solutions, increasing the TRL of various approaches and the coherency of the energy research landscape with an increasingly systemic focus.

The **SCCER Mobility** can rightly be described as an experiment whose aim was to merge engineering and social science knowledge in terms of content and methods. It thus not only generated new knowledge but also fostered a broader understanding among the researchers involved in terms of how their respective contributions are embedded in the overall sum of knowledge about the transport system.
The SCCER Mobility developed relevant elements for successful personal and professional discussions across disciplinary boundaries, which will continue beyond the duration of the Energy Funding Programme. Together with JA Mobility, the SCCER Mobility paved the way for integrated energy and mobility research in Switzerland.
It clearly demonstrated the contribution that innovative technologies in the transport sector – and especially in vehicles – can make to reducing CO_2, but also that this alone will not be enough. Rather, behavioural changes will also be essential, changes which are unlikely to be realised without influencing measures. This also applies to technologies that are currently still in a relatively early phase of development, such as connected and autonomous driving. It will then become increasingly important to broaden the scope to include the risks of rebound effects. Digitalisation, real-time connection of vehicles and the availability of data will permit customised and efficient mobility services, including smart trip and traffic planning. Establishing a better link with the user perspective, not only in terms of immediate needs but also with a view to users' rational and emotional attitudes, will enable new technologies to make a greater contribution to the achievement of energy and climate goals.

The **SCCER CREST** was initiated to address the realisation that the transformation of the energy system is not only a technical endeavour but importantly also requires societal, political and economic changes. The SCCER CREST proved the relevance of this notion, demonstrating that the energy transition is indeed contingent on policies and regulations that steer societal, political and economic changes. At the level of households, policies for reducing energy consumption should be targeted at specific groups and lifestyles and should typically combine monetary incentives with non-monetary measures. However, there are still a large number of unknowns regarding households' energy-related behaviour and the possible ways in which this can be changed.
It is also important to better understand the demand for energy services in all other sectors of the economy and to be able to predict energy consumption for different purposes at different times of the day and year. This will be vital for planning the supply side of the energy markets.
The SCCER CREST showed that markets need to be adjusted or redesigned if they are to support a high share of renewable energy without continued market interventions. Designs need to

be identified and implemented that provide sufficient incentives for investments in efficiency improvement, renewable generation, backup capacity and storage and grid extension at the scale needed for the energy transition.

The SCCER CREST also demonstrated that energy policy needs to be adapted at all levels to enable actors to test ideas, business models and new patterns of collaboration. The SCCER CREST itself experienced the difficulties involved in moving from small pilot projects and field experiments to larger transition programmes together with businesses and policymakers. There is still scope for new market designs and corresponding regulations, particularly those that facilitate sector coupling. More concrete information is also still required on how to implement such desirable regulatory and policy contexts at a political level. The diffusion of successful new concepts and products across Switzerland needs to be encouraged.

The SCCER CREST observed that there are still a large number of uncertainties regarding the relationship between Swiss and EU policies and regulations, the cooperation options that would have public support in Switzerland, the mutual benefits of cooperation for Switzerland and the EU, and how this cooperation could be governed.

Any outlook for possible future developments should consider that the energy sector has fundamentally changed since the start of the SCCER CREST project. Economic, innovation, digital and sustainability policy are converging at the political level. All industries are confronted with the increasing importance of a sustainability-driven purpose, and this is also changing the behaviour of investors. New issues such as data sovereignty have gained in importance, resulting in new requirements for energy governance. Innovative business models at the strategic level are being complemented by the emergence of digital AI-based architectures at the operational level, leading to new organisational forms.

The Energy Funding Programme also provided clear insights into not only the specific roles of research and technology, industry and society but also the crucial aspects of the governing regulatory boundary conditions and hence adequate policy measures.

Acknowledging the growing interdependence between different energy conversion and storage technologies along with various socio-economic and political boundary conditions, and hence the relevance of the systemic dimension, the six JAs addressed specific examples of key interdisciplinary research questions that straddle several research fields and two or more SCCERs. The JAs thus not only addressed optimised pathways for complementary technologies in areas such as storage, but also integrated the dimensions of business models, economics, law, policy or social acceptance. In addition, they allowed for increased interaction between experimental proofs of concept and broader modelling approaches. Since the JAs were only launched during the second phase of the Energy Funding Programme, there are many opportunities to further pursue this work and consolidate the initial results obtained. In summary, the eight SCCERs and six JAs made a major contribution to understanding and sharpening the challenges of the Energy Strategy 2050 in relation to the potential of various technologies, their uptake by industry and large-scale deployment, and the corresponding regulatory measures and policy environment needed. Research was clearly strengthened in specific areas and new energy conversion routes explored. This led to critical progress for individual solutions, increasing the TRL of various approaches and the coherency of the energy research landscape with an increasingly systemic focus.

The basic and applied research carried out under the Energy Funding Programme delivered numerous high-quality results that were hugely relevant for the Swiss energy system and its future development. These are documented in a wealth of new scientific publications, PhD theses, review papers and conference contributions. With a total of 23 White Papers covering various subjects in a more easily understandable way (see page 300), the results were also made available to a broader audience – a particularly positive outcome of the programme.

The focusing and alignment of the research landscape achieved through the Energy Funding Programme was remarkable and needs to be maintained in the design of future programmes. Collaboration and interdisciplinarity were key factors in its success. International collaboration in various fields progressed strongly over the course of the Energy Funding Programme, resulting in new relevant international partnerships and projects. Maintaining the cooperative spirit of the SCCERs will be one of the key challenges going forward and an important prerequisite for future innovation in this R&D sector.

Throughout its rather long implementation period (seven years) and significant overall efforts, the Energy Funding Programme also provided clear insights into not only the specific roles of research and technology, industry and society but also the crucial aspects of the governing regulatory boundary conditions and hence adequate policy measures. At the socio-economic level, all results suggest that competitiveness and social acceptance of new solutions will not be sufficient to overcome the challenges of the energy transition. There also needs to be clear will on the part of all stakeholders concerned.

With a total of 23 White Papers covering various subjects in a more easily understandable way (see page 300), the results were also made available to a broader audience – a particularly positive outcome of the programme.

Overview SCCER & JA White Papers

SCCER FEEB&D

Sulzer M. (2020): Paradigm shifts for the Swiss building sector to shape the future energy system.

SCCER-SoE

SCCER-SoE (2020): Sources of Primary Electricity Supply, Synthesis Report, ETHZ (in preparation).

SCCER-SoE (2020): Geothermal Energy, Synthesis Report, ETHZ (in preparation).

SCCER-SoE (2020): Swiss Potential for Hydropower Generation and Storage, Synthesis Report, ETHZ (in preparation).

SCCER-SoE (2020): CO_2 Capture and Storage (CCS) – An Essential Element of the Swiss Climate Strategy, Results from the ELEGANCY Project, ETHZ (in preparation).

SCCER-FURIES

Carpita M., Favre-Perrod P., Razzaghi R., Wang Z., Paolone M., Rachidi F., Dujic D., Christe A., Milovanovic S., Utvic M., Galland O., Allani M., Schultz T., Franck C.M., Tsolaridis G. and Biela J. (2019): Direct current technologies for Switzerland's electricity transmission and distribution.

SCCER-FURIES (2021): Regulatory Barriers for the implementation of smart grid solutions in Switzerland.

SCCER Mobility

Boulouchos K., Cellina F., Ciari F., Cox B., Georges G., Hirschberg S., Hoppe M., Jonietz D., Kannan R., Kovacs N., Küng L., Michl T., Raubal M., Rudel R. and Schenler W. (2017): Auf dem Weg zu einem energieeffizienten und klimafreundlichen Schweizer Mobilitätssystem. SCCER Mobility White Paper 1.

Bach C., Bauer C., Boulouchos K., Bucher D., Cerruti D., Dehdarian A., Filippini M., Held M., Hirschberg S., Kannan R., Kober T., Sugrañes A.M., De Martinis V., Michaud V., Oswald K., Raubal M., Seymour K., Vezzini A. (2021): Pathways to a net zero CO_2 Swiss mobility system. SCCER Mobility White Paper 2.

SCCER CREST

Betz R., Cludius J., Filippini M., Frauendorfer K., Geissmann T., Hettich P. and Weigt H. (2016): Wasserkraft: Wiederherstellung der Wettbewerbsfähigkeit. SCCER CREST White Paper 1.

Ulli-Beer S., Hettich P., Kratz B., Krause T., Kubli M., Walther S. and Kobe C. (2016): Netznutzungstarife im Zielkonflikt: Anreize für den Ausbau erneuerbarer Energien versus Verursachergerechtigkeit. SCCER CREST White Paper 2.

Abrell J., Betz R., Bretschger L., Camenisch L., Cludius J., Heselhaus S., Hettich P., Hoffmann V., Krysiak F., Rausch S., Schleiniger R., Walther S., Weigt H. and Wüstenhagen R. (2017): Was kommt nach der kostendeckenden Einspeisevergütung (KEV): Fördern, Lenken, Abwarten? SCCER CREST White Paper 3.

Burger P., Bezençon V., Brosch T., Carabias-Hütter V., Farsi M., Hahnel U., Hille S., Lanz B., Lemarie L., Moser C., Puntiroli M., Schubert I., Sohre A. and Volland B. (2018): Reduktion der Energienachfrage von Haushalten – erfolgversprechende Schritte auf einem langen Weg. SCCER CREST White Paper 4.

Weigt H., Abrell J., Betz R., Frauendorfer K., Krysiak F., Roux C., Schlecht I., Schleiniger R., Walther T. and Winzer C. (2018): Strommarktdesign: In welche Richtung soll es gehen? SCCER CREST White Paper 5.

Abrell J., Betz R., Kosch M., Piana V., Schleiniger R. and Stünzi A. (2018): Zur schweizerischen Klimapolitik: Wie effizient ist die Bepreisung des fossilen Energieverbrauchs? SCCER CREST White Paper 6.

Thaler P., Hofmann B., Abegg A., Bornemann B., Braunreiter L., Burger P., Dörig L., Ejderyan O., Heselhaus S., Opitz C., Petrovich B., Rinscheid A., Schillig I., Schreiber M. and Sohre A. (2019): Schweizer Energiepolitik zwischen Bund, Kantonen und Gemeinden: Zentralisieren, dezentralisieren oder koordinieren? SCCER CREST White Paper 7.

Filippini M., Burger P., Cerruti D., Gamma K., Haufler F., Lanz B., Patel M., Schubert I. and Sohre A. (2019): Politische Maßnahmen zur Reduzierung der Energieeffizienzlücke. SCCER CREST White Paper 8.

Bencsik B., Kubli M., Markard J., Palmié M., Wemyss D. and Zobel A.-K. (2020): Erfolg durch Partnerschaft: Neue Kollaborationsmodelle für einen Energiemarkt im Wandel. SCCER CREST White Paper 9.

Patel M., Broc J.-S., Cabrera D., Cho H., Eberle A., Federici A., Freyre A., Jeanneret C., Krysiak F., Narula K., Oikonomou V. and Yilmaz S. (2021): Energieeffizienzprogramme – Lehren aus und für die Schweiz. SCCER CREST White Paper 10.

Krysiak F., Burger P, Blumer Y., Braunreiter L., Cometta C., Emmenegger R, Lordan-Perret R., Marcucci A., Roux C. and Sohre A. (2021): Von Modellen zu Visionen: Ansätze zur Ergänzung von quantitativen Energieszenarien. SCCER CREST White Paper 11.

JA White Paper on the Perspectives of Power-to-X technologies in Switzerland

Kober T., Bauer C., Bach C., Beuse M., Georges G., Held M., Heselhaus S., Korba P., Küng L., Malhotra A., Moebus S., Parra D., Roth J., Rüdisüli M., Schildhauer T., Schmidt T.J., Schmidt T.S., Schreiber M., Segundo Sevilla F.R., Steffen B. and Teske S.L. (2019a): Perspectives of Power-to-X technologies in Switzerland – A White Paper. PSI, Villigen (available in German, French and English).

Kober T., Bauer C., Bach C., Beuse M., Georges G., Held M., Heselhaus S., Korba P., Küng L., Malhotra A., Moebus S., Obrist M., Parra D., Roth J., Rüdisüli M., Schildhauer T., Schmidt T.J., Schmidt T.S., Schreiber M., Segundo Sevilla F.R., Steffen B. and Teske S.L. (2019b): Perspectives of Power-to-X technologies in Switzerland – Supplementary Report to the White Paper. PSI, Villigen.

JA Scenarios and Modelling

Marcucci A., Guidati G., Panos E., Kober T., Ramachandran K., Hirschberg S., Bauer C., Schildhauer T., Streicher K.N., Yilmaz S., Zuberi J., Patel M., Schlecht I., Lordan-Perret R., Weigt H., Li X., Gupta R., Damartzis T., Maréchal F., Paolone M., Bolliger A., Murray P., Berger B., Sanchez D.C., Burg V. and Giardini D. (2020): Net-zero greenhouse gas emissions for Switzerland – Results from the Joint Activity Scenarios & Modelling. ETHZ.

List of Abbreviations

°C	Degree Celsius
AA-CAES	Advanced adiabatic compressed air energy storage
AC	Alternating current
AD	Automated driving
ADAS	Advanced driver assistance systems
AGC	Automatic generation control
AI	Artificial intelligence
ARE	Swiss Federal Office for Spatial Development
ASF	Adaptive solar façade
ATLS	Adaptive traffic light system
BA	Bachelor of Arts
BEV	Battery electric vehicle
BFH	Bern University of Applied Sciences
BIOSWEET	Biomass for Swiss Energy Future
BiPV	Building-integrated photovoltaics
bn	Billion
BULGG	Bedretto Underground Laboratory for Geosciences and Geoenergies
CA	Capacity Area
CAS	Certificate of Advanced Studies
CCEM	Competence Center Energy and Mobility
CCP	Capacitive coupled pair
CCS	Carbon capture and storage
CECB	Swiss Cantonal Energy Certificate for Buildings
CEDA	Coherent Energy Demonstrator Assessment
CEMS	Customer energy management system
CFD	Computational fluid dynamics
CHP	Combined heat and power
CLI	Net-Zero
CLS	Center for Law and Sustainability
CNF	Carbon nanofibre
CO	Carbon monoxide
CO_2	Carbon dioxide
$CO_{2\,eq}$	Carbon dioxide equivalent
CO_2/kWh	Carbon dioxide per kilowatt hour
$CO_2/(m^2*a)$	Carbon dioxide per square metre per year
CO_2/m^3	Carbon dioxide per cubic metre
COMSOL	COMSOL Multiphysics® simulation software
COMTES	EU project on compact thermal energy storage technologies
COP	Coefficient of performance
COSMO	Consortium for Small-scale Modeling
CREST	Center for Research in Energy, Society and Transition
CSEM	Centre Suisse d'Electronique et de Microtechnique (Swiss Center for Electronics and Microtechnology)
CTI	Commission for Technology and Innovation
DBSCAN	Density-based spatial clustering of applications with noise
DC	Direct current
DDC	Data-driven control
DEEDS	DialoguE on European Decarbonisation Strategies
DGE	Deep geothermal energy
DME	Dimethyl ether
DNS	Demand-not-served
DSO	Distribution system operator
Eawag	Swiss Federal Institute of Aquatic Science and Technology
EBC	Energy in Buildings and Communities
ECA	External cost assessment
ECES	Energy Conservation through Energy Storage
EEB&D	Energy Efficient Buildings & Districts
EERA	European Energy Research Alliance
EGR	Exhaust gas recirculation
EGS	Enhanced geothermal systems
EHV	Extra-high-voltage
EIP	Efficiency of Industrial Processes
EMC	Electromagnetic compatibility
EMPA	Swiss Federal Laboratories for Materials Science and Technology
EMTR	Electromagnetic Time Reversal
EnAW	Energy Agency of the Swiss Private Sector
EnFK	Conference of Energy Specialists
ENS	Energy-not-served
ENTSO-E	European Network of Transmission System Operators for Electricity
EPE	Electric Power Engineering
EPF	Swiss Federal Institute of Technology
EPFL	Swiss Federal Institute of Technology Lausanne
EPG	Energy performance gap
EPOL	Energy Policy
ESR	Energie Sion Région
ETH	Swiss Federal Institute of Technology
ETHZ	Swiss Federal Institute of Technology Zurich
FEDRO	Federal Roads Office
FEEB&D	Future Energy Efficient Buildings & Districts
FESS	Forum Energiespeicher Schweiz (Swiss Energy Storage Forum)
FHNW	University of Applied Sciences and Arts Northwestern Switzerland
FlexDCS	Design for a flexible DC source
FOAG	Swiss Federal Office for Agriculture
FOEN	Swiss Federal Office for the Environment
FORGE	Frontier Observatory for Research in Geothermal Energy
FRS	Future Resilient Systems
FRTP	Fibre-reinforced thermoplastic
FTE	Full-time equivalent
FURIES	Future Swiss Electrical Infrastructure
g	Gram
GFPP	Gas-fired power plant
GHG	Greenhouse gas
GIS	Geographic Information System
HaE	Heat and Electricity
HEI	Higher education institution
HES-SO	University of Applied Sciences and Arts Western Switzerland
HEV	Hybrid and electric vehicle
HEV TCP	Hybrid and Electric Vehicle Technical Collaboration Programme
HiLo	High performance (structural and comfort) with Low energy (embodied and operational)
HP	Hydropower
HSG	University of St.Gallen
HSLU	Lucerne University of Applied Sciences and Arts
HTG	Hydrothermal gasification
HTHP	High-temperature heat pump
HVAC	Heating, ventilation and air conditioning
HVDC	High-voltage direct current
ICA	Internal cost assessment
ICT	Information and communication technology
IEA	International Energy Agency
IDEA-HDG	Integrated development processes for hydropower and deep geothermal projects

IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IPA	Impact pathway approach
IRENA	International Renewable Energy Agency
ISCHESS	Integration of stochastic renewables in the Swiss electricity supply system
ISGAN	International Smart Grid Action Network
IT	Information technology
JA	Joint Activity
JASM	JA Scenarios & Modelling
K	Kelvin
kg	Kilogram
km^3	Cubic kilometre
KODEWA	Kompakte, dezentrale Warmwasserbereitstellung aus Fortluft und Solarstrom (compact domestic hot water preparation from exhaust air and solar power)
kt/a	Kilotonnes per year
KTT	Knowledge and technology transfer
kV	Kilovolt
kVA	Kilovolt-ampere
kWh/m^2	Kilowatt hour per square metre
kWhel/a	Kilowatt hours electrical per year
kWth	Kilowatt thermal
l	Litre
LCA	Lifecycle analysis
LCP	Liquid crystal polymer
Li-ion	Lithium-ion
LTN	Low-temperature network
LV	Low-voltage
m	Millions
m^2	Square metre
m^3	Cubic metre
m^3/a	Cubic metres per year
MaaS	Mobility-as-a-service
MAS	Master of Advanced Studies
MCDA	Multi-criteria decision analysis
mg	Milligram
mg/m^3	Milligrams per cubic metre
mm	Millimetre
MMC	Modular Multilevel Converter
ms	Millisecond
MSc	Master of Sciences
Mt/a	Megatonnes per year
MV	Medium-voltage
MWh	Megawatt hour
MWth	Megawatt thermal
Na-ion	Sodium-ion
NCCR	National Center of Competence in Research
NEST	Next Evolution in Sustainable Building Technologies
NGO	Non-governmental organisation
NRP	National Research Programme
OEM	Own equipment manufacture
OER	Oxygen evolution reaction
OME	Polyoxymethylene dimethyl ether
OpenFOAM	Open-source software for Computational Fluid Dynamics
OST	Eastern Switzerland University of Applied Sciences
P2X	Power-to-x
PASREN	Provision of ancillary services from regional energy systems
PCA	Principal Component Analysis
PDC	Phasor data concentrator
PELS	Power Electronics Society
PhD	Doctor of Philosophy
PHEV	Plug-in hybrid electric vehicle
PJ	Petajoule
PJ/a	Petajoule per year
pkm	Passenger kilometre
POM	Political Measures
PMU	Phasor measurement unit
PSI	Paul Scherrer Institute
PTFE	Polytetrafluoroethylene
PV	Photovoltaics
R&D	Research and development
RC	Resistance-capacitance
RDES	Renewable decentralised energy system
RED	Romande Energie Demonstrator
REeL	Romande Energie ELectric network in local balance
ReMaP	Renewable Management and Real-Time Control Platform
ROI	Return on investment
RTM	Resin transfer moulding
SCCER	Swiss Competence Center for Energy Research
SEMP	Swiss Energy Modelling Platform
SFOE	Swiss Federal Office of Energy
SHC	Solar Heating and Cooling
SHEDS	Swiss Household Energy Demand Survey
SiC	Silicon carbide
SIoT	Swiss Internet of Things
SME	Small and medium-sized enterprise
SNG	Synthetic natural gas
SNSF	Swiss National Science Foundation
SoE	Supply of Electricity
SOP	Soft open point
SoS	Security of supply
SST	Solid-state transformer
STEM	Swiss TIMES Energy Systems Model
SUPSI	University of Applied Sciences and Arts of Southern Switzerland
SWEET	Swiss Energy Research for the Energy Transition
t	Tonne
TCA	Total cost assessment
TCP	Technology Collaboration Programme
TES	Thermal energy storage
TIMES	The Integrated MARKAL-EFOM System
TJ	Terajoule
TJ/a	Terajoules per year
TREES	Transition Management of Regional Energy Systems
TRL	Technology readiness level
TSO	Transmission system operator
TWh	Terawatt hour
TWh/a	Terawatt hours per year
TWhel/a	Terawatt hours electrical per year
TWhth/a	Terawatt hours thermal per year
UC	University of California
UFD	Ultra-fast disconnector
UMAR	Urban Mining and Recycling experimental unit
UniBas	University of Basel
UniBe	University of Bern
UniFr	University of Fribourg
UniGE	University of Geneva
UniLu	University of Lucerne
UniNe	University of Neuchâtel
USI	Università della Svizzera Italiana
vkm	Vehicle kilometre
VFT	Very fast transient
VSE	Verband Schweizerischer Elektrizitätsunternehmen (Association of Swiss Electricity Companies)
WEC	World Energy Council
WEP	Wind energy plant
WP	Work Package
WS	Workstream
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research
WWTP	Wastewater treatment plant
ZHAW	Zurich University of Applied Sciences
ZnO	Zinc oxide

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