ESC

Energy Science Center

Energy Strategy for ETH Zurich

Energy Science Center

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Editorial

In the fall of 2006, the Energy Science Center (ESC) of ETH Zurich embarked on the task of adjusting its plans for future energy-related teaching and research to match the magnitude of the challenges in the national and global arena. At that time the executive committee of the Energy Science Center instructed an internal working group to begin formulating a research strategy. At the same time, ETH's Vice President for Research assigned to the ESC the task of providing ETH Zurich's Executive Board with guidance on energy issues. This guidance was to include strategic considerations for a future sustainable energy system as well as an assessment of ETH's strengths and its prospects for continuing research in areas highly relevant for the future.

Three-quarters of a year and many meetings later, the working group presented its first draft strategy. This described the current status of energy research at ETH as well as important contributions of the researchers involved. After the conclusion of internal consultations, the members of the ESC decided to produce a final report and to make it accessible to a wider audience for internal and external communication.

An important message of the strategy is this: Energy research needs additional basic knowledge and new technologies to fulfill demanding social expectations and to grapple with the immense tasks assigned to it. However, innovative research projects and concepts do not rely solely on the natural and engineering sciences. Significant contributions from the social sciences are just as essential.

The Energy Science Center, active now for three years, has contributed significantly to the integration of specialists and disciplines and has already become indispensable for the coordination of energy-relevant activities in research and teaching at ETH Zurich.

The ESC members will continue to be actively involved so that the cross-cutting strategic and operational effort just begun here in energy research and teaching can yield fruit. This strategy report constitutes a first important step towards an intensified dialogue both within ETH Zurich as well as with interested partners in industry, government, and society.

For the Energy Science Center of ETH Zurich,
Konstantinos Boulouchos

Strategy for energy research at ETH Zurich: History and goals

The Energy Science Center (ESC) of ETH Zurich, which was founded in early 2005, now numbers some 40 affiliated professors and institutes working on various themes in the energy field. Together, over the past 12 months, they have developed a strategy for energy research and teaching at ETH. The strategy's goals are to:

- Exchange information about current activities and existing knowledge in the ETH community of researchers, teachers, and students. The current network should be further strengthened by the addition of interested external specialists, and dialogue among all the participants should be intensified;
- Develop a plausible vision of a possible transformation path that reduces greenhouse gas emissions from the global and Swiss energy systems in the 21st century, with emphasis on the role of science and technology;
- Formulate a set of recommendations to ETH Zurich's Executive Board with regard to future areas of strategic importance in the field of energy; and at the same time formulate measures to position the energy research and teaching undertaken at ETH Zurich more prominently in the international arena;
- Promote a sustainable energy system and indicate possible paths leading to the development of such a system. An energy strategy report should allow the ESC and ETH Zurich to act as an "honest broker" in national and international discussions on energy problems.

Work approach

The ESC executive committee appointed a working group consisting of Konstantinos Boulouchos (chair), Claudia Casciaro, Klaus Fröhlich, Stefanie Hellweg, Hansjürg Leibundgut, and Daniel Spreng for the development of the research strategy. The working group decided on an approach based on the following steps:

- Compile information from all ESC members on their current activities and future interests in energy research;
- Demonstrate the performance, relevance, and potential of energy-related research and teaching at ETH Zurich;
- Determine the key fields for future energy technologies and research, taking the central challenges for the global energy system in the 21st century as a starting point.

Overview of current energy-related activities within ETH Zurich

Energy-related themes are being investigated in 12 of ETH Zurich's 16 departments. In addition to the work within individual disciplines, cross-cutting relationships are also being examined, including technological, economic, and social-science aspects. The following themes illustrate some of the current emphases in research and teaching:

- Renewable energy carriers, the storage of electrical energy, and the development of new materials for the energy system.
- The development of clean and efficient technologies for energy conversion and distribution. Research here is focused on areas such as fuel cells, combustion processes, nuclear technology, heat transfer mechanisms, simulation and control methods as well as supply networks.

- Research into environmentally-friendly transportation technologies. This includes the development of efficient and emission-optimized low-carbon fuels and the simulation of transportation and urban planning concepts.
- The development of methods of life-cycle analysis as well as material- and energy-flow analysis, which can help identify optimization potentials capable of fully exploiting increases in energy efficiency.
- Innovations in energy systems require not only technologies but also the interplay of technology, actors, institutions, and rules. Thus, in joint projects among several institutes, social scientists actively participate in researching and developing sustainable energy systems.
- Since 2007, the interdisciplinary "Master of Science in Energy Science and Technology" program has been offered, and the "Master in Nuclear Engineering" program will begin in 2008 together with Ecole Polytechnique Fédérale de Lausanne (EPFL) and with the support of the Paul Scherrer Institute (PSI) and Swissnuclear. These complement the long series of energy-related courses on offer.

The major challenges

A plausible sustainability vision should be responsive to the central challenges facing the global energy system. The ESC intends to adjust its priorities for energy research accordingly.

- **Challenge 1: Climate change**
  Greenhouse gas emissions, closely coupled to energy use, must be quickly and comprehensively reduced. The concentration of CO_2 should be about 500 ppm if the average temperature increase on earth — according to the Intergovernmental Panel on Climate Change (IPCC)[1] — is to be limited to 2° C.
- **Challenge 2: Access to energy services**
  Fundamentally limited, non-renewable energy sources require making secure and reliable access to largely renewable energy carriers paramount. Measures should be chosen that provide for the necessary energy services and that neither hinder the social and economic development of a country nor cause international conflicts.
- **Challenge 3: Local pollutants**
  Locally- and regionally-relevant pollutants such as fine particulates, hydrocarbons, NO_x, and SO_x as well as other harmful emissions (ozone, particulate matter) should be minimized. In addition, the quantity of problematic long-term (nuclear and other) waste should be reduced.
- **Challenge 4: Risks and societal benefits**
  Technological, economic, and corporate risks within and around the energy system should be balanced by considerations of their benefit to society.

1 Source: Intergovernmental Panel on Climate Change, Summary for Policymakers, Emission scenarios, 2000, ISBN: 92-9169-113-5

Vision of a transformation path for a sustainable energy system

The ESC vision shall point to a plausible path towards stabilizing global CO_2 emissions at a climate-compatible level. The transformation path is to link increases in energy efficiency with substitutions for fossil energy. The vision draws on existing national and global energy concepts and scenarios. Elaborating the vision and the path to its realization yielded the following important conclusions:

Switzerland's primary energy flow and energy-related CO_2 emissions should conform to the global per capita average value. This means that towards the end of the 21st century, the primary energy demand should be between 4 and 6 kilowatts per capita. The exact value depends on the level of improvement attained in energy efficiency as well as on the mix of CO_2-free primary energy from which electricity is generated. Here the emissions limit of 1 ton of CO_2 per capita must be strictly adhered to. In detail, the following benchmark data are significant for the transformation path:

- The energy needs for long-distance mobility (people and freight, by air, sea, and land) will be met to a large extent with fossil primary energy in the form of hydrocarbons. The corresponding primary energy demand amounts to about 400 watts per capita. Associated with this is an emission of close to 1 ton of CO_2 per capita.
- The primary energy demand for the heating sector (low, medium, and high temperature) is covered with about 1,100 watts per capita — solar thermal, with ambient heat and biomass (without taking into account the electricity needed for heat pumps). This area will be decarbonized, i.e. CO_2-free.
- About 1,100 to 1,200 watts per capita of end-energy, which must be in the form of electricity, is necessary in addition to current energy services, which must be provided more efficiently, so that capacity is freed to power heat pumps as well as to cover the energy needs for short- and mid-range transportation (people and freight). This assumes that the appropriate infrastructure has been sufficiently developed and that weather-dependent energy generated from renewable sources can be efficiently stored.

For the time being, that is over the coming decades, increased energy efficiency will play a critically important role. In this transition phase various primary energy carriers coexist (fossil fuels with CO_2 sequestration, hydropower, nuclear, and wind power). Photovoltaics will take on an especially important global role in the second half of the century. Only solar-derived electricity has the long-term potential to cover the largest portion of demand. However, enormous technological progress and a massive reduction in costs are necessary to realize this. In the long-term a change to low-carbon and carbon-free primary energy carriers is necessary in order to effectively lower CO_2 emissions. An essential element of this strategy is increasing electricity's share to about 50% of final energy demand and to about 70% of primary energy demand. In this way the decarbonization of first the heating sector (completely) and later the transportation sector (extensively) can be accomplished. Here, though, the long duration of reinvestment cycles for the corresponding infrastructure must be taken into consideration.

The vision outlined above delineates, from today's perspective, a temporally-harmonized, optimal transition from measures necessary to increase energy efficiency to the substitution for carbon-based energy sources. The ESC vision supports without qualification the promotion of increased energy efficiency as required by the concept of the 2000 Watt Society. However, whereas the latter concept is to be understood as a qualitative metaphor for limiting primary energy while ensuring adequate energy services, ultimately, the ESC transformation strategy is focused on the overriding goal of lowering emissions to 1 ton of CO_2 per capita. We do not regard a concrete figure for the primary energy demand per capita as a meaningful strategic goal for the long term, although the lowest possible level should still be an aim. The sustainable quality of the primary energy carriers is of far greater significance: Not only decarbonization but also equitable access, security aspects, costs to the economy, and environmental compatibility are to be taken into consideration.

Finally, it is to be emphasized that this ambitious, technology-oriented transformation path can only be realized if the requisite technological innovations are accompanied by the provision of the required economic and social framework. This pertains to the requirement for a consistent and goal-oriented "Policy Design."

Implications and recommendations for ETH Zurich

Implications for education and research can be derived from the vision. It is, however, not meaningful to use it to establish an actual research plan. The transformation path has its own forks and hurdles stemming from system-dependent uncertainties in making assumptions and predictions.

Research

From its own situation analysis, the ESC working group defined 30 fields for ETH Zurich to start with that could be considered key themes for future energy research. These fulfill important criteria for a sustainable energy system, such as competitiveness in the research environment, technical growth potential, significance for the future energy system, and relevance for Swiss industry. ETH is considered to have a strong position in more than half of the fields investigated, and aims to strengthen them in the future. These fields include research in solar fuels, electricity networks, transportation technologies, fission, power electronics, energy economics, and the development of low-energy buildings. Areas in need of strengthening include storage of electrical energy, photovoltaics, bioenergy, and CO_2 separation technologies.

The ESC therefore recommends to the ETH Executive Board the creation of about 10 new professorships, which are to be be partly financed by industry. For their part, the ESC members would like to play an active role in developing appropriate joint projects and in winning over industry.

Education

The “Master of Science in Energy Science and Technology” program, offered for the first time in September 2007, will require significant support in the coming years. A collaboration with industry to develop a scholarship system that allows the international recruitment of highly talented young professionals is especially needed.

Knowledge transfer

Close interaction with the economy and society are important for research and teaching in the energy area. So-called “lighthouse” projects have the potential for effectively facilitating research transfer. Offerings in continuing education can promote knowledge transfer and networking among future decision makers. Useful contributions to public and political discussions are to be strived for.

Collaboration

The ESC wants to help tap the full potential of synergies within the ETH domain, and in addition, wherever constructive, it would like to strengthen its collaboration with universities (incl. those for applied sciences), in particular considering the relevant competence centers within the ETH domain. Collaboration worldwide with the best experts and institutions is a key factor for sustaining success. Contacts shall be systematically cultivated with actors in energy policy, both nationally and internationally.

Goals of the Strategy and Working Method

Goals of the strategy

In the fall of 2006, the executive committee of the Energy Science Center (ESC) began internal discussions with the aim of crafting a coherent strategy for energy research and education at ETH Zurich. At the same time, ETH's Vice President for Research submitted a request to the ESC instructing it to present strategic guidelines for energy research to the ETH Board. To that end, the ESC has developed a strategy with the following goals:

- To provide the internal research community with an information base concerning the full range of energy-related projects being conducted at ETH Zurich. This will serve as a starting point for the development of a more extensive network and for the planning of common projects and interdepartmental educational offerings, particularly at the Master's and doctoral levels (MSc / PhD);
- To provide decision makers — as well as interested members of the public — with fundamental knowledge to resolve strategic questions concerning the future of energy politics on the basis of scientific expertise.
- To identify areas of special interest for future research and teaching in the energy area that will require support at ETH Zurich through funding of additional professorships or through the provision of other resources. Recommendations for these should be forwarded to ETH Zurich's Executive Board.
- To initiate research programs for knowledge transfer through dialogue with important industry and business partners. These programs should have the aim of enhancing the competitiveness of the Swiss export industry by providing it with energy-related knowledge.

Working method

The working group, which was tasked by the ESC executive committee with the development of an energy strategy, selected the following procedure:

(i) Inclusion of the ESC members was important. This was ensured in two ways: first by a survey and second by giving all the ESC members and committees an opportunity through a consultative process to express their views on the drafted strategy.

(ii) The information gathered was synthesized and a summary is presented in the chapter on energy research at ETH Zurich. The summary has served as the basis for the evaluation of future developments.

(iii) Together with the boundary conditions and global challenges, a small group of possible scenarios form the starting point for an environmentally-friendly energy system in the 21st century. The definition is based primarily on the mid-range scenario from the 2007 report of the Intergovernmental Panel on Climate Change (IPCC).[2]

(iv) To achieve the strategic goals, paths are drafted which are geared to the most desirable general outcome, the optimal technological solutions, and the constraints of energy politics. Thermodynamic (and where possible, economic) coherence is considered to have priority.

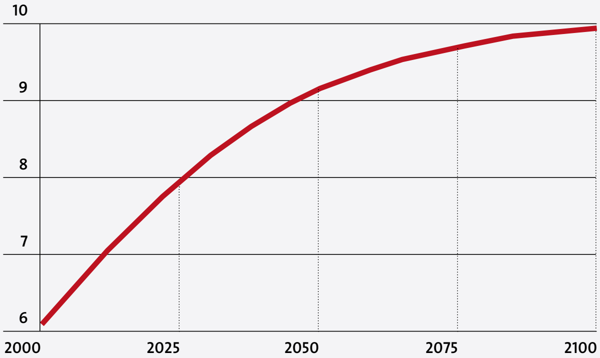
(v) The strategy is structured around various temporal horizons: through 2025, through 2050, and the second half of the 21st century. The main focus is on Switzerland, but global factors of climate, available resources, demographics, and the economy are also considered. Anticipated global development takes precedence over other factors.

2 Source: Climate Change 2007 - Summary for political decision makers, IPCC, ISBN 978-3-907630-28-0

Current understanding

Providing clean water, food, and health for more than nine billion people (Figure 1) is among the greatest challenges of the 21st century. Ensuring a sustainable supply of these fundamental needs will require resources and energy.

Figure 1: Population growth worldwide
(estimated in billions: Source: World population to 2300, UN 2004, mid-scenario)



Demand for primary energy will climb by 53% by 2030 according to the reference scenario in the 2006 World Energy Outlook (Source: IEA, ISBN 92-64-10989-7). Around half of this increase can be accounted for by the growing demand for electricity. In 2004, global power generation stood at 7,408 terawatt hours (TWh). By 2030 it is expected to double (see the reference scenario of the International Energy Agency). Currently, electricity is being produced with a fossil fuel component of approximately 64%. The expected increase in coal use in particular will have a negative effect on CO_2 emissions.

The volume of personal and freight transportation is rapidly increasing worldwide, at a rate that is more or less comparable to the need for electricity. Developing countries are following the consumption trends of the industrialized nations. Private transportation may very well double in volume over the next three decades. Air traffic will grow at an even greater rate. Finally, the rapid expansion in global trade is likewise resulting in a steadily increasing volume of goods being transported by land, water, and air.

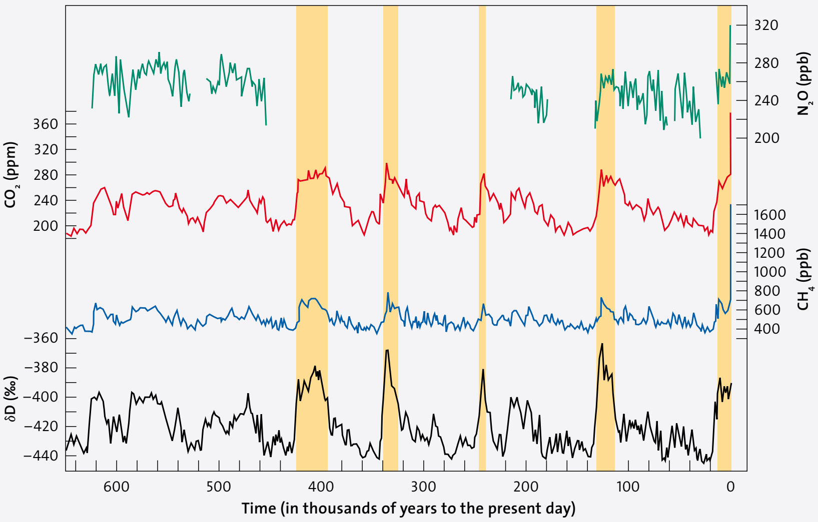


Figure 2: Glacial-Interglacial Ice Core Data

Variations of deuterium (δD) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in air trapped within the ice cores and from recent atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm periods.

(Source: Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J.Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007: Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.)

As published in the 2007 report by the Intergovernmental Panel on Climate Change (IPCC), climate change is being driven largely by anthropogenic greenhouse gases (Figure 2). Carbon dioxide emissions result primarily from the burning of fossil energy carriers. A lesser share of emissions is produced by agriculture. The carbon dioxide concentration in the atmosphere currently stands at a level 28% greater than the highest concentration it reached at any time in the past 650,000 years. Even if CO_2 emissions are immediately and drastically reduced, due to the longevity of carbon dioxide and the sluggishness of the climatic system, the earth's mean temperature will rise by between 2° C and 4° C over the next 100 years. This will primarily affect the geographical distribution of water over time. Renewable energy sources, such as wind, water, sun, and geothermal energy, are available in sufficient quantities. Their principles of extraction are also well understood. Suitable technologies for implementing cost-efficient and environmentally-sound solutions are lacking, however. To achieve a minimal supply rate of 20% with renewable energy sources, appropriate resources must therefore be provided for research and investments. Research activities addressing energy production technologies — such as deep geothermal energy, thermoelectricity, the generation of clean fuels through solar energy — as well as efficiency increases of established sources (wind, photovoltaics, biomass, hydropower) should be promoted.

However, wind and sun are dependent on the weather and are not available in unlimited amounts in all places and at all times. An effective support network will thus require extensive energy storage or an energy transport network covering large distances — for example, in the transport of wind energy from the "offshore" turbines on the North Sea to the pumped-storage lakes in the Alps.

On a global level, hydropower still has some room for development, while in Europe this potential has largely been exhausted. Here, pumped storage is the only adequate means of storing energy. But the ecological circumstances must still be considered if hydropower is to be expanded to any great degree.

Biomass is a CO_2-neutral source that can make a valuable contribution to the base load, even though it is limited in quantity. The same can be said of deep geothermal energy, although its production technology is still in the early stages. A wide range of issues remains to be addressed in the research, such as how to identify suitable drilling locations, acquire knowledge of geological

Figure 3: Percentage of renewables in the production of electrical energy
(Source: World Energy Outlook 2006, IEA, ISBN 92-64-10989-7)

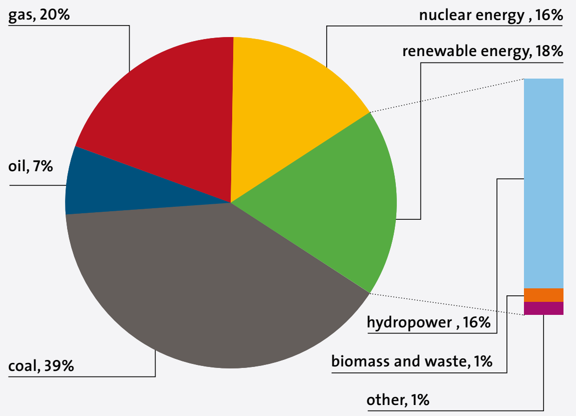
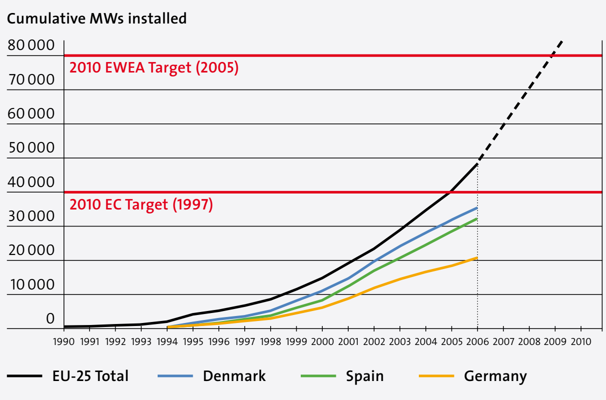


Figure 4: The growth of installed wind energy output in the European Union
(Source: European Wind Energy Association EWEA)



joint formations at deep levels, and reduce the cost-intensiveness of drilling technology. This calls for a broad spectrum of research to be carried out into aspects such as determining the position of borehole locations, improving expertise in geological rock fragmentation processes at deep levels, and reducing the cost of drilling technology.

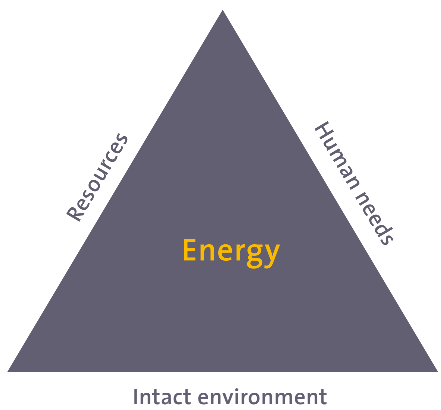
In the near future, power generation on a global level will become infeasible without nuclear power. The efficiency and safety of the life-cycle of nuclear fuels as well as the reduction of nuclear wastes thus remain challenging areas for research.

The Role of the ESC

The ESC aims to provide a conceptual foundation for the creation of a sustainable energy system. Such an energy system must be viable given the limited available resources; it must also relieve the strain on the natural environment and not compete with the basic needs of the world's population (Figure 5). The ESC focuses on minimizing carbon dioxide emissions without losing sight of the overall picture. It realizes that the emission of conventional pollutants is just as relevant to the quality of life and the health of people. In actual fact, current research efforts are paving the way for conditions under which the emission of pollutants by fossil systems could approach zero within the next two or three decades. A strategy for the containment of climate change that focuses on increased efficiency and the substitution for energy carriers will automatically mitigate the resource problem of the fossil energy carriers oil, gas, and coal.

The ESC is convinced that basic knowledge and technologies are still lacking. Not only do the natural sciences and technical disciplines have to take part in the creation of a sustainable energy system, but those research areas that focus on socioeconomic issues and on behavior at the individual level must also play a role. A radical transformation of the energy system and the necessary investments in a new infrastructure will involve substantial lead times. But a restructuring is urgently needed in both the technological and economic sense. Research into this will require not only natural science and engineering but also the involvement of socioeconomic and research into the patterns of behavior of individual and institutional users.

Figure 5: Dimensions of the energy problem



Promising new developments, such as the ultra fuel-efficient PAC Car II prototype and the almost energy-autonomous Monte Rosa lodge, indicate just how active ETH researchers have been in the energy field. The range of research activities listed in Table 1 illustrates the considerable presence of ETH Zurich researchers and institutes working intensively on energy-related issues.

This includes both research on fundamental principles and the development of new marketable technologies. The participating research groups often work in an interdisciplinary manner and collaboratively explore tasks that involve a cross section of common questions in the energy field.

Within the approximately 40 research groups currently associated with the Energy Science Center, about 200 doctoral students are working on topics in the area of energy research. The overall budget for research activities in the energy area is over 50 million francs. A listing of the names of participating professors and institutes is provided in the appendix.

Please note that the overview of energy research at ETH Zurich provided in this chapter in no way constitutes an exhaustive account. Rather, the various research fields are presented here for purposes of offering descriptive elaborations and a sense of some of the representative projects.

Table 1: Overview of energy research activities at ETH Zurich and the related institutes and chairs. The green fields designate a primary research activity or aim; yellow represents a substantial involvement.

	CEPE	CER	EEH	ECON	GEO	GEP	HBT	ICB	ICOS	IED	IFM	IFU	IGMR	IMRT	IPE	IVT	LAC	LAV	LKE	LSA	LSM	MATL	PES	PRE	SUS	VAW
Energy supply																										
Energy production (esp. from renewable sources)			Y		G				Y		Y	G	G		G		Y	Y	Y	Y	G			G		G
Energy conversion and storage			Y		Y				Y		G			G	Y		G	G	G	Y	G	Y	Y	G		Y
Energy transport and distribution			G	Y					Y		Y			Y				Y	Y		Y		Y	Y	Y	Y
Energy use																										
Transportation and land-use planning	Y		Y							Y				Y		G		Y								
Buildings	G						G			Y																
Equipment, parts, processes	G		G				G	G															G			
Interaction with society and environment																										
Ecological systems analysis	Y	Y				G		Y		Y		G	Y			Y				G						
Economy, society, and politics	G	G	Y	G						G						Y				Y					G	

Key to list of institutes

CEPE	Centre for Energy Policy & Economics
CER	Center of Economic Research
EEH	Power Systems and High Voltage Laboratories
ECON	Chair of Economics
GEO	Geological Institute
GEP	Institute of Geophysics
HBT	Institute for Building Technology
ICB	Institute for Chemical and Bioengineering
ICOS	Institute of Computational Science
IED	Institute for Environmental Decisions
IFM	Institute for Mechanical Systems
IFU	Institute of Environmental Engineering
IGMR	Institute of Isotope Geochemistry and Mineral Resources
IMRT	Measurement and Control Laboratory
IPE	Institute of Process Engineering
IVT	Institute for Transport Planning and Systems
LAC	Laboratory of Inorganic Chemistry
LAV	Aerothermochemistry and Combustion Systems Laboratory
LKE	Laboratory of Nuclear Energy Systems
LSA	Laboratory for Safety Analysis
LSM	Turbomachinery Laboratory
MATL	Chair of Nonmetallic Inorganic Materials
PES	Power Electronic Systems Laboratory
PRE	Professorship in Renewable Energy Carriers
SUS	Group for Sustainability and Technology
VAW	Laboratory of Hydraulics, Hydrology and Glaciology

Energy supply

Energy production

Renewable energy

Considerable efforts are being made to increase the efficiency and capacity of hydropower and to minimize its harmful effects on the environment. Specific research topics include:

- an assessment of existing hydraulic resources available for hydroelectric use and of interaction with the ecosystem through hydro-management;
- an analysis of air-water mixtures, spillways, emersion points for large dams, cavitation (pressure changes) and vibration, as well as pressure tunnel ventilation and general pressure systems.

Various research activities concerning deep geothermal energy are in the works. The analysis of borehole- and microseismicity data from deep "enhanced geothermal systems" is helpful for better understanding the process of increasing permeability in the subsurface. Other research topics include numerical model calculations of complex and coupled processes and the estimation of seismic risk associated with borehole injections; the modeling of interactions between fluid and stone in the long-term operation of a deep geothermal energy system.

To reduce the costs of boring, electrically-driven drill bits are being designed. Here there is a need for both high-temperature stable power electronics and the combined transport of electrical energy and drilling fluid deep below the surface. Parallel to this, an option for deep drilling is being researched in which the seam is reached by means of electromagnetic fragmentation in deep water at (supercritical) temperatures above 500° C.

Wind power and solar energy are also a part of energy research. Fluid-dynamic models are thus being used in individual projects to increase the efficiency of wind generators. In addition, this should also reduce the noise produced by the rotor blades.

Materials that directly convert heat to electrical energy in the temperature range of 100° – 800°C can also be used for energy production. Possible applications of such materials are therefore being studied for the construction of a heat-driven generator. However, the goal of matching conventional methods by this means remains elusive.

Bioenergy

Biofuel production (of the first and partly also the second generation) competes i.a. with the cultivation of foodstuffs and with maintaining biodiversity (through the clearing of old growth forests, etc.). Appropriate areas of research therefore concern the design of a sustainable production system and the cultivation of energy crops in infertile soil (desert areas, etc.). The genetic improvement of cultivated plants, for example, may lead to increased crop yields.

In the development of biorefining, several options are available that depend on the biomass type, the refining procedure, and the products derived from the refinement. But the objective is primarily to identify conversion processes in which biofuels and other fine chemical products — e.g., bioplastics and biopolymers — are produced. The vegetable base material, starch, can be split either chemically or organically. Among the processes currently being researched are, for example, heterogeneous catalysis and organic partitioning procedures, which are conducted in a bioreactor using microbes, bacteria, and fungi. In the area of high-pressure lignin conversion and biocatalytic process design, ETH Zurich can build on its own previous experience.

The bio-energy initiative at ETH Zurich is still in its early stages. The intention is to greatly intensify and expand current research. New methods of systems biology, molecular engineering, and in silico design (simulating natural processes on a computer) will be used for the selection and development of thoroughly optimized production chains, from bio-waste transformation and suitable energy plants to viable end-use energy carriers.

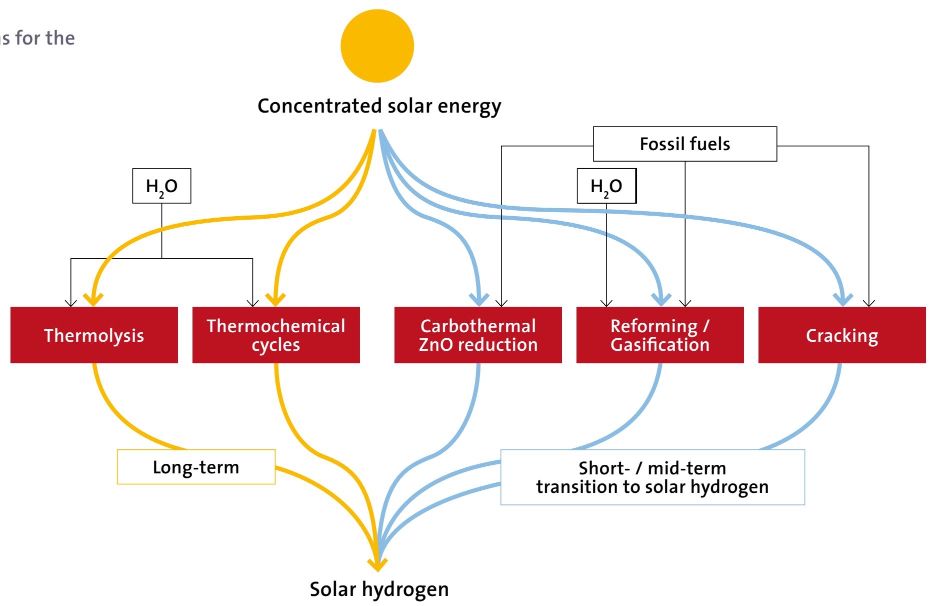
Project: Solar energy-derived fuels

The goal here is to be able to generate solar fuels from sunlight and water. The solar-thermal production of hydrogen (H_2) from water (H_2O) is a chemical process with potential appeal. H_2 can be used for fuel cell propulsion, among other purposes.

The emphasis is placed on developing solar-chemical reactors for fuel production at 800 to 2000° C (e.g. hydrogen, zinc, synthesis gas) and on those materials whose preparation consumes large amounts of energy (e.g. lime and metals). The thermochemical production processes for solar hydrogen depend on concentrated solar radiation as an energy source for high-temperature process heat (Figure 6). Radiative transfer and the resulting chemical reaction kinetics represent a complex phenomenon being investigated using CFD ("Computational Fluid Dynamics") and "Monte Carlo Ray Tracing" methods. An additional subject treated in the research is the modeling of heat- and mass-transfer in chemical reactor systems.

One very promising solar reactor, which can be used for splitting water, is based on the ZnO/Zn cycle. In it, zinc oxide is converted to zinc. This metal, which is useful in storing solar energy, can be used in the catalytic production of hydrogen as well as in zinc-air batteries. Although intensive research is being conducted, it will still be some time before the new technology is ready for large-scale commercial applications. ETH Zurich and the Paul Scherrer Institute (PSI) are working together in this area of research. Additional information on this topic is available at www.pre.ethz.ch (Professorship in Renewable Energy Carriers, Institute of Energy Technology).

Figure 6: Five thermochemical paths for the production of solar hydrogen (H_2)



Energy conversion

Energy conversion and transportation technologies

Technologies for a climate-friendly mode of power generation and transportation require conversion devices with higher efficiencies and lower pollutant emissions. Research is being conducted on basic principles and on a series of supporting technologies, such as:

- Developing accurate and powerful methods of calculation (reactive thermofluidics);
- Developing real-time and miniaturized sensors for diagnostics and monitoring;
- Developing control algorithms;
- Precise mechanical modeling of individual component behavior, to assess thermomechanical fatigue, deformation behavior, and damage to high-temperature components.

Power generation and combined heat and power generation (cogeneration)

High-efficiency systems for combined heat and power generation and large-scale power plants still need to be optimized. For this, attention should be paid to the management of thermal power generation plants as well as processes for ultra-low emission combustion systems. In addition, the use of geothermal energy and waste heat depends on the thermoelectric conversion of low-temperature energy (below 200° C) to electricity.

In nuclear power research, the focus is on thermal and fluid-dynamic modeling for atomic energy systems, reactor dynamics, technologies for measurement and control, and nuclear waste disposal.

In the future, Carbon Dioxide Capture and Storage (CCS) will take on great significance. It may become possible to store carbon dioxide as carbonates in minerals, for example. In addition, research is being conducted on combining storage in coal beds with the simultaneous utilization of methane gas (enhanced coal bed methane recovery (ECBM), the separation of CO_2 through pressure swing adsorption (PSA), and the separation of CO_2 from the air.

An area increasingly of interest is local power generation, usually with combined heating and cooling. Here primary energy — of either biological or organic origin — is also used. Due to innovations in combustion technology, researchers succeeded in crafting a demonstration model of a block heat and power plant capable of record performance. Nitrogen oxide emissions (NO_x) are likewise at an all-time low. The natural-gas powered “Swiss Motor” leads worldwide in electrical and overall performance. It is specially designed for large plants of over 100 kilowatts of electrical energy (kW_{el}). Development of both smaller and larger performance models is currently in the planning stage. This ETH Zurich technology has been successfully brought to market by Swiss companies.

Research is also being conducted on a microturbine that is designed for a very low output of 100 watts of electric energy (W_{el}) (Figure 7). Five groups from three ETH Zurich departments are participating. The goal of the teamwork is to achieve a breakthrough in the following technologies: catalytic combustion; materials; ultra-high speed pivot bearings; electric machines; loss-minimized turbo-engines, and miniaturized sensors used for diagnostics and controls.

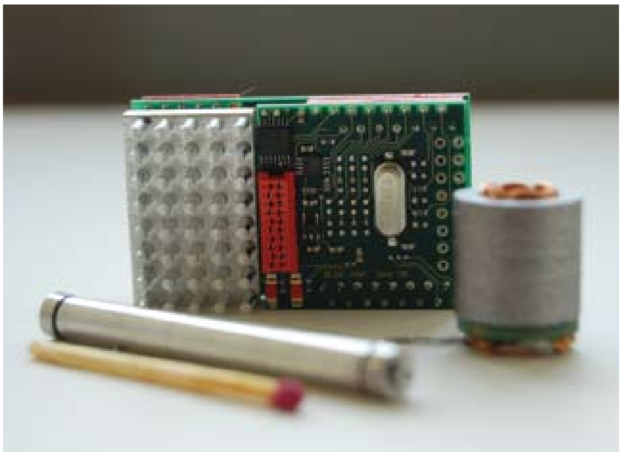


Figure 7: Size comparison of components of the microturbine

Transport, distribution, and storage

In the past, the transport and distribution of energy — regardless of its source — was managed in a relatively direct manner going in a single direction from the producer or suppliers to the consumer. The electrical power supply grid ensures that the source network constantly delivers exactly the amount of energy required by the consumer. In such a relatively straightforward transport and distribution system, the energy flow is determined by consumer behavior and price. Intermediate storage of large quantities of energy is only possible with matter-based energy carriers (gas, oil, coal) or with hydropower in reservoirs.

But innovative networking concepts on the research agenda will call for more efficient energy transport over long distances and electrical energy storage on a large scale. Various research groups at ETH Zurich have been involved in interdisciplinary efforts to design the prototype of a functioning energy distribution network to cover the needs of the next 20 to 50 years. The initiative is especially well-suited to the integration of conventional sources and weather-dependent electrical sources (wind, solar energy), as well as energy storage. The network's essential feature is the provision for a mix of energy carriers, as is needed in large metropolitan centers. The main focus is on such aspects as network security, complex controls, communication, and monitoring. Additional technologies are also being studied, such as those needed for the underground transport of various energy carriers and storage materials (electricity, thermal energy, gas, and liquid).

Such networking concepts are dependent on the development of converters that far exceed current technology in terms of efficiency, scale, temperature stability, and reliability. Here, indispensable tools are being created to enable low-loss and secure implementation of different electric sources in a reliable power supply grid. Research is also being conducted on the implementation of automated complex controlling and monitoring for the network.

Intensive research is being done on electrochemical batteries to increase their energy content and on alternatives for electric energy transport with storage capability. This includes the search for efficient methods of conversion from electricity to a matter-based energy carrier such as hydrogen (H_2).

Project: Vision of future energy networks

The main components of the future energy network are energy hubs of varying sizes that form the nodes, along with connectors ("interconnectors") as the binding element (Figure 8). In general, the hub connects all conceivable energy carriers with one another. A hub is connected with the local sources and the energy storage mechanism. From here the conversion can go in any direction.

This abstract network structure has proved to be a viable approach to starting to optimize the current mix of energy carriers for local supply in terms of cost and ecology. A case study designed for a mid-sized Swiss town has already been started.

The project also examines how an energy carrier mix can be transported. The required technology remains to be developed — as an input for industry's know-how.

To assess consumer-dependent supply scenarios, various algorithms have been worked out. These include for example an evaluation of the usage location and the size of energy storage in order to adjust for the weather-dependent availability of wind power and photovoltaics. Energy storage is especially indispensable for residential areas (neighborhoods, towns, cities) that wish to manage their supply using emission-free electrical energy.

The energy supply system of the future is being studied by ETH Zurich's High Voltage Technology and Energy Transmission Systems groups in collaboration with a consortium of the Swiss electricity suppliers, the three largest European builders of power plants (ABB, AREVA, and Siemens), and several European universities. Further information can be found at www.future-energy.ethz.ch.

Figure 8: Schematic display of a future multiple energy network with the energy hub as a node and an "interconnector" as a connecting element.