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 21^{st} 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.

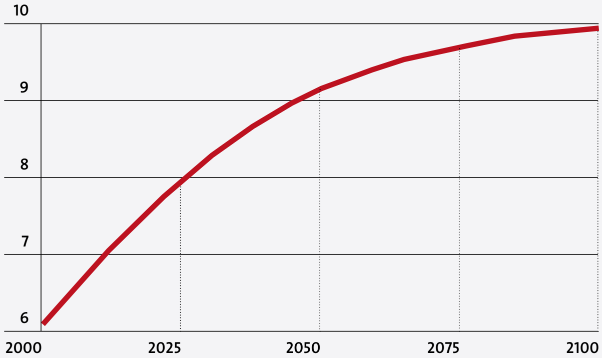
(v) The strategy is structured around various temporal horizons: through 2025, through 2050, and the second half of the 21^{st} century. The main focus is on Switzerland, but global factors of climate, available resources, demographics, and the economy are also considered. Anticipated global development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

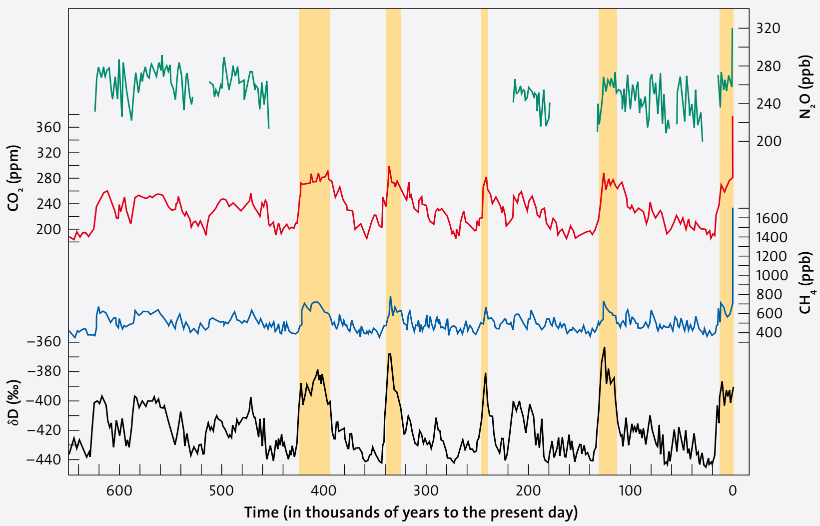


Figure 2: Glacial-Interglacial Ice Core Data

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)

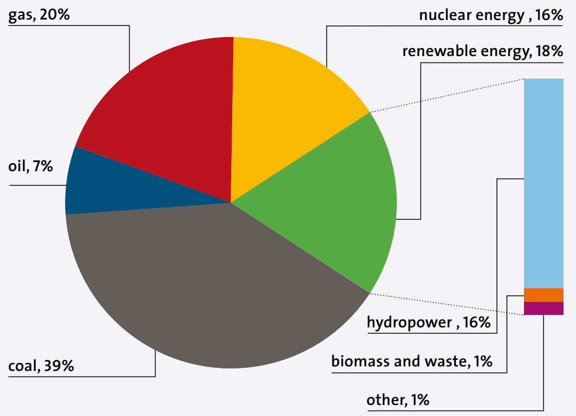
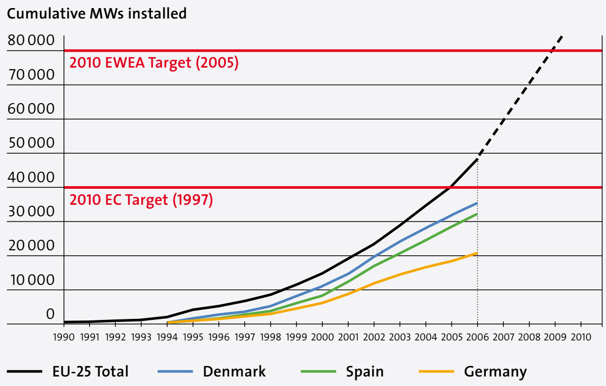


Figure 4: The growth of installed wind energy output in the European Union
(Source: European Wind Energy Association EWEA)



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.

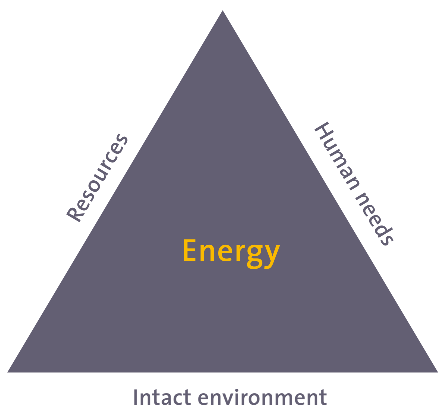
In the near future, power generation on a global level will become infeasible without nuclear power. The efficiency and safety of the life-cycle of nuclear fuels as well as the reduction of nuclear wastes thus remain challenging areas for research.

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)			yellow		green				yellow		yellow	green	green		green		yellow	yellow	yellow	yellow	green			green		green
Energy conversion and storage			yellow		yellow				yellow		green			green	yellow		green	green	green	yellow	green	yellow	yellow	green		yellow
Energy transport and distribution			green	yellow					yellow		yellow			yellow				yellow	yellow		yellow		yellow	yellow	yellow	yellow
Energy use																										
Transportation and land-use planning	yellow		yellow							yellow				yellow		green		yellow								
Buildings	green						green			yellow																
Equipment, parts, processes	green		green				green	green															green			
Interaction with society and environment																										
Ecological systems analysis	yellow	yellow				green		yellow		yellow		green	yellow			yellow				green						
Economy, society, and politics	green	green	yellow	green						green						yellow				yellow					green	

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.

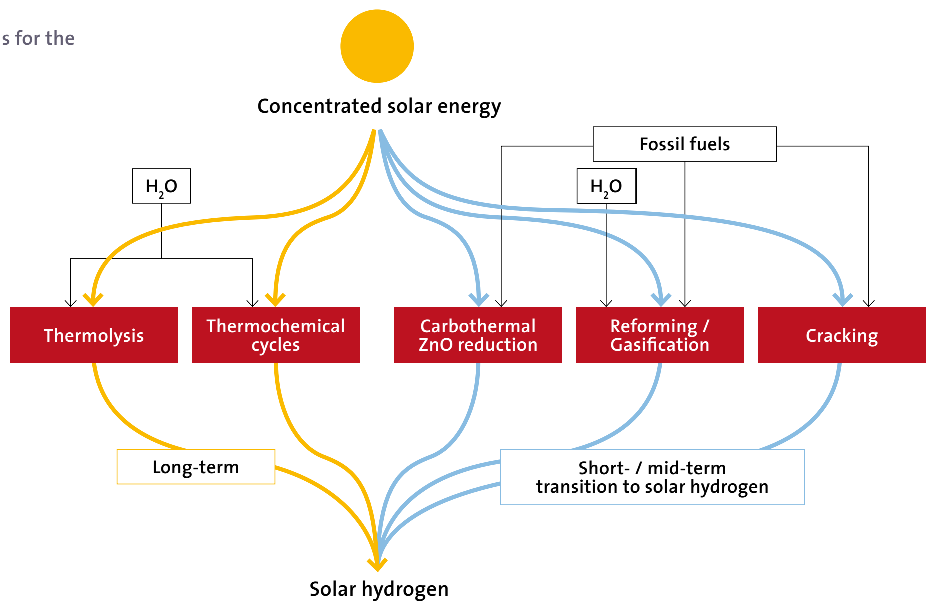
Project: Solar energy-derived fuels

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.

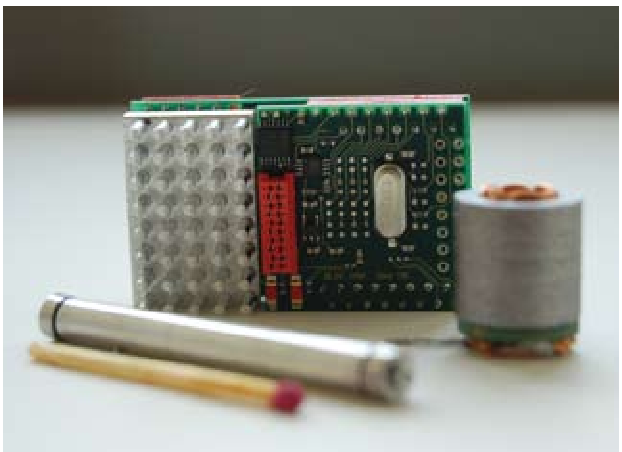


Figure 7: Size comparison of components of the microturbine

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.

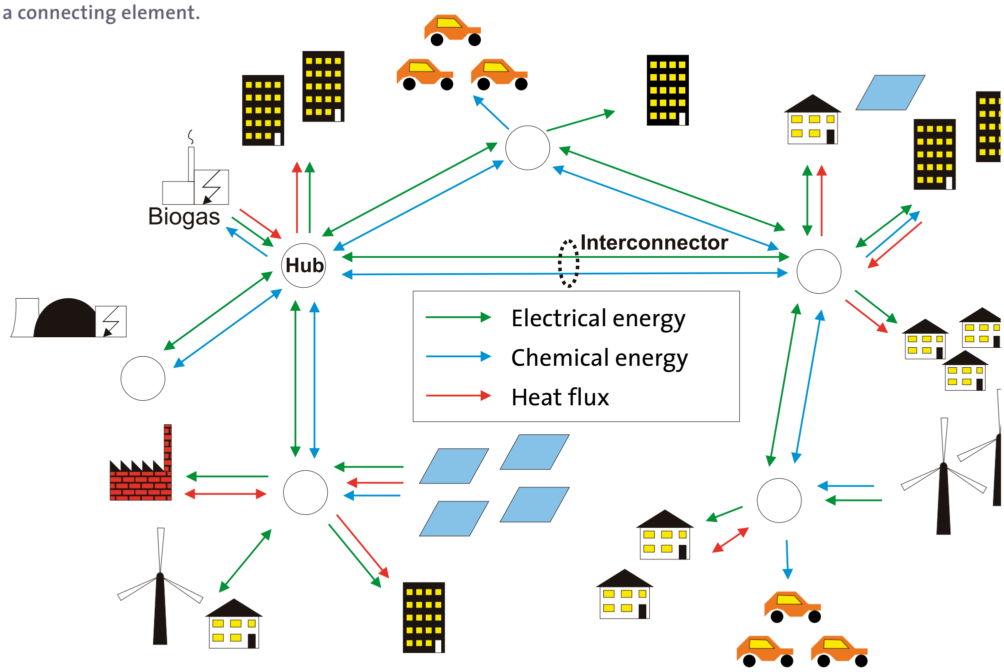
This abstract network structure has proved to be a viable approach to starting to optimize the current mix of energy carriers for local supply in terms of cost and ecology. A case study designed for a mid-sized Swiss town has already been started.

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.



Energy use

Transportation and land-use planning

Transportation of freight and people

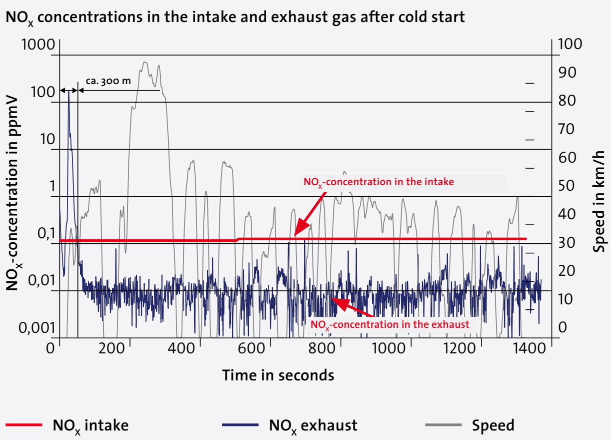
ETH Zurich's innovations in favor of eco-friendly transportation have in many instances been met with a resounding international response. Its innovations have included the PAC Car II* vehicle prototype, which holds the current world record for fuel efficiency, and the Clean Engine Vehicle (CEV), which was developed in collaboration with Empa and emits less nitrogen oxide (NO_X) than is present in the surrounding air (Figure 9). Since ships handle about 90% of the overall freight volume worldwide, legislators are increasingly focusing on eco-friendly ship propulsion. An experimental vehicle for ship propulsion, the only one of its kind in the world, was designed at ETH Zurich in collaboration with Swiss and European industry for the purpose of researching new combustion processes and fuels.

Among the interdisciplinary projects, research is being conducted on technological, economic, and social-psychological aspects of the general problem of "transportation and mobility." This entails both basic research and a knowledge transfer that can be advanced through close cooperation with international industry. Other focal areas of research are the following:

- Minimizing pollutant emissions with potent local and regional effects: NO_X, soot, and hydrocarbons, which are considered precursors of smog and fine-particle pollution. To this end, systematic research is being conducted on homogeneous combustion processes, new operating processes for vehicle propulsion, and the use of fuels containing oxygen (O_2) and hydrogen (H_2). The basic features of catalysis during exhaust after-treatment and efficient control algorithms are also being researched.
- The development of functional materials for the "on-board" storage of electricity and chemical energy. Among other things, we mention here innovative electrodes, systems for high-performance batteries, super-caps (double-layer condensers), as well as procedures for efficient H_2 storage.
- The advancement of the pioneering work done in the late 1990s in developing hybrid vehicles. An interdepartmental project will have the goal of developing transportation concepts for large agglomerations. The anticipated increase in the electrification of engines in personal and freight vehicles will play a key role in the future.
- The recording, forecasting, and optimization of traffic patterns. This includes an analysis of the investment and purchasing decisions made by consumers. The questions are approached from a regional planning, economic, and social-psychological perspective.

* with a fuel cell developed at PSI.

Figure 9: The Clean Engine Vehicle (CEV) emits less nitrogen oxide (NO_X) than present in the surrounding air.



Buildings

The Swiss Federal Energy Research Commission (CORE) is directing the research objectives for energy use in buildings with the aim of ensuring that CO_2-free operation is attainable by the year 2050. The energy accounts include all systems of energy conversion inside and outside of a building. In particular, this also includes external electricity generation systems.

The energy and material flows required to construct and maintain a building are a means to an end. Of special interest are thus the services that a building furnishes for people. These include, among others, thermal and hygric comfort, high air quality, visually-pleasing surroundings, and substantial opportunity for the creation of added value.

Research addresses each area of the energy conversion chain and is concentrated on

- First, primary energy (solar radiation, wind, hydropower, fuels, etc.);
- Second, end energy (energy storage, transformation, transport, etc.); and
- Third, effective energy (conversion of energy to applications, controlling systems in response to the time and quantity of demand, etc.).

The architecture department at ETH Zurich has the task of bringing the researched systems together into a complete building installation system or a single building — in both a formal and functional sense. The research efforts are based on the following criteria:

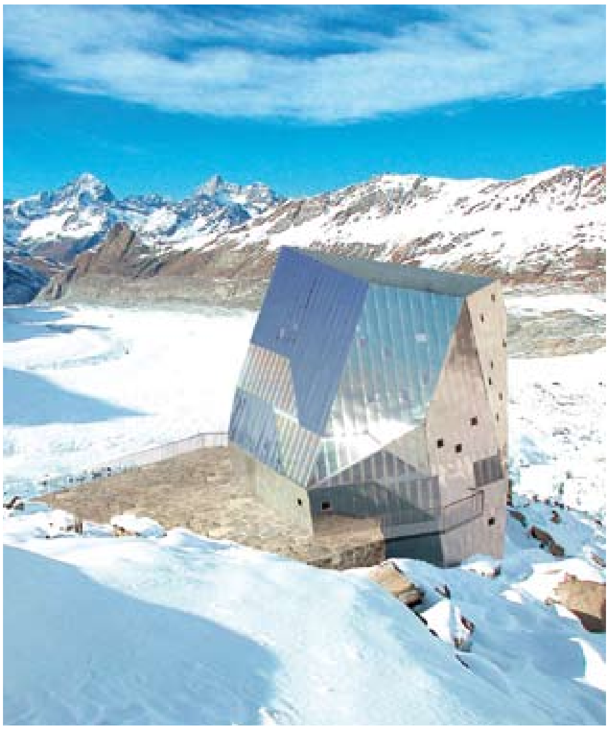
- **Increasing exergetic[3] efficiency**
  Providing energy services with a minimal amount of (high-value) exergy.
- **Reduction of work hours at full load**
  Providing the desired energy service with the lowest possible energy usage per annum. When measuring how efficiently a system creates an energy service, a distinction must be drawn between full load and partial load states.
- **Decarbonization of energy conversion processes**
  Replacing systems that have open fossil carbon material flows with low-carbon or carbon-free processes.

A thorough understanding of the physical and chemical aspects involved is a prerequisite for significant improvements in energy efficiency. It takes only a few years to improve the efficiency of a process by 10 to 20%. Indeed, efficiency improvements by a factor of 1.5 or 2 are entirely possible. However, depending on the product, these typically require development times of 10 years. Usually, solutions such as these are only possible through interdisciplinary efforts. Industry becomes involved at different stages of development, depending on the product or process. The potential for developing new products for the world market is relatively high. In various technical areas, ETH Zurich still currently leads the way in the international research community — particularly in research projects specializing in exergetic efficiency.

3 Exergy refers to the amount of energy that is capable of doing work when brought into thermodynamic (thermal, mechanical, and chemical) equilibrium with its environment.

Project: Monte Rosa lodge

The new Monte Rosa lodge project demonstrates that sustainable building is possible even in the middle of a glacial landscape. Together with students, professors, and specialists, ETH Zurich has put together a project for the Swiss Alpine Club (SAC) that is ready to be built and will be realized beginning in 2008. The building technology for the new Monte Rosa lodge goes in new directions to attain a maximum degree of self-sufficiency and environmental safety in its energy and water use. Contributing factors include ample active and passive use of solar energy, good heat insulation and regeneration from outgoing air, as well as the use of efficient devices. The new Monte Rosa lodge, with a building energy self-sufficiency level of over 90%, will serve as an example of sustainable construction and planning both in Switzerland and worldwide. Further information is available at www.deplazes.arch.ethz.ch/monterosa



Devices, components, processes

Energy efficiency in industry

Industry is the largest consumer of final energy worldwide and accounts for 30% of the energy resources supplied to OECD countries (Source: World Energy Outlook 2006, IEA, ISBN 92-64-10989-7). Since many industries operate in an energy-intensive manner, there is considerable motivation to promote energy efficiency in industry. The economic reasons are clear: the rise in energy prices from 2005 to 2006 and the likelihood of their remaining at a high level. A wide variety of strategies, programs, and products is being used by industry to promote energy efficiency, which has already resulted in significant advances. While the industrial output of OECD countries has doubled since 1970, the amount of energy consumed has remained virtually constant (World Energy Council 2004). Nonetheless, the potential for efficiency gains in industry remains considerable. Energy efficiency programs typically have a target improvement of 10% in the short-term and 25% in the long-term. The following instruments are needed:

- Systematic energy accounting is a key element for industrial companies to ensure their ability to estimate potential savings and identify appropriate measures.
- Benchmarking facilitates making comparisons of processes and systems. This way, energy use in a single plant or in a production sector can be analyzed systems.
- Monitoring and targeting methods provide invaluable information on the implementation and enhancement of energy efficiency measures.

Material efficiency in industry

Material efficiency can be improved either by using less source material for an end product or reducing the material demand of the production process. Generally, material efficiency is directly related to the source raw materials and the recycling of residual materials in production. Three strategies contribute to increasing material efficiency:

- Weight reductions in the production process (“lightweighting”) reduce the material consumption per product while retaining its functionality.
- Most important for the reduction of waste in the production process is the reuse of energy-intensive waste materials and/or residual materials that have a high energy content (for example, recycling solvents in chemical manufacturing).
- The recycling of materials in the production process reduces not only raw material requirements but also the use of energy in its acquisition. This way the quantity of waste, which would otherwise have to be deposited or incinerated, is also reduced.

Project: Analysis of energy efficiency in the chemical industry

The research activities of the Safety and Environmental Technology Group at ETH Zurich (www.sust-chem.ethz.ch) are concentrated on energy efficiency in the chemical industry. Optimization efforts are being supported by the Swiss Federal Office of Energy. The primary goal of the project is the development of a dynamic equilibrium ("energy balance") for complex chemical production processes. The current project involves production processes for about 40 chemical products. The instruments used for analysis and modeling allow for a calculation, with an accuracy of 10%, of energy consumption (steam, electricity, and cooling energy) for each process activity, without requiring an individual measurement of consumption. The potential for energy efficiency, defined as a ratio of the thermodynamically predetermined need to the actual energy quantity required, is between 40 and 70% for individual process units.

The results of the research will be generalized and made available as a software solution for the monitoring of energy efficiency at chemical production sites in Switzerland and the EU. The implementation of potential energy-saving measures and the investments required for them are the responsibility of the individual companies.

Interactions with society and the environment

Ecological systems analysis

Energy, for example in the form of electricity, useful heat, or mechanical energy, is required for most human activities. A holistic approach to systems thinking is necessary in order to identify potential areas of ecological improvement. Hereby, the omnipresent energy processes in the economy and the existence of complex interactions can be best understood. The field of ecological systems analysis is concerned with the examination and ecological optimization of technological and economic systems through the efficient management of energy and resources.

ETH Zurich is producing pioneering research into developing new eco-accounting methods. One example of a comprehensive ecological systems analysis is the quantification of all energy- and stock flows in a system, as well as the assessment of the resultant environmental impact and risk. In so-called "life-cycle analysis," all effects of the production system on the environment are quantified over the entire life-span of the product, from extracting resources and manufacturing, through usage, maintenance and transport, to eventual recycling and disposal.

Several research groups are addressing questions of energetic and ecological systems analysis and configuration. The following are a few examples:

- Analysis and minimization of risk for systems of energy production and supply networks.
- Investigation of the interdependencies between energy demand and changes in the environment, for example the impact of the greenhouse effect on the availability of hydropower.
- Development of decision-making instruments for industry and for consumers in order to optimize energy efficiency and increase the demand for energy from clean sources.
- Development of agent-based models for transportation systems that will enable the identification of energy-efficient scenarios.
- Development of approaches for recycling and the closure of material flows and the lowering of the demand for energy through environmentally-conscious process (re-)design.
- Development of robust "road maps" for future energy systems, with special reference to the development of new technologies.

One exemplary success stemming from ETH Zurich's research is the world's largest database of ecological life-cycle data, Ecoinvent. Ecoinvent contains data on over 1000 resources as well as the emission flows from over 3500 product systems and processes from the fields of energy systems, transport, production, materials and chemicals, and disposal processes. Ecoinvent was originally created by ETH Zurich and the Paul Scherrer Institute (PSI). The database is utilized by a multitude of businesses, public authorities, and research institutes for producing comprehensive environmental analyses, and it is called upon for ecological decision-making. In many cases, Ecoinvent is deployed in order to detect potential areas of ecological improvement and for increasing the energy efficiency of production processes. The database is jointly kept up-to-date by ETH Zurich, PSI, Empa, and the Agricultural Research Station (ART).

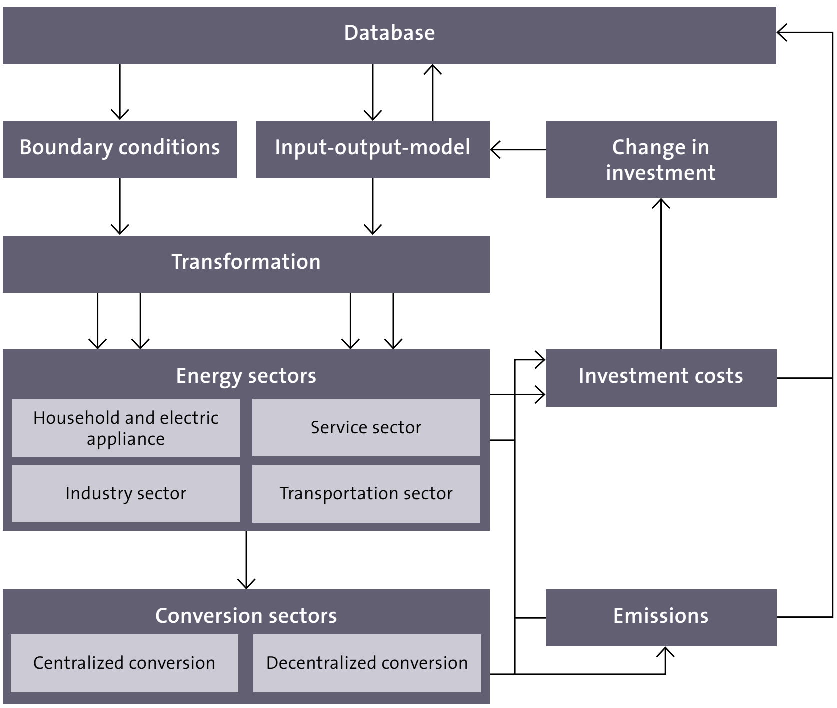
Project: Energy Navigator

The Energy Navigator uses computer-aided modeling to represent an energy system for Switzerland that describes the demand for energy and CO_2 emissions for the period 2002 to 2035 as a function of technological, economic, and social development (Figure 10). Variants, new scenarios, and their sensitivities can be calculated with this model. Not only are the power supply options ascertainable with their costs and benefits, but their structural effects on economic development can also in principle be forecast.

This project is meant to show that developments made in an industrialized country through energy-efficient systems and technology can, despite very complex inter-relations, be communicated appropriately and intelligibly. The computer-based model has a relatively easy-to-use operator interface and makes it possible to work with adjustable parameters. With the assistance of the developers, the model offers decision makers (from governament, industry and society) a useful instrument for assessing possible strategies based on different energy and climate policies.

This research and demonstration project is highly inter-disciplinary. Developing the project involved applied information technology and systems modeling in addition to technical-scientific and economic input. ETH Zurich's Aerothermochemistry and Combustion Systems Laboratory at the Institute of Energy Technology (www.lav.ethz.ch/index_EN) and the Centre for Energy Policy and Economics (www.cepe.ethz.ch) were responsible for its development.

Figure 10: Overview of the Swiss sectoral energy system model (Energy Navigator).



Economics, society, and politics

An energy system consists of hardware and software components. Hardware and software develop hand in hand; the energy system only functions in its totality (Figure 11). The hardware includes infrastructure: industrial equipment, machines, and facilities. The software side, meanwhile, includes know-how and behavior of different actors and institutions as well as rules and laws. Comprehensive understanding and further development of this system in its totality are only possible through the collaboration of the engineering sciences with the social sciences.

The Energy Science Center offers an ideal platform for nourishing the exchange of information between the engineering sciences and the social sciences as well as for directing possible joint projects. Economists, sociologists, political scientists, and psychologists conducting research at ETH Zurich have the advantage of being systematically included in energy research and thereby greatly contribute to ETH Zurich's standing in this field.

The interactions between hardware and software have exceptional relevance to society and can only be adequately researched by a combination of researchers from "both cultures" or by researchers who have acquired sufficient competence in both fields of inquiry. The sizeable problems of the energy system can only be perceived on the basis of hardware-software interactions:

- Security of supply is only in part a technological problem. The supply of fossil fuels to net-importing countries is also influenced by geopolitics. Consider, for instance, the high revenues that crude oil affords certain producing countries at present. Assessing the riskiness of these mounting capital stocks requires detailed knowledge of the various states, cultures, and actors — in addition to knowledge of the resources and the potential sales in the producing countries. It makes no sense to lump together Russia, Nigeria, Iraq, and Saudi Arabia in an undifferentiated analysis. Nor can easily storable crude oil and grid-bound natural gas be classified as comparable raw materials. Knowledge of the profitability and possible applications of alternative energy resources is equally indispensable.
- Both the security of supply and the environment would be served by a significantly lower energy demand. Saving energy is the most cost-effective and fastest strategy for safeguarding the climate. Characterizing energy saving as a purely technological issue or reducing it to enhancing energy efficiency is wrong, for increased energy efficiency itself very often leads to increased energy consumption: The efficient technology is cheaper, and thus demand for it goes up. Furthermore, the money saved on energy is then spent elsewhere. As a general rule, this additional financial expenditure for its part requires more energy. In economics, this interconnection is termed the *rebound effect*.
- Energy conservation is just one of several aspects of technological product development. Often, features such as user-friendliness, the range of application, and cost are concurrently improved, which leads to an increase in the demand for the new technologies. To accomplish lower energy use through energy efficiency at the national level, it has to prevail via effective public policy and be rendered attractive to consumers — with-

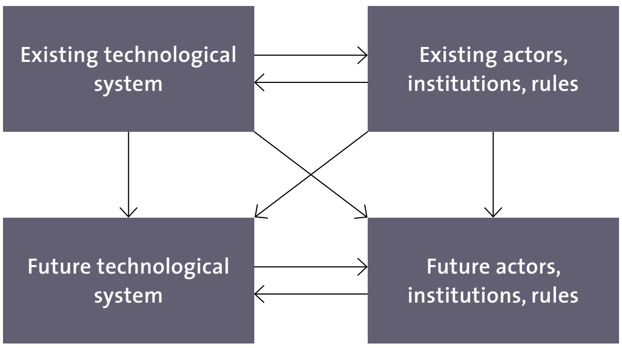
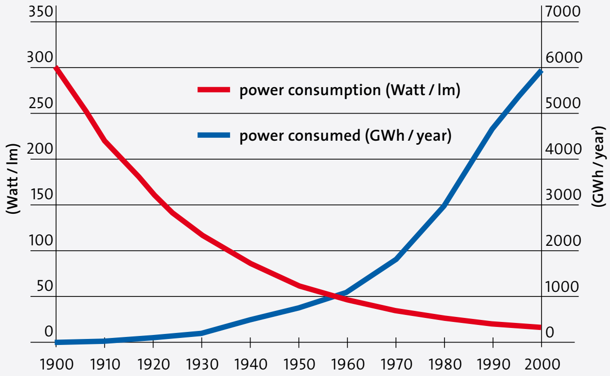


Figure 11: Interactions between hardware and software components form the current and future energy systems.

out bringing about negative repercussions on the quality of life and social cohesion. How this can be achieved is one of the most urgent, and to a large extent socioeconomic, research questions of our time (Figure 12).

Figure 12: Specific power consumption [Watts/lumen] and total power consumption [GWh/Year] for the generation of light in Switzerland.

Despite the significant technological progress represented by a decline from 300 to 4 Watts/lumen in the power consumption needed to generate a particular quantity of light, overall the power consumed for lighting rose sharply over the last century.



- Climate policy has benefited significantly from advances in socioeconomic research. Research recommendations on trade in emissions certificates are already being implemented. A great deal of work still remains to be done in order best to meet new challenges at the level of firms and to prevent unwanted negative repercussions at the level of the national economy, such as the risk of corruption through "Clean Development Mechanism" (CDM) money flows between industrialized and developing countries.
- An energy system is a large, tightly knit, and lethargic structure. Investment decisions must be made long-term, and new measures in energy policy must be planned long-term as well. In addition, computer-based prognostic models bring out the interactions between the economy and the environment and contribute to the development of targeted strategies. Model calculations are indispensable for public policy advice as well as for large companies.
- Without innovation, a positive energy future is unimaginable. The study of technological (and social) innovations helps not only better to grasp their significance but also potentially to support further specific processes of innovation.
- Various research groups at ETH Zurich are dealing intensively with (energy-related) issues surrounding consumer behavior. They are applying methods of experimental economics, psychology, and market research. Issues being worked on for that purpose include the following: What is the background and motivation behind a decision to purchase capital goods such as automobiles and residential dwellings? What do consumers know when they decide to make a purchase? What do they do with the money saved when they opt for a money-saving alternative? How great is their willingness to pay for energy-efficient products? Which measures taken by businesses and public authorities do customers respond to and in what ways?

ETH Zurich aims to make a contribution towards a sustainable future energy system through its own ongoing research efforts. However, in addition, there is a need for academically trained specialists to take care of the planning, development, and operation of this system. It is therefore essential to the energy strategy that the academic program at ETH Zurich be structured to provide for all these needs both up to and beyond the Bachelor's level. This is to ensure that businesses in the energy sector and related organizations can find employees capable of rising to the growing challenges.

ETH Zurich is currently offering comprehensive energy-based education opportunities through a number of programs of study. Energy is a major within both the Bachelor's and Master's programs in electrical and mechanical engineering. Other departments also offer lectures in which various aspects of the supply, transformation, and consumption of energy are explored in depth. The economic aspects of energy systems are addressed in lectures at the Centre for Energy Policy and Economics (CEPE), and their interactions with the environment are the subject of lectures by the Department of Civil, Environmental, and Geomatic Engineering as well as the Department of Environmental Sciences. In all, some 70 lectures at ETH Zurich currently feature various aspects of energy. In recent years, the number of students choosing to specialize in the field of energy has risen markedly. Every year, about 100 students graduate from the Master's program, in which they have also deepened their knowledge through the completion of a Master's thesis.

It is to be assumed that in the future, the job market will demand ever-increasing numbers of graduates with broad interdisciplinary training in the energy sector. Alongside traditional engineering know-how, an in-depth knowledge of economic contexts will be sought after. In response to this demand, ETH Zurich is offering a new Master's program in Energy Science and Technology (MEST). The aim is both to give engineering graduates a broad foundation in the interrelationships in the energy sector and to allow specializations in specific areas of application. This study program was launched in the fall of 2007 and received good reviews from international students of various origins who took part in it.

The scenario described below represents a very ambitious transformation path for the global and Swiss energy systems. It is intended to enable the long-term stabilization of atmospheric CO_2 at less than 500 ppm. According to IPCC prognoses, this level will limit the global mean temperature increase to about 2°C in the 21st century.

The type of development embodied in the vision is nonetheless achievable with concerted efforts by the international community if vital technological developments are promoted and appropriate economic conditions are efficiently put in place.

From our primarily scientific/technological point of view, the transformation path presented below is distinguished by its plausibility and consistency while maintaining compatibility with the thermodynamic foundations of the energy conversion process. Of course, it is not the only conceivable one that can meet the challenges cited earlier. The transformation vision is based on a series of existing concepts and scenarios such as the energy scenarios of the Swiss Federal Office of Energy, the CORE-Roadmap, and the White Book of Energy-Efficient Technologies.[4] It also takes into account the perspectives of the International Energy Agency (IEA), the scenarios of the Intergovernmental Panel on Climate Change (IPCC), and the Stern Review, among others.

Global energy system

Phase A (short-term — approximately the next 20 years)

- Governments, the economy, and society have agreed upon clear goals and binding measures (regulatory and market-based steering mechanisms) for containing climate change and for the short-, medium-, and long-term reduction of greenhouse gas emissions. Agriculture and land use are included here according to their share of greenhouse gas emissions. Lower household and industrial energy consumption is promoted through targeted incentive schemes and market-based instruments for decision-making.
- A means of allocating future CO_2 emissions among industrial, emerging, and developing countries — taking into consideration developing nations' need to catch up and industrial nations' historical impact — has been worked out by 2015 and is now binding on the international community.
- Buildings are renovated and restored faster, and new buildings are only approved if they meet low-energy standards. No new fossil-fuel power plants are built toward the end of the period without adducing proof of robust separation and storage of CO_2. Incentives to reduce traffic-specific emissions of CO_2 are being developed.
- A basic premium on fossil-fuel energy sources based on the "polluter pays" principle shows the first signs of a breakthrough in the form of efficient and low-carbon technologies across all energy sectors. Nuclear energy's share is not appreciably expanded, but it is also not abandoned (existing power plants are, safety provided, allowed to operate until around 2025 in order to "gain time").
- The life-cycle of materials is optimized according to ecological considerations, and material flows are closed to a large extent. If material re-use or recycling is not ecologically advantageous, the energy recycling option with the greatest calorific value is to be preferred (for

4 Source: A White Book for R&D of Energy-Efficient Technologies: Steps towards a Sustainable Development; Eberhard Jochem, (Novatlantis 2004).

instance, co-incineration of scrap materials as a substitute for combustibles in the manufacturing sectors).

- Hence, by the end of Phase A in about 2025, worldwide CO_2 production can be successfully stabilized at 30–32 Gt CO_2 per year.[5] World population is then 7.5–8 billion.

Phase B (medium-term — until roughly the middle of the century)

- The true costs relating to the resource "climate" have been established. The low-temperature heat sector has been extensively decarbonized in a growing number of countries. The power generation network finds itself in a state of major change between 2020 and 2045. By this time, the mix of primary energy sources already consists of a high proportion of CO_2-free gas- and coal-fired power plants as well as of renewable energy sources (solar, wind, hydropower), at best even geothermal energy. Should Generation IV bring proof of the inherent safety of nuclear fission, as well as of the minimization of radioactive waste and proliferation while clearly improving fuel efficiency, one can expect it to increase its contribution to the power supply. A significant commercial contribution from fusion by the end of Phase B is rather improbable.
- Electricity storage technologies experience a commercial breakthrough between 2020 and 2050. Biomass is used primarily for steady-state applications and in smaller plants (<10MW), above all for industrial heat and/or power production.
- Air and shipping traffic as well as extensive long-range freight transportation by land continue to require fossil fuels. Automobile traffic and short-range freight transportation undergo a gradual electrification (from normal cars via plug-in hybrids to fully electric vehicles) over the course of the next 30 to 40 years (i.e. until just before 2050). A noticeable proportion (<=20%) of the hydrocarbons intended for transportation are produced synthetically using advanced biotechnologies, provided ecological repercussions can be avoided.
- Distribution and transportation systems for electricity are adapted to large stochastic renewable energy sources (efficient storage including DC-technologies/new network structures).
- Hence, for a global population of approximately 9 billion by the middle of the century, a reduction in CO_2 emissions to about 20 Gt CO_2 / year can be achieved. On the whole, this is aligned with the stabilization path recommended by the IPCC.

Phase C (long-term, i.e. in the second half of the 21st century)

- The power generation network is CO_2-free as far as possible, and renewable energies dominate. Heat is produced from the sun, ambient environment, renewable biomass, and heat pumps, using little electricity. Fossil-fuel power plants equipped for sequestration, possibly along with nuclear power plants, play a supporting role if necessary. Robust networks for efficient electricity transport over long distances, together with decentralized storage systems, are also available.
- Transportation requirements are still met using liquid hydrocarbons for long-range journeys (planes, ships); for all other transportation, CO_2-free electricity and small quantities of biogenous, at best solar-chemical, fuels are used. On account of the extremely inefficient energy conversion chain, hydrogen produced from electrolysis is not considered a meaningful option for transportation.
- Power generation towards the end of the 21st century depends extensively on renewable energies; photovoltaics probably dominate here, distantly followed by solar thermal electricity, hydropower, and wind energy. The greater the share of solar-produced electricity — even compared to CO_2-free fossil-fuel or nuclear power generation — the higher the primary energy flow is; even for values around 6 kW per capita, significantly less than 1% of the continental earth's surface would be sufficient, taking total global solar irradiation into

5 All CO_2-emission balance values are calculated without incorporating the effect of land use.

account. Technological progress and, above all, massive cost reductions are, however, essential to that end.

- Thus, under optimal conditions, the goal of a "1t CO_2 per capita per annum" society is achieved, meaning that by the end of the 21st century, no more than 10 Gt CO_2/year are being produced — assuming a world population of 9 to 10 billion and a global prosperity level in 2100 similar to that of Switzerland today.

The particular situation of Switzerland

The following description of qualitative characteristics of Switzerland's energy future focuses on those aspects that differ from the global development trends described above.

- Switzerland's good starting position and the high quality of its building technologies allow for a faster reduction of CO_2 emissions compared to the international average. In particular, the "Minergie-P"-Standard and the consistent exploitation of ambient heat through heat pumps should be mentioned.
- The demand for transportation services (both freight and personal transportation) will reach saturation levels earlier than in the rest of the world, where it will take longer to catch up. In the case of air traffic, complete integration into the CO_2 tax system can and must be effected over the next 20 years.
- As the main pillar of renewable electricity generation, hydropower offers a large competitive advantage (and a "pawn in negotiations") over several decades, since it contributes to the stabilization of the electricity network (in central Europe at least) during the increased deployment of weather- and location-dependent solar and wind energy.
- True-cost pricing of all non-renewable primary energy sources and energy conversion technologies is implemented by around 2020. Economic instruments for promoting renewable energy sources are deployed during a transition period (2010–2035) in order to overcome the "lock-in" situation arising from the structures of the current energy system. The use of these instruments declines over time. Switzerland shapes the required bundle of preferable market instruments in active collaboration with the leading countries in this field.

Conclusion

Towards the end of the 21st century, Switzerland and the rest of the world will, at least in part, bring the structure of their energy systems into alignment with each other with respect to per capita primary energy flow.[6]

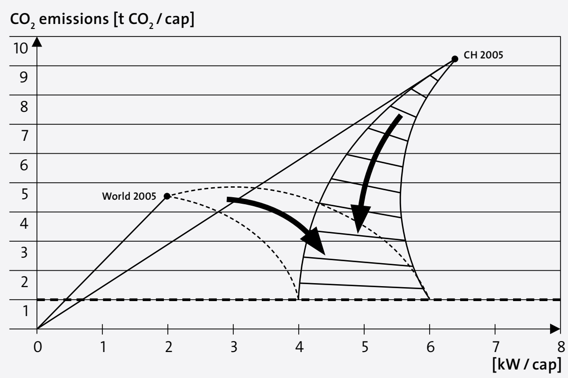
With respect to per capita energy-related CO_2 emissions, Switzerland is slowly but surely approaching the global (worldwide) mean. Under the assumption that — in accordance with the IPCC's rather optimistic scenarios A1T and B1 — the average worldwide per capita income by 2100 will roughly correspond to that of Switzerland today, Switzerland's energy system can be seen as effectively setting a target value for a simplified world trend.

Following the short-, medium- and long-term transformation path to its conclusion, we can quantify the final state as follows:

- About 400 W per capita of fossil-fuel primary energy is to be reserved in the form of hydrocarbons for long-range transportation, which is associated with an output of somewhat less than 1t of CO_2 per capita.
- About 1,100 W per capita of primary energy (solar-thermal, ambient heat, biomass) is required to meet demand in the decarbonized heat sector (low-/medium-/high-temperature).
- Some 1,100 to 1,200 W per capita of final energy is required in the form of electricity. Depending on the type of power generation, the primary energy demand for this amounts to between 2,500 and 4,500 W per capita. It is therefore clear that in the future, electricity-based energy services will have to be more efficiently provided. The resultant savings would be sufficient to power heat pumps alongside moderate expansion of current energy services as well as to meet the energy demand for short- and medium-range transportation for people and freight. The preconditions here, apart from expanding and upgrading the infrastructure (networks), are a means of efficiently storing the stochastic energy accumulated from renewable sources not including hydropower, and also, if necessary, a limited number of CO_2-free power plants for the base load supply. In the long-term, however, only solar power has the full potential to deliver a large part of this electricity.
- This results in a primary energy demand of approximately 4,000 to 6,000 W per capita for sustainable coverage of the total energy demand. The precise value depends on the type of CO_2-free primary energy used to generate electricity and how much progress is made in increasing effciency, whereby the primary goal is to reach an emissions limit of 1t of CO_2 per capita.
- Based on a rough estimate, the limited supply of fossil energy sources will still be sufficient to facilitate the transition phase of the transformation of the global energy system in the 21st century.

A likely (and promising) development along the transformation path towards a climate-compatible energy system in Switzerland, characterized by a very high share of (increasingly) CO_2-free electricity in the overall energy

Figure 13: 1 t CO_2 per capita can be realized towards the end of the 21st century in Switzerland and worldwide by the complete exploitation of realistic efficiency potentials and the targeted decarbonization of all energy sectors to the greatest possible extent.



Plausible primary energy range for 1 CO_2 / Cap in year 2100, depending on electricity generation mix (fossil/nuclear/solar/wind/water)

6 Identification of the primary energy flows of the energy carriers alone using primary energy factors taken from the current version (fall 2007) of Ecoinvent-database 2.0, with the exception of photovoltaics, for which the photoelectric conversion efficiency ratio is explicitly accounted.

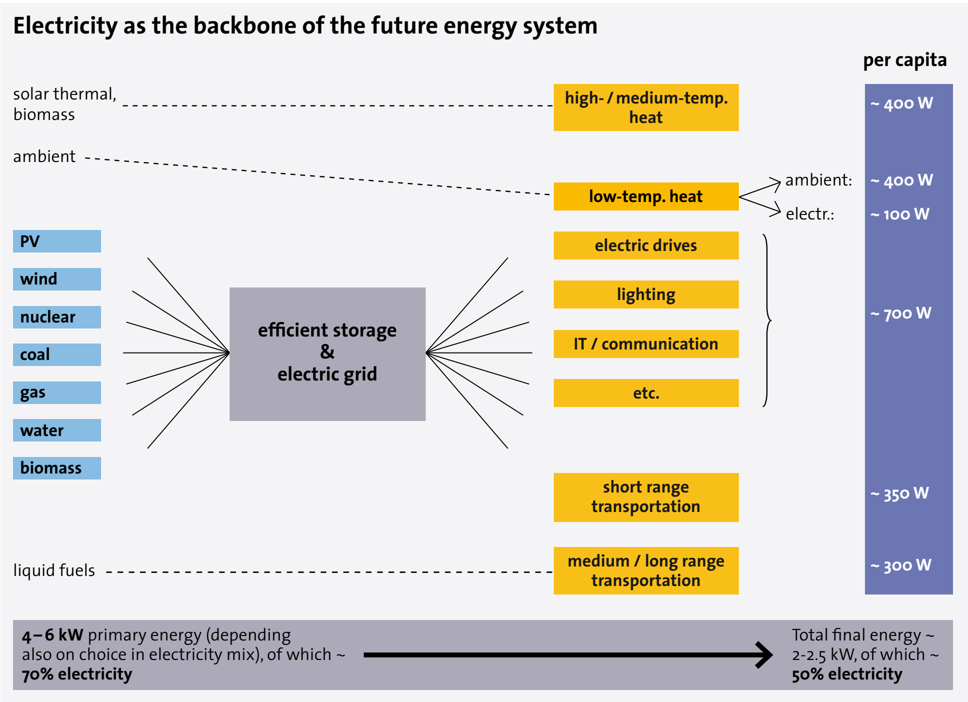
mix, would accordingly look something like the following: In the coming decades, increases in energy efficiency will make the largest contribution. After that, the change to low- (zero) carbon primary energy carriers will have a greater impact on CO_2 emissions.

Figure 13 illustrates the transformation path for the energy system in Switzerland. Over the coming decades, energy efficiency will need to be improved; the use of low-carbon or even carbon-free primary energy carriers will accelerate further reduction in CO_2 emissions. The climate-compatible transformation path is thus characterized by a total energy mix containing a large proportion of electricity that is being increasingly produced CO_2-free (Figure 14). In the next two to three decades along the efficiency path, compatibility with the qualitative goal of the 2000 Watt Society (understood as a metaphor for the globally-reduced demand for primary energy) is assured; over and above this, however, the focus should be put on the overriding importance of the target of 1t CO_2 per capita. Emphasis must be placed on the substitution of carbon-based energy carriers and thus on efficient decarbonization of the greater part of the energy system processes. The global energy system can also be configured in a sustainable manner at a level of 4–6 kW per capita of primary energy. This requires quality and economically affordable availability of the energy sources at the right levels.

It has therefore to be stressed that even this ambitious, technology-oriented transformation path cannot be realized unless suitable economic and socio-scientific frameworks are put into place. This necessitates a consistent and target-oriented policy design.

A well-aligned and consistently and widely-supported energy policy over the long-term is therefore necessary. This calls for taking into account external costs and the related monetary valuation of resources that have been costlessly exploited until now, such as climate quality. Political support and acceptance on a worldwide level will be of deciding importance to reach this end.

Figure 14:
The strategic climate-relevant goals for the future energy system can be reached through a combination of increases in the efficiency of the entire conversion chain together with a significantly higher proportion of low-CO_2 electricity in the entire energy mix.



Introduction and plausibility

The transition to a sustainable energy system is described as a vision, one that the ESC working group considers plausible. This vision provides the basic principles on which ETH Zurich can base its education and research. However, the implications for ETH Zurich described in this chapter should be understood as qualitative, since at this point it would not be sensible to move from the outlined transformation path directly to an operational research program. The delineated path has its own peculiar hurdles and forks stemming from system-dependent uncertainties in making prognoses.

For one thing, the vision is based on the assumption that the threat of climate change will be taken seriously. Many other issues are unresolved. For example, how long fossil fuels will last depends not only on resource potentials but also on producers and consumers. The degree of crude oil production in oil-producing states is also politically determined. All of this can extend the fossil-fuel age or shorten it. If the latter comes about, energy conservation will take on enormous importance, as assumed in the ESC vision.

As another example, the technologies for separating and storing volatile CO_2 are of great importance and can minimize the effects of climate change. These technologies can likewise contribute to extending fossil fuel supplies. While the ESC vision identifies these technologies as important building blocks of a sustainable energy mix over several decades, questions concerning their institutional implementation and associated risks have not yet been comprehensively answered.

The development of energy demand is also an open question. The technological and economic reasoning underlying the transformation path requires that enormous energy-saving potentials be exploited. Whether this actually occurs depends on a variety of factors, including the presence of sufficient economic incentives.

Uncertainty also surrounds the use of solar-power technology for electricity generation. If the associated costs cannot be reduced in the assumed time-frame, solar power will remain expensive. Good production sites will thus be particularly valuable and sought-after. Such a scenario, which likewise deviates from the ESC transformation path, is contingent on an intensified and accelerated use of additional primary energy sources, among them fossil fuel carriers with sequestration as well as nuclear power. Both of these, however, also require significant technological progress, political willingness to institutionalize suitable frameworks and addressing the considerable problems pertaining to risk and acceptance. Thus, in the long-term, a research emphasis on photovoltaics within the framework of international research makes a great deal of sense.

Research in key areas

In defining priorities in key areas for the future, the working group has attempted on the one hand to consolidate the individual viewpoints of ESC members according to an earlier survey, while also drafting its own qualitative assessment matrix based on this. The matrix combines an element of overarching significance (consisting of three parameters: positively contributing to the future energy system, demonstrating academic challenge, and benefiting Swiss industry) with an element relating to the currently observed competitive position or the existing potential for future growth. Of course, it is not possible to evaluate these components quantitatively. Nevertheless, from an original group of 30 thematic subject areas, the working group chose approximately 15 whose significance for the future they deemed especially high.

The consensus emerged that ETH Zurich holds a strong position in approximately two-thirds of these, which by all means must be maintained. As for the remaining third, it was considered absolutely necessary, to implement targeted measures to ensure improvement. Research fields from the first category — i.e. those associated with a strong competitive position — cover topics such as solar fuels, electrical networks, technologies for environmentally-friendly transportation, power electronics, intelligent sensors and controls, energy economics, as well as (especially but not exclusively in cooperation with PSI and/or Empa) nuclear energy (fission), fuel cells, fuel research, and minimal-energy buildings, among others.

Examples for areas where activity needs to be substantially strengthened include:

- Electrical energy storage, e.g. electrochemical and electrostatic components and systems with high energy storage and power density with a simultaneously high degree of conversion efficiency, along with an extensive life-cycle, low investment costs, and a favorable environmental balance in the life-cycle analysis; on the user side, an optimal integration of stochastically occurring (usually local) renewable energy carriers into the entire electric power system must be achieved.
- Photovoltaics, for which an effort should be made to foster both pure research and the translation of new concepts into cost-effective mass production; the development and characterization of new solar cells, especially thin-film systems, while utilizing new raw materials, multifunctional layers and interfaces, and nanotechnology. Along with increasing the level of efficiency, areas of particular interest are practices and production processes featuring maximum material utilization, short energetic payback times, and a high potential for a radical reduction of investment costs. Solar cells with a high potential for a radical reduction of investment costs should also be an aim.
- Hybrid systems and combined thermodynamic cycles for optimal integration of intermittent renewable energy sources like solar-thermal/fossil-, biomass-/fossil-fuel power plants. Also, high-temperature energy storage and efficient use of moderate- and low-temperature heat as well as research on suitable working media for the above-mentioned combined cycles.
- A “Material Sciences and Energy” research area with a focus on one or more of the following areas:
  a. Materials for energy conversion and storage (e.g. high-temperature materials, permanent magnets, materials for new photo-catalysts);
  b. Materials for photovoltaics (e.g. organic nanoparticle- and quantum-well cells);
  c. Materials for new catalytic converters (for combustion processes) and/or energy storage devices;
  d. Materials for wind- and hydro-turbines, and for nuclear- and high-voltage systems.

- Development of radically new bio-energy carriers, both in the area of plant growth, including the ecological effects of broad-scale cultivation of energy plants, and in the area of plant use (new catalysts for their decomposition, microbe cultivation, process optimization for efficient conversion of biomass to fuels on an industrial scale).
- Power plants and other large industrial energy conversion plants with (integrated) removal/safe storage of CO_2. Efforts should be made in this area of research to identify both technological and institutional approaches. Here, a long-term, global approach should take priority over short-term economic considerations.
- Technology-based methods for describing and optimizing multi-scale processes (from the nano- to the system-level) while considering various physical mechanisms (in terms of fluid-mechanics, thermodynamics, chemical reactions, mechanics, electrical/electronic, etc.). The availability of the most advanced computer hardware for parallel computations on a massive scale is of central importance for the international competitiveness of energy-science research at ETH Zurich.
- The design and implementation of intelligent algorithms, sensors, actuators, as well as information and communication methods for "on-line" monitoring, functional control, and comprehensive optimization of complex energy systems (intelligent transportation systems, power plants, buildings, end devices and their integration).
- Integrated models for energy system analysis, with special consideration of resource-efficient and emission-free production of industrial goods. One area of focus is the technical design and operation of energy- and material-efficient industrial processes as well as the use of clean, safe, and economically competitive systems for local energy production.
- "Policy design": an important research area is the development of effective instruments for implementing energy policy goals. This area of research must be extended beyond the individual technical disciplines, since measures taken will impact several areas and might trigger negative effects in any one of them. ETH Zurich is especially well-qualified to undertake interdisciplinary research, as it represents many different disciplines.
- "Energy and Development": Access to clean energy is an important part of the development of countries and regions. The entire economy, including private households and firms, profits from it. Energy provision shows strong interdependencies with the economy and society as well as with public health and the environment. In-depth research of these interdependencies will yield well-founded recommendations for the construction of fast-growing energy systems in developing countries.

On the basis of a priority analysis, the Energy Science Center strongly believes that each of the above-mentioned themes should be covered by one or more dedicated professorships. It therefore recommends to ETH Zurich's Executive Board that approximately 10 new professorships be created all together. These should be based in key areas of future energy research. The funding for some of these professorships should be borne by the private sector to a significant extent. Here the ESC is willing and able, in cooperation with the individual departments and the ETH Foundation, to make an active contribution towards peaking industry's interest (for which purpose numerous contacts already exist) and towards defining potential common priority areas.

Implications for ETH Zurich

Teaching

The new “Master of Science in Energy Science and Technology,” first offered in September 2007, needs to be supported consistently over the next several years. This requires more than just increased participation from the professors, however. The most important thing is to recruit young talents from all over the world and this requires a scholarship system to be developed in cooperation with industry. In addition, the development of a PhD program in the energy area is conceivable, and the development of continuing education for employees in management of integrated energy systems should be planned.

Knowledge transfer and service to society

Interaction with the economy and civil society is important for research and teaching in the energy area. This can be achieved by

- Identifying areas of cooperation between ETH and industry and developing effective long-term “lighthouse” projects;
- Developing qualitatively outstanding continuing education in energy technologies and energy management; and
- Strengthening ETH Zurich and the ESC as institutions that make important scientific contributions to the public discussion and to political agenda-building in the coordinated role of “honest brokers.”

National collaboration

In the academic environment, the ESC and ETH Zurich would like to exploit synergy potentials within the ETH domain. For example, the full potential in the framework of the CCEM and CCES Competence Centers should be tapped, and collaborations with universities (incl. those of Applied Sciences) should be pursued wherever practical. A systematic exchange with important players in energy policy (for example in the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN)) should be cultivated.

The international arena

Collaboration with the best specialists and institutions in the world is a key factor for sustainable success. One promising option is the consolidation and intensification of the collaboration begun in 2007 with our partners of the IDEA League (Imperial College London, TU Delft, RWTH Aachen, Paris Tech) as well as of the Alliance for Global Sustainability (MIT, University of Tokyo and Chalmers University of Technology). Collaboration in teaching and research within this partnership is to be concretized. In addition, strengthening alliances with leading institutions in up-and-coming countries such as China, India, and Singapore is strategically important for our global presence, and work in this area is well underway.

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