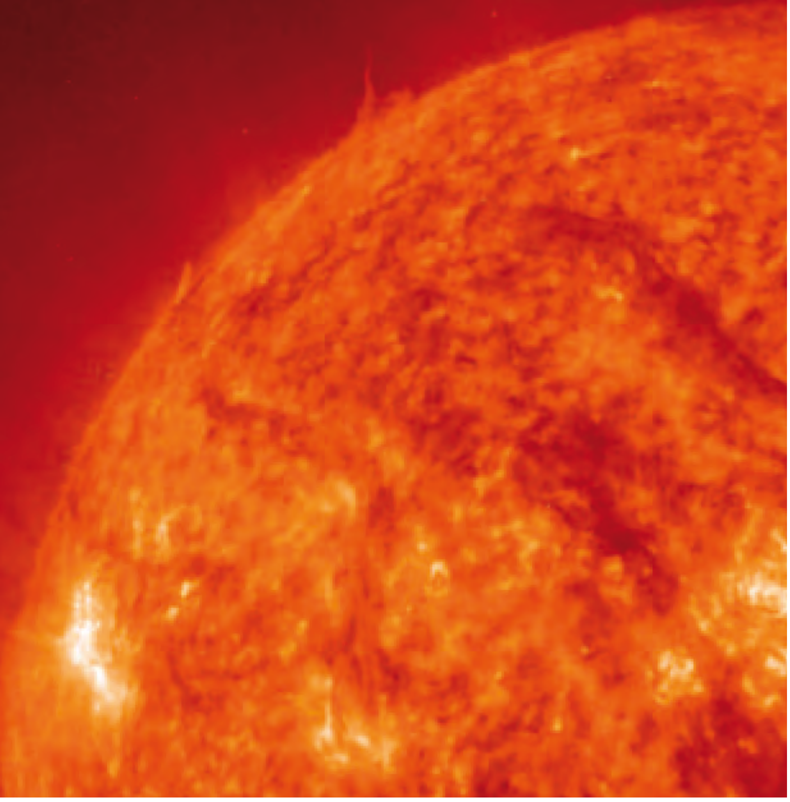
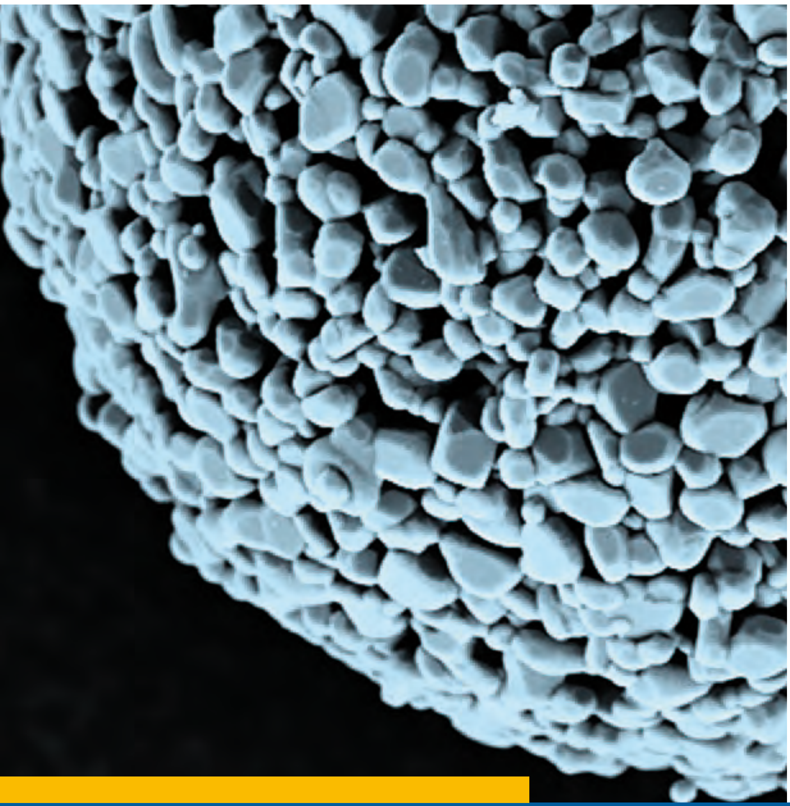




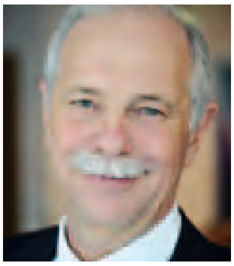

ENERGY
RESEARCH FOR TOMORROW

HELMHOLTZ
ASSOCIATION

CONTENTS

Front cover:
The sun – our greatest source of energy (top left; SOHO [ESA & NASA]). Straw – a source of bioenergy outside the food chain (top right; www.istockphoto.com). Porous granulate for lithium-ion batteries (bottom left; scanning electron microscope image; Karlsruhe Institute of Technology). Radial compressor for compressing carbon dioxide (bottom right; German Aerospace Center).

FOREWORD



Prof. Dr. Jürgen Mlynek

Prof. Dr. Eberhard Umbach

Eine Initiative des Bundesministeriums für Bildung und Forschung
Wissenschaftsjahr 2010
Die Zukunft der Energie

DEAR READERS,

One of the central challenges of the 21st century is to ensure a sustainable energy supply for the world's people and its economy. That's why scientists are searching for solutions that will provide sufficient amounts of energy – reliably, affordably and without endangering the natural environment on which our lives are based.

One thing everyone agrees on is that there are no obvious solutions. No single energy carrier or technology will suffice to safeguard our future energy supply. Consequently, researchers must examine a broad range of options and develop many different kinds of technologies. This is the only way to create a sustainable energy system that adequately takes local environmental, political, social and economic conditions into account.

Germany's largest scientific organisation, the Helmholtz Association of German Research Centres, is carrying out world-class research into diverse aspects of this existential challenge in its Research Field Energy. A broad spectrum of energy sources such as the sun, nuclear fusion, fossil fuels, geothermal energy, water, wind, nuclear fission and biomass are being investigated – but this is not all. Technologies for energy storage, energy distribution and efficient energy use also play a key role. This comprehensive approach corresponds to the energy concept of the government of the Federal Republic of Germany, which calls for a dynamic energy mix that includes the expanded use of renewable energies, a corresponding extension of the power grid, the development of new energy storage systems and increased energy efficiency.

The scientists of the Helmholtz Association are investigating entire chains of energy processes, including boundary conditions and side effects such as the impact on the climate and the environment and acceptance issues. They are taking into account interactions with other sectors such as the raw materials, construction and mobility industries. Energy research is directed at industrial application and is therefore closely linked with industry. German companies aim to play a leading role in the necessary restructuring of the global energy system.

Ministries of the German government and federal states, as well as EU institutions, are financially supporting our research activities. We would like to take this opportunity to express our sincere thanks for their support.

This brochure offers some insights into selected areas of our work and a look at potential future developments. Our research is for you – so that you will continue to have an adequate supply of energy at an affordable price in the future!

Prof. Dr. Jürgen Mlynek
President of the Helmholtz Association of German Research Centres

Prof. Dr. Eberhard Umbach
Vice President of the Helmholtz Association, Coordinator of the Research Field Energy and President of the Karlsruhe Institute of Technology

ENERGY RESEARCH – RESEARCH FOR TOMORROW

The Helmholtz Association of German Research Centres works on major challenges facing science, economy and society in order to safeguard the basic conditions of human life over the long term. Outstanding scientists, strong infrastructures and modern research management sustain systematically organised strategic research in six areas: Energy; Earth and Environment; Health; Key Technologies; Structure of Matter; and Aeronautics, Space and Transport.

The transition to a sustainable energy system is one of the greatest challenges of the present and the future. With its energy concept, the German government is formulating a long-term, holistic strategy for a reliable, affordable and environmentally compatible energy supply. Its plans include the expansion of renewable energies as a main pillar of the future energy system; the development of a flexible power plant network in which, among other things, highly efficient fossil-fuel power plants are available as reserve and balancing capacities; consideration of nuclear fusion as a climate-friendly option; and the retention and further development of existing expertise in the area of nuclear safety research.

Key elements of this concept include technologies for enhancing energy efficiency and a modern infrastructure with smart grids and high-performance storage units. These are essential if renewable energies are to be integrated and interact with conventional energy sources. In the area of mobility, the energy concept envisages the continued promotion of hydrogen and fuel cell technology, forging ahead with the use of biofuels, and putting more electric vehicles on the road.

For some time now, the Helmholtz Association has been pursuing the tasks and goals recently formulated by the German government in its energy concept. In the process, its researchers have steadily been investigating new aspects. These, too, are compatible with the German government's energy concept. In its Research Field Energy, the association is working out appropriate solutions, which range from the exploitation of renewable energy sources to the development of innovative storage technologies.

Reliable and sustainable solutions

The scientists at Helmholtz research centres are investigating the potential of renewable energy sources such as the sun, geothermal energy and biomass. They are developing new technologies that utilise these resources efficiently, integrate them into the overall energy system, and ensure that the energy supply chain will continue to function reliably in the future. In the field of solar energy, the focus is on thin-film photovoltaic cells that use less material than conventional systems and on solar thermal power plants. Bioenergy research focuses on biogenic waste materials outside the human food chain.

In the longer term, nuclear fusion constitutes a clean, safe and almost inexhaustible source of energy and therefore a worthwhile option. The Helmholtz Association is making significant contributions to international research into nuclear fusion and the development of fusion power plants. In parallel, Helmholtz researchers are working on materials and technologies that boost the efficiency and climate-friendliness of power plants operated with fossil fuels. When it comes to the distribution and utilisation of energy – for example, in power grids, the construction industry and the production of lightweight components – solutions that improve efficiency are given a high priority.

A climate-friendly thermal power plant: A scientist measures how well a ceramic membrane allows oxygen to pass through.
Forschungszentrum Jülich

Energy efficiency can also be increased through storage. This is why the Helmholtz Association is developing high-capacity electrochemical, chemical, electrical, thermal and mechanical energy storage technologies. Researchers are striving to develop batteries, fuel cells and hydrogen technologies for electric vehicles. Thanks to its researchers‘ unique expertise in the area of nuclear safety research, the Helmholtz Association is contributing not only to the safe operation of nuclear reactors but also to the treatment and disposal of highly radioactive waste. Finally, Helmholtz researchers are investigating energy systems in a holistic manner. To this end, they trace the entire chain of energy processes, while also considering the ecological, economic, political, social and ethical aspects of new technologies.

Interdisciplinary and networked

The Research Field Energy, like Helmholtz research in general, is characterised by broad-ranging expertise, large-scale research facilities for science, close cooperation between colleagues in various disciplines, the linkage of basic and applied research, and fruitful cooperation with partners from industry. The researchers at the Helmholtz centres work together in strategic programmes that cross the boundaries of institutions and disciplines. This enables them not only to work intensively on individual issues but also to devise holistic solutions to complex problems.

The Helmholtz centres have an outstanding scientific and technological infrastructure that is matched by only a few other locations in the world. Alongside significant large-scale facilities – such as particle accelerators and sources of synchrotron radiation, neutrons and ions – high-performance measuring and laboratory equipment attracts top researchers and promising young scientists from all over the world. Such facilities greatly enhance Germany’s appeal as a research location.

As result, the Helmholtz Association is ideally positioned to work out solutions for a sustainable energy supply. It will continue to expand its strengths – after all, the energy issue will be one of the key factors that determine our quality of life in the future.

Concentrating solar power systems

FOCUSSED ENERGY FROM THE SUN

Solar thermal power plants generate sustainable energy in dry, sunny areas. With the help of heat storage, they can provide electricity even when it's cloudy or at night. What's more, the waste heat produced can also be used to desalinate seawater. Solar thermal research and development work at the Helmholtz Association focuses on making such systems more efficient and more economical.

The sun provides energy in abundance. The solar radiation that reaches the earth could theoretically supply well over 10,000 times the energy required by the world's population. Researchers are seeking to develop efficient and affordable technologies in order to exploit the huge potential offered by this climate- and resource-friendly energy source. As far as German industry is concerned, solar energy also represents a great opportunity to do good business on international markets. The DESERTEC concept developed by the Helmholtz Association opens up new possibilities for North-South cooperation as well. This is because it is primarily based on solar thermal power plants and envisages a situation in which some of the power generated in desert regions could be used in Europe.

Electricity around the clock

Because concentrating solar power systems require direct sunlight, they are ideal for dry, sunny regions. The heat they generate can be temporarily stored in large heat stores – for example, in molten salt or special types of concrete. Concentrating solar power plants can therefore also produce electricity at night or when it is cloudy. Moreover, waste heat from solar thermal power plants can be used to desalinate seawater – a very attractive option in dry regions. Particularly in developing arid regions, such as North Africa, solar thermal power plants can make a key contribution to establishing a sustainable energy supply to cover a significantly growing need for power in the coming decades.

With a worldwide installed electrical capacity of approximately 650 megawatts, concentrating solar power plants are still in an early stage of development. Their current position is comparable to that of fossil fuel power plants at the beginning of the 20th century. Much research and development work therefore still needs to be done, especially in terms of fundamental processes, the construction and process materials used, the optimisation of power plant operation and the integration of solar thermal facilities into existing power supply structures. Researchers at the Helmholtz Association are examining innovative concepts and technologies that would substantially reduce the cost of concentrating solar power systems and significantly improve the contribution they could make to establishing a sustainable energy supply.

Field of mirrors at the Plataforma Solar de Almería solar tower plant in Spain (left).
German Aerospace Center

Parabolic mirrors focus solar radiation onto an absorber tube mounted in front of the mirror (right).
German Aerospace Center

The Helmholtz Association has more than 30 years of experience working with solar thermal power plants and is leading the way forward in the global solar thermal sector. The organisation can point to outstanding expertise in all of the relevant research and development fields – in other words, in thermal process technology, gas turbines, storage technology, ceramic materials for high-temperature applications, wind tunnels and flow simulations for heliostat and collector fields, satellite remote sensing, and system analysis models.

Higher temperatures boost efficiency

Concentrating solar power systems need to attain higher temperatures if their electricity generation costs are to be lowered. A higher temperature increases the cycle efficiency, which reduces the number of collectors needed for each kilowatt-hour of electricity generated. It also increases the capacity of a heat store without the need to increase its volume, lowers efficiency losses in dry cooling processes and improves the energy yield from fossil fuels in hybrid operation. Key development work at the Helmholtz Association is therefore geared toward achieving higher temperatures in the parabolic trough power plants already being used and in innovative systems such as solar tower plants, Fresnel collectors and dish/Stirling systems. To this end, scientists are studying new heat storage media such as salt, sulphur, gas and gas-particle flows.

Extended testing in southern Spain

Although the Helmholtz Association has its own solar energy infrastructure, it also cooperates closely with partners in order to gain access to larger-scale facilities. In Cologne, the association operates a highly concentrating solar furnace and stands that are used for testing solar thermal processes. In Jülich, it conducts high-temperature technology experiments with a solar tower plant. A large number of research facilities developed and built in a German-Spanish partnership are located in Almería in southern Spain. Whereas the German technology development systems are generally on a laboratory scale, the hot and sunny climate in Almería makes the facilities there ideal for long-term experiments under real conditions.

Research and development work on solar thermal power plants at the Helmholtz Association is based at the German Aerospace Center (DLR).

Open-air test stand: Taking measurements at an absorber tube.
German Aerospace Center

SOLAR THERMAL POWER PLANTS

Solar thermal power plants convert radiation from the sun into thermal energy. When such plants concentrate this radiation, they can achieve temperatures of between 400 and 1,000 degrees Celsius. These concentrating solar power (CSP) plants are equipped in one of three ways: with parabolic-shaped mirrors that focus rays onto a tube (parabolic trough power plants), a series of nearly flat mirrors that are all focused on a single point (solar tower power plant), or linear Fresnel collectors consisting of long panels of flat mirrors. The concentrated thermal energy they produce can initially be converted into mechanical energy using a Stirling engine or in a steam power plant. This mechanical energy then drives a generator to produce electricity.

SOLAR POWER AT ITS BEST

From sunlight to electricity: Thanks to its huge technical and economic potential, photovoltaics will make a major contribution to sustainable energy supply systems in the future. Helmholtz researchers are developing thin-film solar cells that require not only less material but also less energy during production. The result is lower costs.

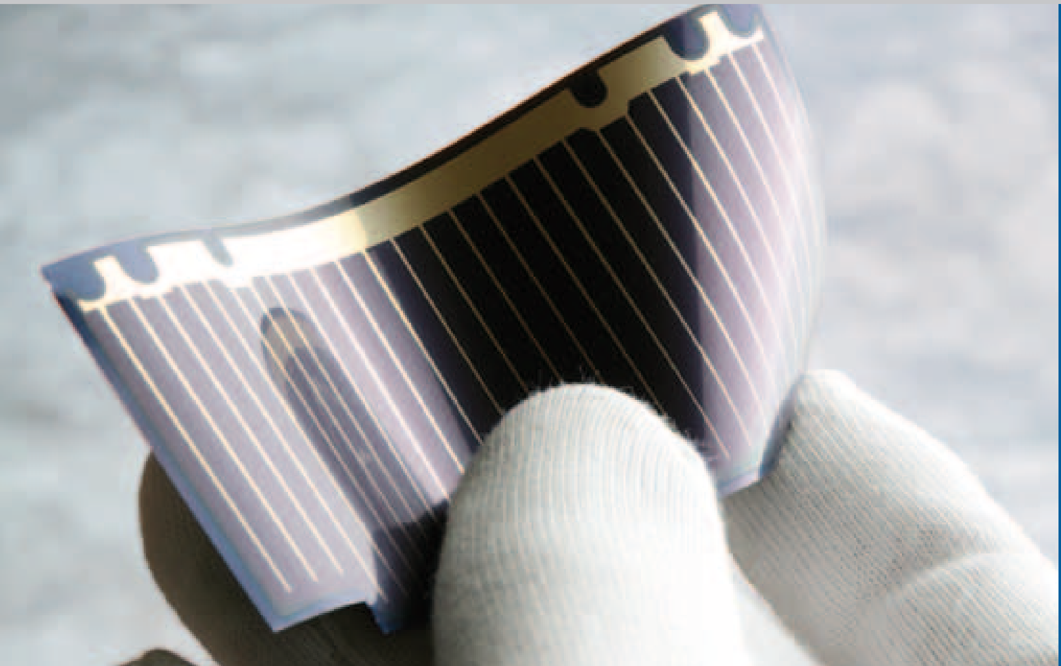
The sun sends more energy to the earth in an hour than the world's population uses in a year. Photovoltaic systems offer one possibility for tapping into this energy. In such systems, solar cells convert sunlight directly into electricity. The most important component in these solar cells is a light-absorbing semiconductor layer coating, which these days usually consists of highly pure silicon wafers. Manufacturing these wafers requires a lot of material and energy, however – which is why Helmholtz scientists are working on a new generation of solar cells characterised by an ultra-thin light-absorbing coating less than one hundredth times the thickness of a silicon wafer.

Because such thin-film solar cells substantially reduce the amount of material required for their production, less energy is needed to manufacture them. Moreover, the manufacturing process employed makes it possible to construct complete modules in one process cycle rather than just individual cells. All of these factors help to reduce costs. Combining ultra-thin films with suitable encapsulating materials such as glass or conventional films also opens the door to new applications and architectural design options. In addition to making thin-film solar cells more efficient, research at the Helmholtz Association focuses on reducing the production costs. To this end, the Helmholtz scientists don't just rely on silicon for the light-absorbing film; other semiconductors such as chalcopyrites are also used.

Better use of light

Thin-film solar cells based on amorphous (unordered) silicon are already on the market. A Helmholtz team is now studying microcrystalline silicon carbide – a material made of tiny crystals. Each crystal consists of silicon atoms and carbon atoms in equal numbers. In addition to being transparent and stable, silicon carbide is ideal for use as a transparent solar cell window layer – in other words, for the side that captures the sunlight. That's because it reduces light reflections, thereby allowing the solar cell to make better use of the light.

To ensure that the material exhibits specific optical properties and that light of different wavelengths can be absorbed, Helmholtz researchers are combining amorphous and microcrystalline silicon in a single solar cell. They are also striving to integrate a third layer – for example, a silicon-germanium alloy – so that a larger portion of the solar spectrum can be exploited. Even higher efficiency levels can be achieved with cells whose semiconductor material has an ordered, crystalline structure. That is why thin films of crystalline silicon are another key research topic at the Helmholtz Association.



Flexible thin-film solar cells for space applications (left).
Helmholtz-Zentrum Berlin

Coating chamber for ultra-thin solar cells (right).
Helmholtz-Zentrum Berlin

Efficient absorption

The Helmholtz Association is also investigating other environmentally friendly semiconductor materials besides silicon. These include chalcopyrites – a group of semiconducting compounds with a typical crystal structure similar to that of diamond. Particularly interesting for photovoltaic applications are copper indium gallium selenide (CIGS) and copper indium sulphide (CIS) cells. Chalcopyrites absorb light much more efficiently than silicon. As a result, the films used for solar cells can be extremely thin. A company in Berlin is already operating a production facility for CIS solar cells with an annual capacity of 200 megawatts. The technology utilised at this factory is based on the results of Helmholtz research.

Thin-film photovoltaic research at the Helmholtz Association covers the entire value chain for solar cell and solar module technology – from fundamental physical and material properties to manufacturing processes and industrial-scale production. To help ensure the success of the research efforts, outstanding physicists, chemists, materials scientists and electrical engineers work together in interdisciplinary teams.

Fuels from sunlight

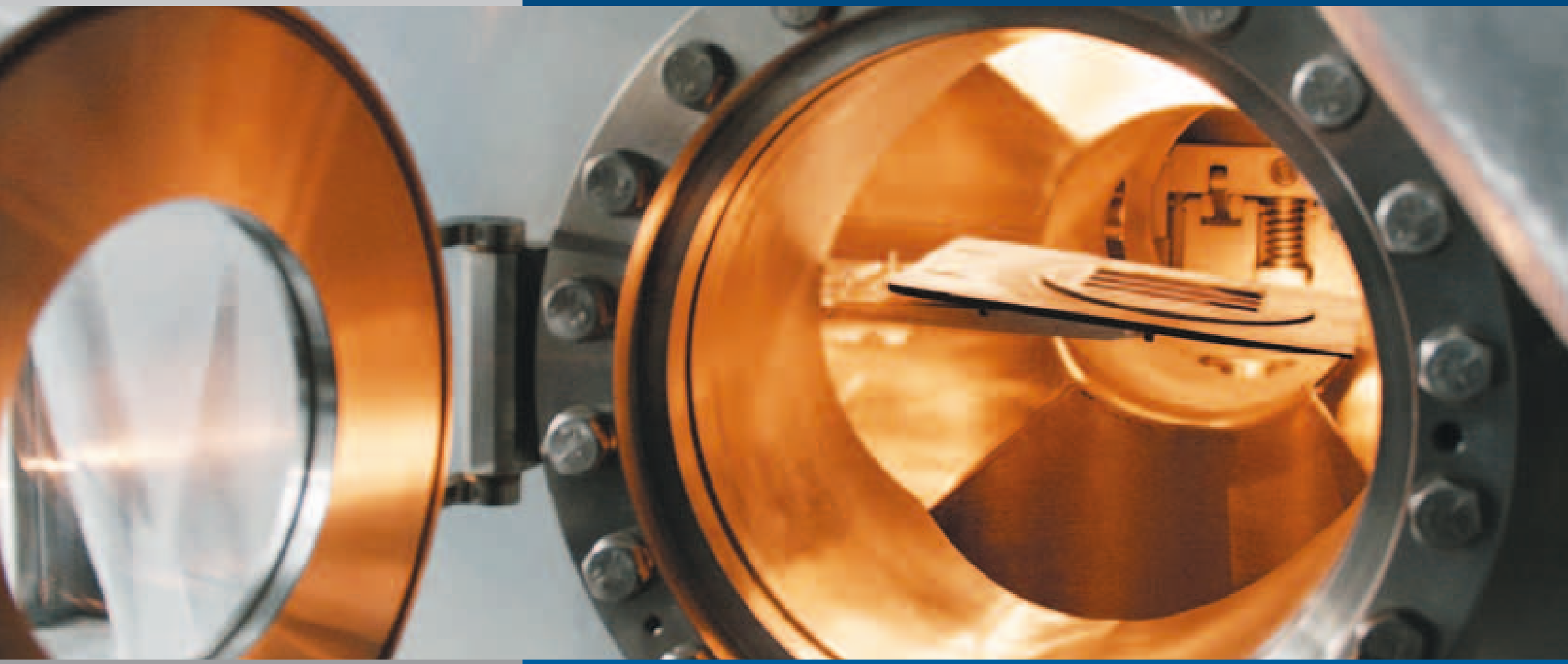
In addition to generating power, solar fuels and energy storage materials will also contribute to the development of a sustainable overall energy supply system in the future. Helmholtz scientists can produce hydrogen in a monolithic (one-piece) material system that combines a semiconducting absorber and a catalyst in a single structure. Here, the chemical energy generated from sunlight can be stored and used for mobile applications as well.

The Helmholtz Zentrum Berlin for Materials and Energy and Forschungszentrum Jülich participate in research into thin-film photovoltaic systems. Rapid implementation of research results in industrial applications is ensured by cooperation with renowned industrial partners and by the PVcomB (Competence Center Thin-Film and Nanotechnology for Photovoltaics Berlin), which is operated in cooperation with Technische Universität Berlin.

Thin-film modules on a building façade.
Helmholtz-Zentrum Berlin

PHOTOVOLTAICS

The direct conversion of solar energy into electrical energy is based on the so-called photovoltaic effect. Incoming sunlight creates mobile electrical charge carriers in the solar cell's semiconducting absorbent material. These charge carriers are separated and collected at two different contact layers on the front and the back of the absorber. This creates a voltage, which can be tapped at the contacts. Adding an electrical device completes a circuit in which a current flows.



Bioenergy

STORABLE AND VERSATILE

The distinguishing features of biomass as a renewable energy source are that it can supply base load, be stored economically and is versatile. Research at the Helmholtz Association primarily concentrates on biogenic residues outside the human food chain – such as straw and wood waste, which can be processed into high-value fuels.

Fossil energy carriers such as coal, petroleum and natural gas have a high energy density. In addition, they are relatively easy to exploit, transport and use in mobile applications. Many areas, including road transport and air travel, are hardly imaginable without them. However, these resources are limited and their use produces climatically active CO_2 emissions. Biomass, like fossil energy carriers, contains carbon. However, when burned, biomass only releases as much CO_2 as the plants originally removed from the atmosphere during their growth. Biomass is therefore more climate-friendly. Among the renewable energy sources, biomass – like geothermal energy – is distinguished by its ability to supply base load. What's more, it can be stored, transported and used in a wide variety of ways at an acceptable cost.

Efficient biogas plants

The Helmholtz research mainly concentrates on the energetic utilisation of biomass that occurs outside the human food chain. It thus focuses on the exploitation of residual and waste materials. The first priority is to optimise already known processes and increase their efficiency. In this context, biogas generation is currently the dominant process in Europe. Biogas has the advantage that it can be distributed via the existing infrastructure – in other words, the gas and power grids. Nonetheless, the energy yield from today's biogas facilities is unsatisfactory. To some extent, this is because we don't yet adequately understand the microbial processes underlying the production of the gas. As a consequence, we cannot influence them in a targeted manner. The work of the researchers at the Helmholtz Association is therefore aimed at acquiring a more exact understanding of these processes so that they can be accurately controlled. The results will make it possible to design a new generation of biogas plants.

Fuel from straw

Synthetic biofuels are another focus of research. BTL (biomass to liquid) fuels are produced from straw and waste wood in the bioliq® pilot plant near Karlsruhe. The concept used involves several process steps. In the first of these, dry biomass is converted to an intermediate product using flash pyrolysis. The conversion process, which takes place in regionally distributed decentralised facilities, produces a slurry of coke in liquid hydrocarbons. This suspension's

Harvesting fast-growing tree species such as poplars or willows on a short-rotation plantation (left).
Helmholtz Centre for Environmental Research

The first stage of the bioliq® pilot plant (right).
Karlsruhe Institute of Technology

energy density is more than ten times that of the starting material. Because concentrating the energy density by means of a decentralised process reduces both transport distances and CO_2 emissions, this method substantially improves the economy and environmental compatibility of the overall process.

The suspension is then transported to large-scale central plants, where it is processed – initially by converting the material into synthesis gas in an entrained-flow gasifier. It is subsequently used to synthesise made-to-measure fuels. The suspension can also be traded as an intermediate product that can be further processed for various purposes. For example, it is conceivable that entire process chains currently based on crude petroleum could in the future use biogenic residual materials instead. The bioliq® concept is extremely suitable for other areas, both in terms of the raw materials used and the user requirements. The Helmholtz Association owns a facility in which all of the process steps up to and including production of the liquid fuel will be realised before the end of 2011. It thus has a pilot plant for the production of second-generation biofuels that is unique in Germany and is attracting a lot of interest throughout Europe and beyond. In conjunction with a large number of partners from Germany and abroad, the Helmholtz researchers are tackling various scientific questions relating to the structure and operation of the plant.

Economic and ecological aspects

The development of these technologies within the Helmholtz Association is embedded in a technical, economic and ecological holistic evaluation process that extends from the land used to cultivate the biomass to the utilisation of the biogenic energy. This is crucial because new technologies will only succeed if they are technically feasible, profitable and offer ecological advantages.

Research and development projects that address the utilisation of biomass energy are based at the Karlsruhe Institute of Technology (KIT) and the Helmholtz Centre for Environmental Research – UFZ in Leipzig. The research work is interdisciplinary, especially when it comes to the topic of a sustainable bioeconomy.

Bioenergy can be obtained from straw as agricultural residue and waste.
Karlsruhe Institute of Technology

BIOMASS

Biomass includes all organic substances produced by plants and animals. It is produced by photosynthesis: By means of dyes, plants absorb energy from light, which they convert into chemical energy. In this way, they synthesise energy-rich organic compounds from energy-poor inorganic materials. Animals take in the biomass produced by plants as food.

Humans use biomass both for its material properties – for nutrition, as animal feed, chemical feedstocks, working materials and active ingredients – and for its energy content. Heat and power can be generated directly from biomass in combustion plants and power plants. Biomass can also be used indirectly via chemical energy carriers such as biogas, fuels or hydrogen.

POWER AND HEAT FROM THE DEPTHS

Geothermal heat is available everywhere and at all times, regardless of the time of day, season, climate or weather. It is almost inexhaustible, virtually free of emissions and provides not only heat but also power that is suitable for base load. The Helmholtz Association develops solutions aimed at promoting the economic and sustainable utilisation of this energy source from the depths.

Today, geothermal energy is already one of the most widely used renewable energy sources in the world. And the Intergovernmental Panel on Climate Change (IPCC) estimates that in around 40 years' time geothermal energy sources could generate around 160 gigawatts of electrical power and over 300 gigawatts of heat power that could supply base load. That corresponds to roughly 7.5 times the gross installed power generation capacity of Germany's nuclear power plants and 1.5 times the total German energy consumption for space heating and hot water in 2007. Geothermal energy also has great potential in Germany.

Geothermal plants utilise local energy and thus represent a secure energy supply that is independent of imports. They don't need much space and emit a fraction of the amount of CO_2 emitted by burning fossil energy carriers. An increased base load supply of geothermal heat and power would therefore greatly help Europe and the world to achieve their climate protection targets.

Geologically representative: Groß Schönebeck

In several large-scale plants, Helmholtz Association researchers are studying new processes that could also make the utilisation of geothermal energy economic and competitive in Germany. Here, experiments at reference locations have a key role to play. The Groß Schönebeck location in the North German Basin, for example, is geologically representative of large parts of Central Europe. Processes that can be carried out successfully there can thus be transferred to regions with similar geological conditions.

The in situ research laboratory at Groß Schönebeck is the only facility worldwide that has been conceived to study sedimentary geothermal reservoirs under natural conditions. The researchers there exploit new borehole measurement processes and test technical system components in operation, which they then develop further. Two research boreholes provide access to two water-bearing horizons at depths of between 3.9 and 4.3 kilometres and temperatures of around 150 degrees Celsius – the minimum temperature necessary for the efficient conversion of geothermal heat to power. The process relies on water already present underground or water fed in from the surface. As it flows through hot rock, the water absorbs heat, which it transports to the borehole.

Stimulation under high pressure

As the natural permeability of the rock is normally low, it must be stimulated by artificially fracturing the rock so that the water can circulate better. The stimulation, in which large quantities of water are injected underground at high pressure via a borehole, creates a widely branched system of fissures in the rock. This process is part of the enhanced geothermal systems (EGS) concept, which aims to make reservoirs economically viable. It improves the yield of geothermal reservoirs and lowers the risks associated with trying to locate such reservoirs.

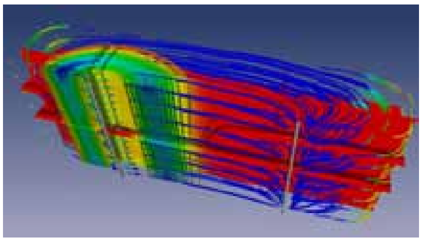
Geothermal power generation requires sustainable thermal water circulation, an above-ground power plant and two boreholes. The water is extracted from underground via the first borehole; after its thermal utilisation in the power plant, the water is fed back into the reservoir via the second borehole. Above ground, the heat of the water is transferred to a working medium with a low boiling point in a heat exchanger. In a secondary cycle, this working medium drives the generator to produce power. When such a process involves the use of an organic liquid with a low boiling point it is referred to as an organic Rankine cycle (ORC).

Low-temperature power generation

The stimulation has made the boreholes in Groß Schönebeck so productive that it would probably make sense financially to operate a power plant there. The Helmholtz Association is currently building a research facility for power generation there. Studies of process technology and energy economics as well as the numerical simulation of the mutually coupled thermal-hydrological-mechanical-chemical processes (THMC) are making it possible to refine the system technology.

Another large-scale experimental facility currently set up in Karlsruhe is being used to further develop a low-temperature power plant process on the basis of an ORC. This facility permits the cycles involved to be adjusted and optimised. Both locations – Karlsruhe und Groß Schönebeck – offer excellent opportunities for validating all modelling work so that these instruments can be reliably integrated into the planning processes.

Research into geothermal energy is carried out by the GFZ German Research Centre for Geosciences in Potsdam, the Helmholtz Centre for Environmental Research – UFZ in Leipzig and the Karlsruhe Institute of Technology (KIT).



3D visualisation of a simulation of thermal, hydraulic and mechanical processes in a geothermal reservoir.
Helmholtz Centre for Environmental Research

GEOTHERMAL ENERGY

The term “geothermal energy” refers to the study, exploitation and use of the earth’s heat.

Some of the heat in the accessible parts of the earth’s crust is residual heat from the time of the earth’s formation; some of it is the result of radioactive decay processes in the crust. On average, the temperature of the earth’s crust increases by one degree Celsius for every 33 metres below the surface. The heat is transferred from deeper parts of the earth to accessible depths by means of conduction and convection.

Near-surface geothermal energy directly utilises the heat of the earth at depths extending from a few metres to a few hundred metres for heating and cooling purposes. Deep geothermal energy exploits heat at significantly over 100 degrees Celsius, which can be used directly as heat or to generate power. Here, it is usually necessary to bore to depths in excess of 3,000 metres.

The geothermal power plant at Hellisheiði near Reykjavik (left).
Karlsruhe Institute of Technology

Installing the pipework in the borehole of the geothermal laboratory at Groß Schönebeck (right).
German Research Centre for Geosciences

Fusion

SOLAR FIRE FOR THE EARTH

Fusion lights up the sun and the stars. If we succeed in utilising this source of energy on earth, humanity will be guaranteed a long-term supply of power and heat. Scientists around the world are working on complex technologies for future fusion power plants – and the Helmholtz Association is participating with a leading role.

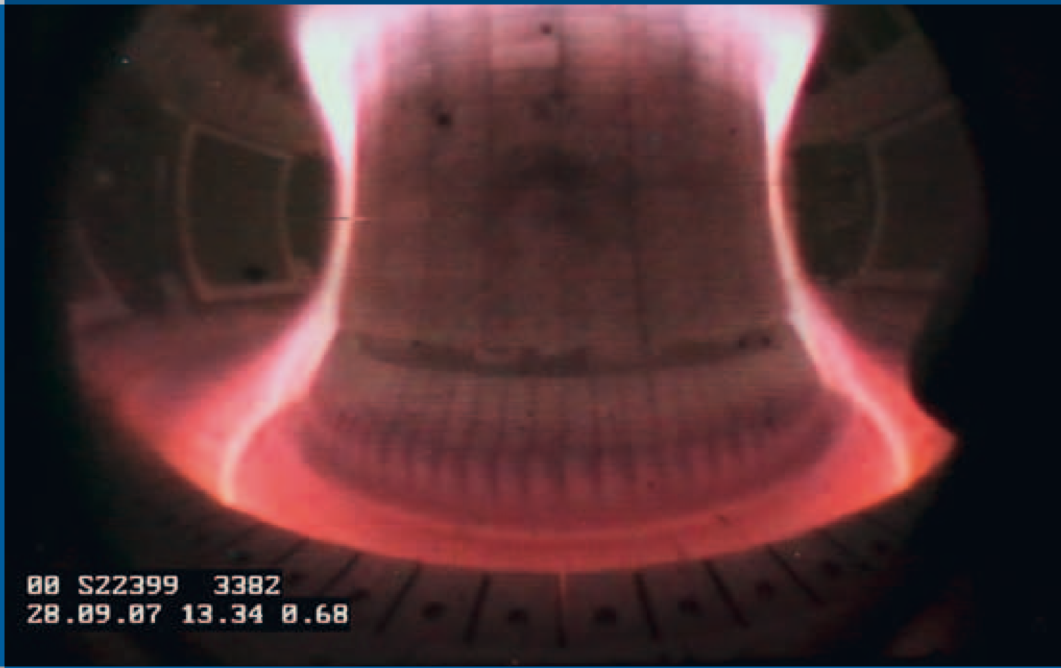
Global demand for electric power is expected to grow around six-fold in this century alone. Global fossil energy resources are limited; petroleum and natural gas will only cover demand for a limited time. What's more, due to the increasing CO_2 content of the atmosphere their use is to be reduced. Thanks to bridging technologies such as the nuclear fission of uranium and carbon sequestration, we still have a few decades in which to expand the use of renewable energy sources – such as solar and wind power – and further develop technologies for intelligent power grids and energy storage. None of the currently known technologies, however, will be able to cover the forecast demand alone.

One way of supplying the growing global population with economic, reliable and environmentally friendly power and heat is to exploit nuclear fusion, an virtually inexhaustible energy source. This is the energy conversion process that powers the sun and the other stars. There it takes place more or less automatically. In contrast, on earth it requires highly complex technology, but the effort is worthwhile. If we succeed in bringing the controlled solar fire to earth, we will have an opportunity to master one of the future's greatest challenges.

Nuclear fusion on the experimental scale has long been a reality on earth. Scientists worldwide are now working on fusion power plants. German research into fusion is based at the Max Planck Institute for Plasma Physics (IPP) in Garching and Greifswald, the Karlsruhe Institute of Technology (KIT) and Forschungszentrum Jülich. The work is part of the European coordinated and funded fusion research programme (EURATOM). It is clearly divided between the facilities named, which are international leaders in many areas of both plasma physics and fusion technology.

Fuels from water and minerals

The fuels for fusion are available worldwide in almost unlimited quantities, as constituents of water and minerals. The hydrogen isotopes deuterium and tritium are most suitable for use in a power plant. Deuterium is present in natural water. Tritium has a half-life of just 12 years and thus hardly occurs naturally. However, it can be bred from lithium, which in turn can be extracted from minerals, brine or sea water. A bathtub full of water and the lithium in an old notebook battery could supply the electricity needs of a family for 50 years. Nuclear fusion, however, only takes place at astronomic-



A look into the plasma vessel of Germany´s largest fusion facility, ASDEX Upgrade at Garching, near Munich (left).
Max Planck Institute for Plasma Physics

The plasma that is being studied using the ASDEX Upgrade is of very low density but extremely hot (right).
Max Planck Institute for Plasma Physics

ally high temperatures. The fuels are then in plasma form – in other words, they exist as ionised gas. Only in this fourth state of matter can the atomic nuclei overcome their mutual repulsion and fuse with one another. Accomplishing this feat on earth requires a temperature of over 100 million degrees Celsius – that's six times the temperature in the interior of the sun. The pressure of the plasma, however, is much less than the pressure inside the sun. There, pressures are measured in billions of atmospheres, whereas an earthly fusion plasma can get by on around two atmospheres.

Clean and safe

Fusion is a clean source of energy. It produces neither CO_2 emissions nor long-lived radioactive wastes. Tritium is a radioactive element, and the walls of a fusion power plant are activated by the fast neutrons produced during the fusion reactions. However, because the radioactivity thus produced decays relatively rapidly, there is no need for a geological permanent disposal. Fusion is also a safe source of energy. There is no possibility of a core meltdown or explosion. After all, the power plant cannot run out of control for physical reasons. If the operating conditions deviate from normal, the energy release immediately shuts down. In addition, the interior of a reaction chamber in a fusion power plant is similar to a vacuum; it only ever contains the small quantity of fuel necessary for operation.

Sustainable and usable for base load

Unlike the classic renewable energy sources of solar, wind and hydro power, fusion has an extremely high energy concentration. It is not subject to fluctuations due to the time of day, season, or weather. What's more, it can be used anywhere and does not require much space. These properties make it ideally suited to supplying base load for conurbations and large-scale industry. Fusion power plants would also have a role to play in an electricity-based economy that is dominated by renewables – not least as a buffer for the strongly weather-dependent wind and solar power plants. Fusion would thus be an ideal component of a future energy mix.

Fusion-oriented plasma physics has made dramatic progress worldwide over the last few decades. This is demonstrated by the fusion power achieved, which has increased from a few milliwatts in the 1970s to the 16 megawatts achieved for a short period a few years ago in the Joint European Torus (JET) – a European cooperation project experiment – at Culham, UK. Fusion power has thus increased considerably faster than, for example, the number of circuits on a computer chip, which in accordance with Moore's law doubles every 18 months. In reaching this figure, JET has come close to the breakeven point at which the heating power applied is equalled by the fusion power released. Overall, the research is just one order of magnitude short of the target value for a burning plasma.

TOKAMAK AND STELLARATOR

Fusion research is currently concentrating on two power plant concepts: the tokamak and the stellarator. Both types of power plants use a ring-shaped and twisted magnetic field to confine the plasma. Tokamak-type plants use electric current flowing in the plasma itself to produce part of the magnetic confinement field. At the moment, most of the experimental plants worldwide are tokamaks. The stellarator concept uses only external coils to create the magnetic field. As a result, stellarators afford strengths exactly where tokamaks show weaknesses. Stellarators are suitable for continuous operation, whereas tokamaks can only be operated in pulsed mode. In other words, unless additional provisions are made, they operate with regular short interruptions. The ITER experimental reactor is a tokamak. If experimental operation of the Wendelstein 7-X proves successful, a stellarator could be one of the first demonstration power plants.

Scientists at KIT are developing high-power gyrotrons for the microwave heating of fusion plasmas (left).
Karlsruhe Institute of Technology

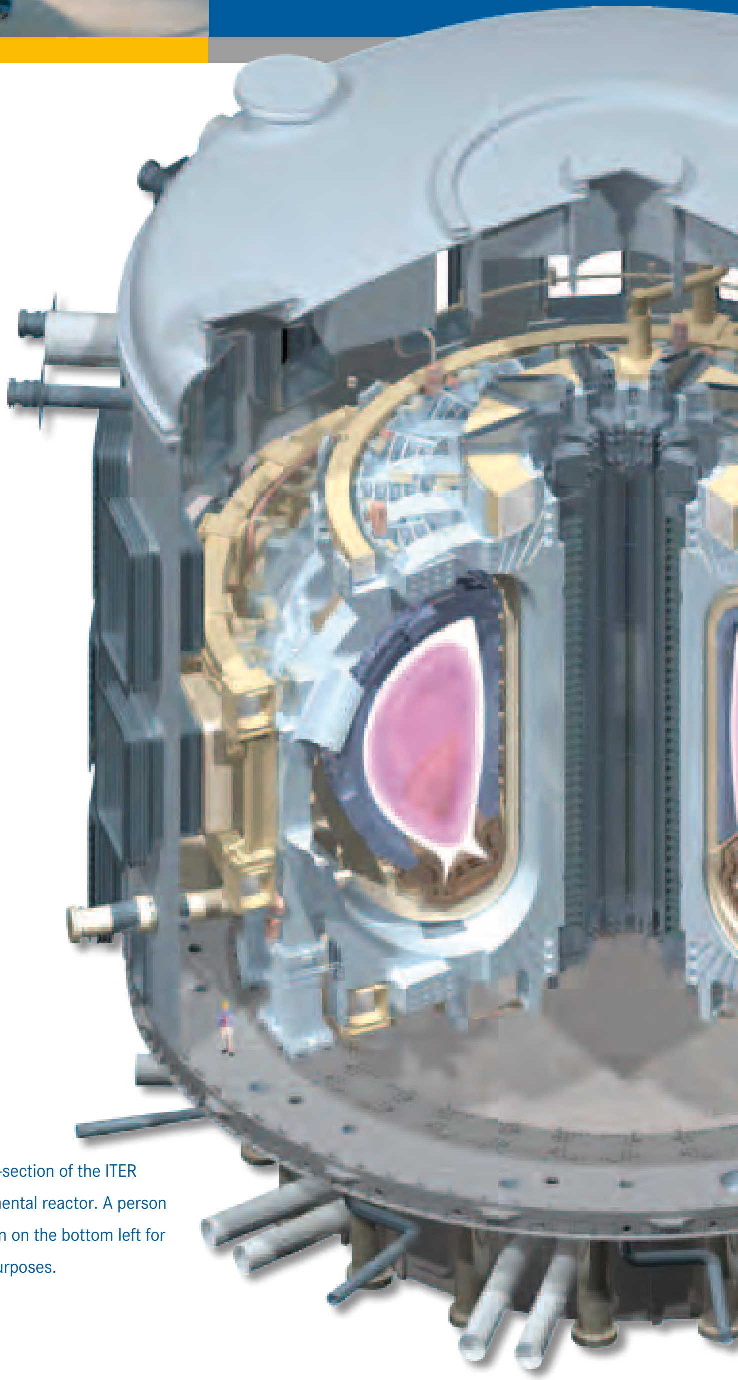
The Wendelstein 7-X fusion experiment is currently being constructed at Greifswald. Its aim is to achieve continuous operation (right).
Max Planck Institute for Plasma Physics

The ITER international experimental reactor

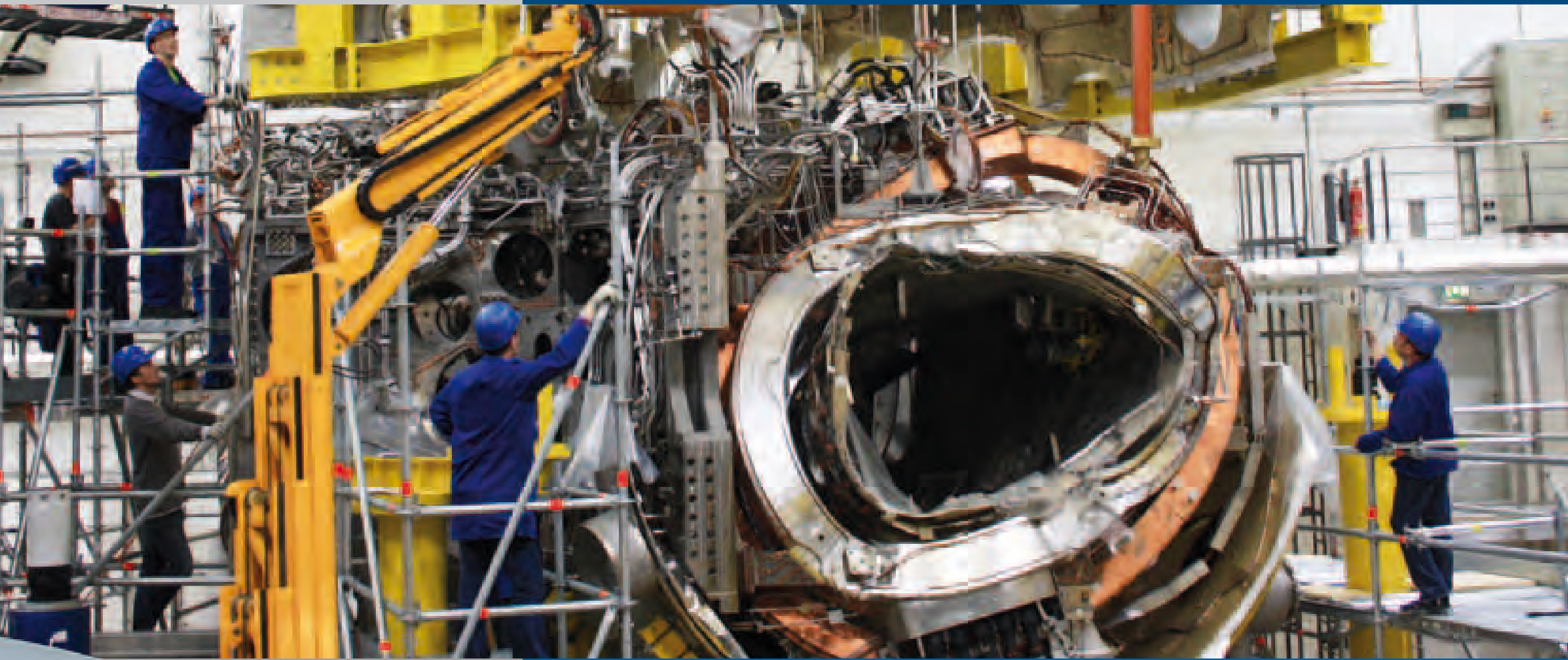
The current large-scale project is the ITER international experimental reactor, under construction at Cadarache in the south of France. Like JET, ITER is a tokamak-type facility. The plan is for ITER to create an energy-supplying plasma for the first time, and in so doing to release 500 megawatts of fusion power – that's ten times the power used for heating the plasma. In addition, ITER will be used to test essential components of fusion power plants in operation. The experience acquired with ITER will then flow into the next large-scale project: the DEMO demonstration reactor. This will be the first fusion power plant to actually generate electrical power for a longer period of time.

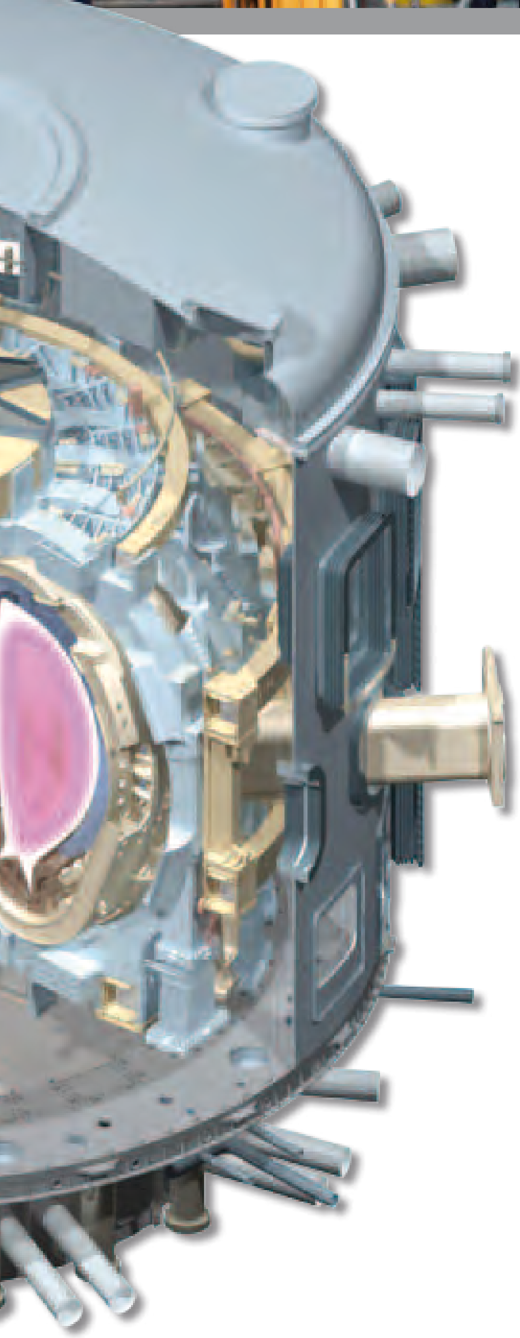
Helmholtz Association researchers played a key role in the basic planning of ITER, are currently helping to construct the device, and will also participate in its scientific operation. With the help of the smaller ASDEX Upgrade fusion device at Garching, they are working out suitable operating modes and developing heating and measuring methods for the ITER plasma. The design of ITER poses a number of challenges, in particular in relation to the development of components that will come into contact with the plasma. To master these challenges, the Helmholtz researchers are not only developing new materials, coatings and joints, but also determining their thermal and mechanical properties, as well as testing them under the type of conditions that will prevail in a fusion reactor.

To ensure that the ultra-low-density plasma cannot cool down as a result of contact with the material walls, powerful magnetic fields confine it in an immaterial cage that is almost contact-free. Superconducting magnet coils and power feeds that will conduct the operating current to the coils are being created by the Helmholtz Association. Another important task is to develop concepts for the so-called blanket, which forms the outer layer enclosing the plasma. The blanket serves three purposes: It converts the neutron energy from the fusion reaction into useful heat, breeds the tritium fuel by means



A cross-section of the ITER experimental reactor. A person is shown on the bottom left for scale purposes.
ITER





of neutron capture in lithium and shields the superconducting magnets from neutron and gamma radiation. The thermal efficiency and power density of the blanket are major factors when it comes to determining the power and the economic viability of a fusion power plant. Two breeding concepts are being given priority in Europe: Helium Cooled Pebble Bed (HCPB), which is being developed at Karlsruhe, and Helium Cooled Lithium Lead (HCLL), which is being developed by the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) in France. Both concepts are to be tested in ITER.

Wendelstein 7-X large-scale experiment

The Wendelstein 7-X large-scale experiment at Greifswald, which was established by the Helmholtz Association, forms a special part of the German fusion research programme. A stellarator device – an alternative to tokamak-type devices – is the focus of attention here. On completion, Wendelstein 7-X will be the world's largest device of its type. Its aim is to demonstrate the stellarator's suitability for use in power plants. At the heart of the device is a system of 70 superconducting magnet coils, whose bizarre forms are the result of sophisticated optimisation calculations. They are designed to generate an extremely stable heat-insulating magnetic confinement cage for the plasma. With their help, Wendelstein 7-X is to highlight the great advantage of the stellarator configuration: its suitability for continuous operation. Helmholtz scientists at Jülich have developed a system of electrical supply lines with superconducting components to provide these coils with power. The superconducting power cables must be capable of withstanding a continuous high voltage of up to 13,000 volts and extreme mechanical forces at a temperature of minus 269 degrees Celsius.

A fusion plant requires a powerful external heating system in order to transform the fuel into a plasma with a temperature of over 100 million degrees Celsius. Microwave tubes known as gyrotrons are used to achieve this objective. Helmholtz researchers at Karlsruhe are developing and building a microwave heating system for Wendelstein 7-X. It consists of ten 140-gigahertz gyrotrons with a total heating power of ten megawatts, an optical transmission line and a flexible optical coupling system that transfers the microwave power into the plasma via reflectors. The system's heating power corresponds to that of around 12,000 domestic microwave ovens.

MORE ELECTRICITY, LESS GREENHOUSE GAS

Thermal power plants and environmental protection do not have to be irreconcilable. The Helmholtz Association is working on technologies and concepts to improve the efficiency of thermal power plants and reduce CO_2 emissions into the atmosphere.

Thermal power plants are the most important sources of electricity and will remain so for the foreseeable future. However, climate forcing carbon dioxide (CO_2) is produced during the combustion of the fossil energy carriers coal, oil and natural gas. The Helmholtz Association is pursuing a variety of complementary approaches to make thermal power plants more climate-friendly and environmentally compatible, including increasing their efficiency, reducing CO_2 emissions and using alternative fuels. The work ranges from the development of materials on atomic scale to the ecological and economic analysis of new power plants. The corresponding technologies and concepts are one focus of research activity at Forschungszentrum Jülich, the German Aerospace Center (DLR), Karlsruhe Institute of Technology (KIT) and GFZ German Research Centre for Geosciences in Potsdam.

But how can we dispose of the carbon dioxide? The answer is CCS, which stands for carbon capture and storage. CCS makes it possible to reduce climate forcing emissions, particularly in the fast-developing emerging markets, which are dependent on coal. The idea is to separate CO_2 out of the power plant waste gas and sequester it permanently underground. There are already power plants in which absorbents are used to scrub CO_2 from the exhaust gas. This method, however, is complex, requires a lot of space and – most importantly – substantially degrades the efficiency of the power plants. Helmholtz Association scientists are using novel membranes to separate the CO_2, an approach that significantly reduces the energy loss.

Membrane instead of scrubber absorbent

There are three ways of achieving this feat. In the post-combustion process, the waste gas is passed through a CO_2-permeable membrane that filters out the greenhouse gas. As the name implies, this is performed after combustion. The membrane replaces the scrubber absorbent used in the conventional method. This is the only method suitable for retrofitting existing power plants.

The pre-combustion process is applied before combustion. Coal is burned with pure oxygen to create a mixture of hydrogen and carbon monoxide. The latter is converted into CO_2 using steam with the production of additional hydrogen. Membranes separate the CO_2 so that the gas turbine is fired with nearly pure hydrogen, whose only combustion product is water.

A third possibility is oxyfuel technology. Here, a membrane removes the nitrogen from the air, leaving almost pure oxygen. The oxygen is diluted with CO_2 so that the combustion temperatures do not become excessively high. The coal is burned with this gas mixture,

and the end product is highly concentrated CO_2. Helmholtz Association researchers are currently testing all three methods. They are also developing materials for the membranes, which must ensure precise separation, sufficient flow rates and high selectivity. In addition, they must be capable of withstanding extreme loads arising from temperature, pressure and chemical processes.

Once the CO_2 has been separated, it is stored underground. Helmholtz Association scientists are investigating suitable rock structures as part of a pilot project in Ketzin, Brandenburg. To date they have injected some 47,000 tonnes of CO_2 into a layer of saltwater bearing rock in order to study the physical, chemical, geological and biogeochemical processes that occur. The researchers are also developing, testing and comparing various safeguards and monitoring concepts.

The Helmholtz Alliance MEM-BRAIN is developing membranes for the capture of carbon dioxide.
Forschungszentrum Jülich

THERMAL POWER PLANTS

Thermal power plants convert part of the available thermal energy into electrical energy. This occurs in two steps. A machine converts the heat into usable kinetic energy, which a generator then converts into electrical energy. The heat necessary for this process is usually generated in the power plant by the combustion of chemical energy carriers. One of the most efficient designs is the combined cycle power plant, which combines the principles of the gas turbine power plant and the steam power plant.

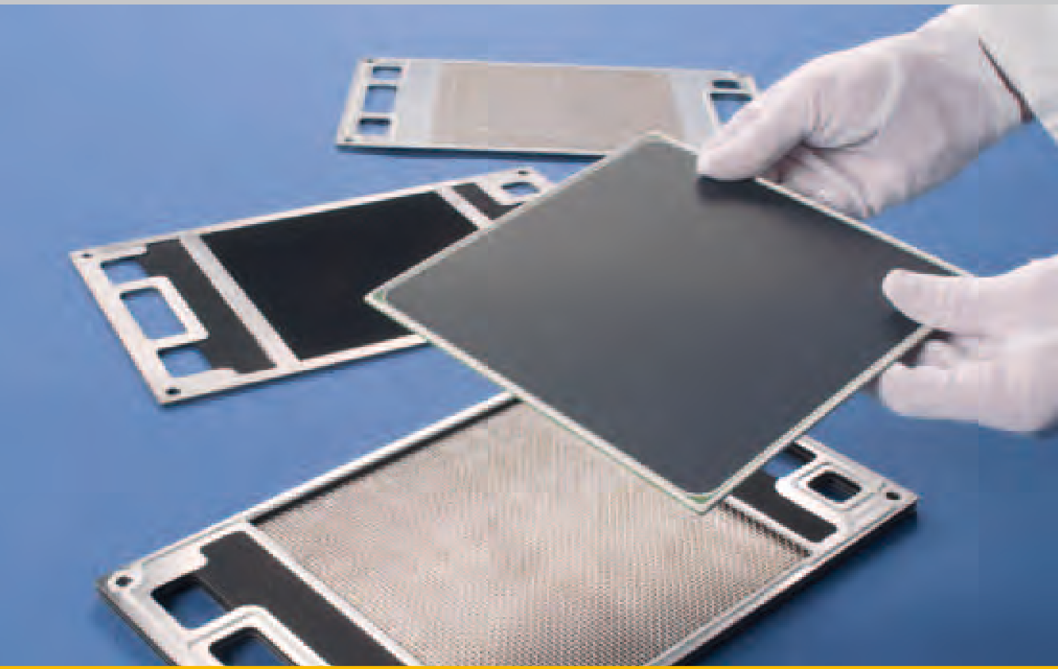
New materials for higher temperatures

Materials play a key role in achieving the higher temperatures necessary to increase the efficiency of power plants. Helmholtz Association researchers are studying the behaviour of high-performance chrome steels and testing complex nickel-based alloys. They are also developing anti-corrosion coatings and ceramic thermal barrier coatings for power plant components. High-temperature materials and components are expected to boost the efficiency of power plants to 60 per cent for coal-based processes and to 70 per cent for combined cycle turbine processes.

At the same time, Helmholtz researchers are working on methods for energy-efficient fuel conversion and subsequent gas purification as well as for the co-combustion of heterogeneous substitute fuels in power plants. The research areas include fuel treatment – for example, the mechanical and thermal pre-treatment of substitute fuels – high-pressure gasification, the modelling and measurement of particle formation during combustion and gasification processes, and multi-substance burners in the power plant combustion chamber.

Radial compressors enable the low-loss compression of carbon dioxide (left).
German Aerospace Center

Image of a flame in an optical combustion chamber (right).
German Aerospace Center



Individual fuel cells are assembled into a stack (left).
Forschungszentrum Jülich

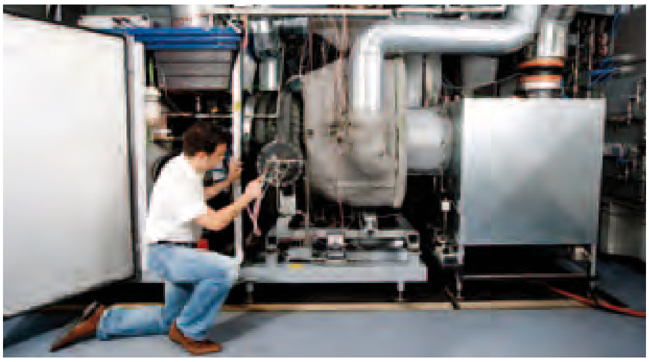
Solidified drops of glass, from which sealant for solid oxide fuel cells is manufactured (right).
Forschungszentrum Jülich

Decentralised supply of energy

SHORT PATHS TO THE CONSUMER

Decentralised plants provide electricity and heat with low losses, achieve high utilisation rates and promote the use of renewable energies. Researchers from the Helmholtz Association are developing efficient combustion systems, fuel cells and micro gas turbine combined heat and power plants.

To meet the growing worldwide demand for electricity in a sustainable manner, smaller decentralised plants must complement the large centralised power plants. Whereas large power plants are characterised by their high electrical efficiency, decentralised plants achieve a high overall utilisation rate because the incidental heat can also be used in the surrounding area. The increasing exploitation of local energy sources such as biomass is also helping to make decentralised plants economically and ecologically attractive. Decentralised plants thus help to avoid the losses that occur over long transport and transmission distances.



Test stand for optimising a micro gas turbine.
German Aerospace Center

Electricity and heat from a single plant

Systems combining high electrical efficiency and comprehensive use of the heat produced already exist today in the form of combined heat and power (CHP) plants. Small CHP plants, known as block-type CHP plants, are also available for natural gas or biogas. New concepts, such as hybrid power plants with fuel cells and micro gas turbines, promise even higher efficiency. Current research and development work is aimed at safe and reliable operation plus high efficiency with minimal emissions of CO_2 and other pollutants.

Helmholtz Association scientists are working primarily on fuels, combustion systems and processes, fuel cells and micro gas turbine block-type CHP plants.

With regard to the fuels to be burned in decentralised load- and fuel-flexible power plants, the primary focal points are methods for energy-efficient conversion and the co-combustion of substitute fuel mixtures using power plant technology. Key issues are fuel treatment; proces-

ses for high-pressure gasification; high-temperature, high-pressure (HTHP) gas purification; HTHP filtration; alternative fuels; and multifuel burners in the power plant combustion chamber.

Block-type CHP plants based on micro gas turbines that are also designed for low-emission operation with alternative and synthetic gases are more versatile and require less maintenance than the engine-driven block-type CHP plants available today. Helmholtz researchers are applying to micro gas turbines the expertise they have gained from optimising power plant turbines. They are also working on coupling a micro gas turbine with a fuel cell, a combination that promises an electrical efficiency of over 65 per cent.

Power from fuel cells

Fuel cells, which convert chemical energy directly into electrical energy, supply clean electricity for a wide variety of stationary and mobile applications. Helmholtz scientists are developing both high-temperature fuel cells that use natural gas and low-temperature fuel cells that convert hydrogen or methanol. Solid oxide fuel cells (SOFC), which can be operated at temperatures of 600 degrees Celsius or more, are best suited for stationary applications. The Helmholtz researchers are developing new materials and cell concepts, working on industrial production techniques and building and studying prototypes. Simulation models help to optimise processes within the fuel cells to achieve system efficiencies of over 60 per cent. One of the greatest challenges in fuel cell development is to slow the aging process in order to extend service life, which is particularly important for the stationary generation of electricity.

A high-performance infrastructure is available for the research and development work. The Helmholtz Association has industrial-quality production facilities, sophisticated analytical instruments and test stands for fuel cells. A demonstration hybrid power plant with a micro gas turbine and a fuel cell is currently under construction.

Within the Helmholtz Association, the German Aerospace Center (DLR), Forschungszentrum Jülich and the Karlsruhe Institute of Technology (KIT) are working on technologies for the decentralised supply of energy.

ENERGY FROM DECENTRALISED PLANTS

The plants associated with the decentralised supply of energy cover an output range of just a few kilowatts to several megawatts. They feed the electricity they generate into a higher-level grid or function as independent off-grid plants. The incidental heat produced can also be used. Locally available energy sources, such as biomass, methane or hydrogen, can be used on site.

Most decentralised plants are fuel cells or gas-engine block-type CHP plants. The small units can also be combined to form virtual power plants, such as fuel cell power plants, micro gas turbines or engine-driven block-type CHP plants coupled with photovoltaic or wind power plants and suitable storage technologies.

LESS IS MORE

It's easier to use energy more efficiently than to increase the amount of energy available. The scientists at the Helmholtz Association are working on solutions for achieving higher energy efficiency in many areas – for example, in power grids, the construction industry and the production of lightweight components for vehicles.

Boosting energy efficiency significantly helps to cover the growing demand for energy, reduce costs, minimise dependence on imports, conserve resources and protect the climate. Germany occupies a leading position in the research and development of the relevant technologies. At the Helmholtz Association, scientists are working on solutions for achieving higher efficiency at every stage of the energy supply chain. For example, they are developing improved fuel cells and innovative materials for generating electricity that will enable power plants to operate at higher temperatures. They are also working on various efficiency-boosting technologies and concepts for the distribution and utilisation of energy.

Transmitting electricity without resistance

One focus of the research is on superconductors for the low-loss transmission of electrical energy. Superconductors are materials that lose their electrical resistance at temperatures below a certain level. They conduct electricity without transforming a fraction of the electrical energy into heat – a fraction that would thus be lost for the desired application. As a result, they can help to address two current challenges in the area of power supply. In the first place, more and more decentralised energy producers are joining the power grid, and the percentage of renewable energy sources is increasing. However, some of these energy sources, such as the sun and wind, are subject to fluctuations depending on the weather and the time of day. This makes it more difficult to stabilise the electrical frequency and the voltage. In second place, the power grid has to be maintained and worn-out parts have to be replaced. Helmholtz researchers are working to develop superconducting operating materials, new grid structures, solutions for the low-loss operation of magnets with strong magnetic fields, superconductors for induction heating and concepts of asset management – in other words, they are focusing on the topics of maintaining power grids and safeguarding the power supply.

Green cement

Other Helmholtz Association projects focus on industrial processes. The efficiency of such processes can be considerably increased by means of innovative materials, shorter cycles, the intensification of processes and the integration of process steps as well as smart combinations of different forms of energy and materials. For the

construction and construction materials industry, Helmholtz researchers have succeeded in developing a high-quality hydraulic bonding agent called Celitement. By comparison with traditional cement, its production requires fewer raw materials and much lower temperatures, saves energy and releases up to 50 per cent less CO_2. Just like Portland cement, this "green cement" can be mixed with water, sand and gravel to make concrete. The process has been tried and tested in the laboratory. In order to further refine it into an industrial production process, the Helmholtz Association has joined forces with an industrial partner to establish a subsidiary, which is building a pilot Celitement plant in Karlsruhe. The potential benefits for climate protection are huge. Today, between five and seven per cent of worldwide CO_2 emissions are generated by cement production – by comparison, air traffic is responsible for only approximately two per cent of CO_2 emissions.

A pilot plant for resource-saving cement production.
Karlsruhe Institute of Technology

Shorter processes thanks to microwaves

Together with another industrial partner, the Helmholtz Association is developing and marketing a line of energy-efficient microwave systems under the name HEPHAISTOS. The microwaves harden high-quality lightweight construction materials, in particular carbon fibre-reinforced polymers (CFRPs), in a cold oven. These materials considerably speed up widely used production processes and make them more energy-efficient. Among other things, HEPHAISTOS makes it possible to produce large CFRP parts for automobiles and airplanes without having to use autoclaves. The finished lightweight construction parts weigh less, and that in turn reduces fuel consumption. Microwave technology can benefit not only the automotive and aircraft industries but also machine and plant equipment production, the construction industry, wind energy technology, the textile industry, medical technology and other sectors. The HEPHAISTOS experimental centre (HEC) in Karlsruhe is opening up new fields of application.

Within the Helmholtz Association, the German Aerospace Center (DLR) and the Karlsruhe Institute of Technology (KIT) are working on technologies for efficient energy distribution and utilisation.

ENERGY EFFICIENCY

Energy efficiency refers to the ratio between the energy used and the result that is achieved. The less energy is required to achieve the desired result, the higher is the energy efficiency. This applies to all phases of the energy supply chain, from the development and exploitation of an energy source to energy conversion, storage, distribution and final use.

HEPHAISTOS, the world's biggest microwave processing plant (left).
Karlsruhe Institute of Technology

High-quality cement produced using energy-efficient methods (right).
Karlsruhe Institute of Technology

A heat pipe-cooled catalyst element for hydrogen recombination (left).
Forschungszentrum Jülich

A pressure tank explosion laboratory for safety experiments with hydrogen (right).
Karlsruhe Institute of Technology

Nuclear safety research

HIGH STANDARDS

The safety of nuclear reactors and radiation protection are the focus of nuclear safety research at the Helmholtz Association. As part of their research into precautionary safety measures for the benefit of society, the scientists are working on the design of safety engineering systems, analysing hypothetical disasters and devising preventive measures.

The nuclear safety research at the Helmholtz Association focuses on the safety of nuclear reactors and on radiation protection. Thanks to the researchers' outstanding scientific and technical expertise and the unique infrastructure, which includes complex facilities for large-scale testing, the test results and the researchers' professional competence are in demand throughout Europe and around the world. This work is based at the Helmholtz Centre Dresden-Rossendorf, at Forschungszentrum Jülich and at the Karlsruhe Institute of Technology (KIT). Almost all of the projects are integrated into international cooperative research networks. In order to safeguard its expertise in the area of nuclear technology in the future as well, the Helmholtz Association is intensely involved in the training and support of young scientists who are working in this specialised field. The organisations that are benefiting from these measures include groups of young scientists and junior professorships set up in cooperation with partner universities and industry, as well as the two national Alliances for Competence in Nuclear Technology and Radiation Research.

Nuclear reactor safety

In order to maintain a high standard of safety for nuclear power plants now and in the future, the Helmholtz Association scientists are doing intensive research on safety technology issues related to the design of the reactors and the plants in normal operation, as well as the phenomena and processes that take place during design basis accidents and beyond design basis accidents. One objective of their work is to develop measures to prevent accidents and limit the effects of serious accidents on the plants themselves. Among these measures is the DYN3D reactor dynamics programme for the detailed analysis of hypothetical accidents, which was developed by Helmholtz Association researchers. Another research focus is on ways to control the release of hydrogen in light water reactors during operation and accident scenarios, for example by monitoring radiolysis gas in boiling water reactors.

In the QUENCH project, researchers are investigating the behaviour of the high-temperature materials in reactor components during the early phase of a hypothetical serious core melt down accident. They are particularly interested in reflooding – the process of introducing water into the overheated reactor core as a protective measure to reduce the temperature and remove the heat. The researchers are also investigating the radiological consequences of accidents due to nuclear technology, as well as ways of improving external emergency preparedness.

There is a growing interest in the flow of liquid metals such as those utilised in Generation IV fast reactors as well as in transmutation plants for burning highly radioactive waste. For the safe operation of such plants, the Helmholtz Association is working on measures such as methods of monitoring the flow of liquid sodium or lead-bismuth eutectic (LBE). For this purpose they are developing solutions such as contact-free magnetic field tomography and ultrasound processes that make it possible to measure the three-dimensional velocity fields in the flow even at temperatures as high as 600 degrees Celsius. Another major research area is the detection of gas bubbles in liquid metals.

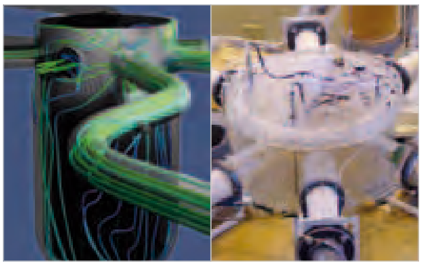
For the calculation of multiphase flows that could occur in hypothetical accidents, the Helmholtz researchers are developing theoretical models of basic phenomena in three-dimensional multiphase systems and testing them in large-scale experiments with unique measuring technology.

In the research area of material and component safety in nuclear reactors, the main focus is the analysis of radioactive reactor materials. For example, the researchers are investigating austenitic reactor steel from the decommissioned Greifswald nuclear reactors by means of fracture mechanics in hot cells. With the help of ultramodern structural analysis processes that are available only within the Helmholtz Association, they are clarifying the material-physics mechanisms of material aging due to radiation.

Radiation protection

In the area of radiation protection research, Helmholtz scientists are developing processes that determine radiation doses in a highly precise and individualised manner. They also recommend protective measures against the radiation emitted by radionuclides in the environment or in food, in cases of exposure to medical radiation and in emergency situations following possible nuclear accidents.

The RODOS (Realtime Online Decision Support System) code for nuclear emergency management in Europe was developed within the Helmholtz Association to deal with the possible release of radiation from nuclear power plants. The system can be adapted to different national and regional conditions and has also been expanded to cover non-nuclear emergencies.



A simulation of the mixing of cooling elements in pressurised water reactors is reviewed at the ROCOM testing facility.
Helmholtz Centre Dresden-Rossendorf

GENERATION IV

The Generation IV International Forum, an international cooperative project in which the European Union is participating, is devoted to research and development in the area of future nuclear reactor systems. Plans call for this new generation of reactors not only to generate power but also to provide process heat and hydrogen and desalinate sea water. The generation IV reactors will have to meet the highest standards of safety, sustainability and cost efficiency. They will make it possible to close the nuclear fuel cycle and decrease the volume of highly radioactive wastes.

LONG-TERM SAFETY

The utilisation of nuclear energy gives rise to radioactive wastes containing long-lived radionuclides. These wastes must be permanently isolated from the biosphere in order to protect humanity and the environment. Scientists at the Helmholtz Association are thus working on solutions for the safe long-term disposal of such wastes.

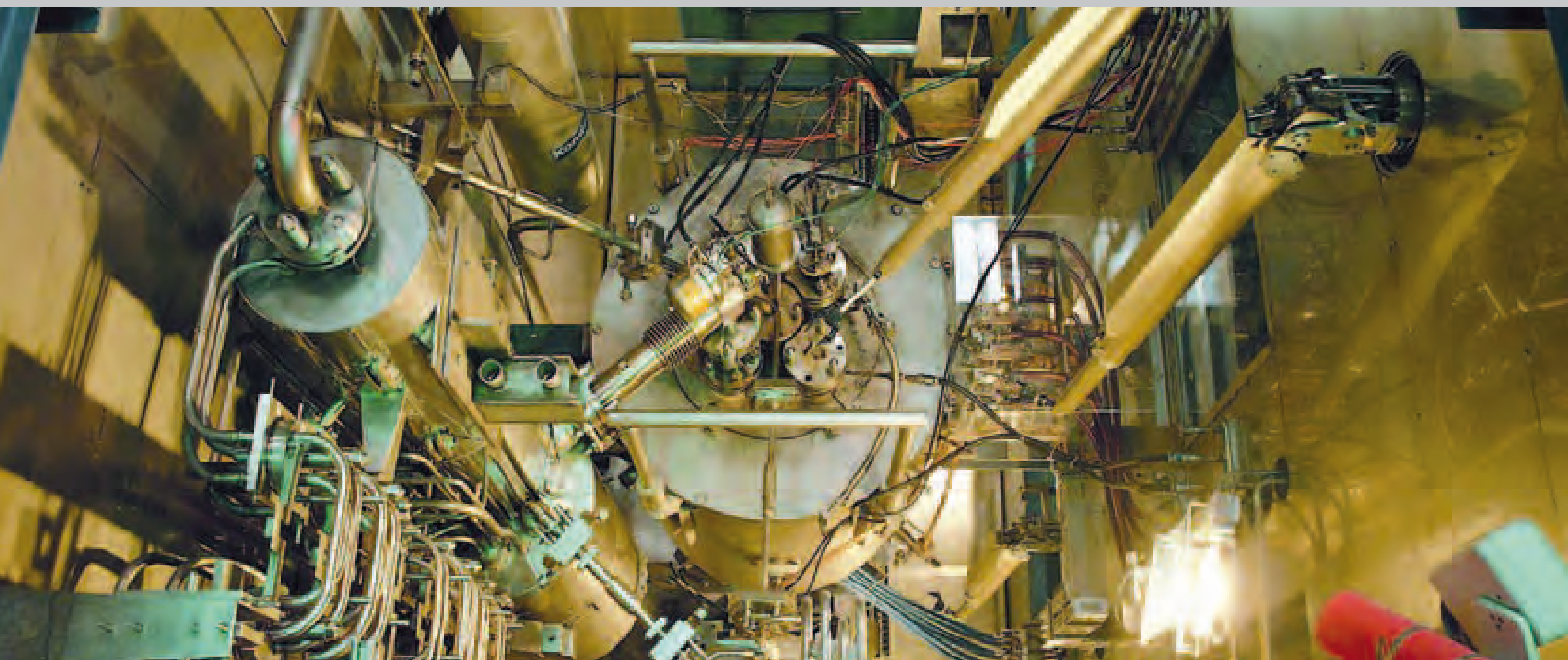
By carrying out research into the disposal of nuclear waste, the Helmholtz Association aims to characterise and immobilise highly radioactive wastes, reduce their radiotoxicity – and thus the associated potential danger – and ensure that the final repository facilities will remain safe over the long term. Thanks to the researchers' comprehensive expertise and a sophisticated infrastructure that offers unique analytical and experimental possibilities, this work is highly regarded internationally. Projects are in progress at the Helmholtz Centre Dresden-Rossendorf, at Forschungszentrum Jülich and at the Karlsruhe Institute of Technology (KIT). The Helmholtz Association supports important national and international networks and projects that are carrying out research into nuclear waste disposal. The work involved includes the ongoing development of the nuclear fuel cycle and the technologies and methods associated with the international monitoring of nuclear material (safeguards).

Characterisation and immobilisation of highly radioactive wastes

Helmholtz Association researchers have developed a special process for the vitrification of high-level liquid nuclear waste from the reprocessing of nuclear fuels. This process involves feeding the waste solution directly into a melting furnace that is lined with high-temperature ceramic. Inside the furnace, a glass melt is electrically heated to around 1,200 degrees Celsius. The glass melt with the bound waste is then filled into stainless steel containers known as canisters. It will be possible to use this technology, which forms the basis of work at the Karlsruhe Vitrification Plant (VEK), in further projects. An alternative concept – encapsulating the especially dangerous actinides in ceramic materials – is also being studied by the Helmholtz Association.

Scientists in the nuclear graphite project are developing concepts for the ultimate disposal and recycling of reactor graphite. Laboratory experiments on the decontamination of radioactive graphite have succeeded in largely freeing the samples from fission and activation products. This has been possible thanks to chemical reagents with which the affected radionuclides form volatile or soluble compounds without attacking the graphite matrix.

Helmholtz researchers have developed a process based on so-called prompt gamma-neutron activation analysis (PGNAA) for the non-destructive characterisation of radioactive wastes. The system consists of a neutron generator, which irradiates the test object with neutrons; a germanium detector, which detects the prompt gamma radiation emitted by the test object; and a graphite measuring chamber, which acts as a neutron reflector and absorber.



Reducing radiotoxicity

Work on reducing the radiotoxicity incorporates experimental and theoretical studies of partitioning and transmutation (P&T). In this strategy, the long-lived radionuclides are separated from radioactive wastes (partitioning) and subsequently converted into short-lived radionuclides or stable elements in so-called accelerator-driven transmutation facilities. If it proves possible to reduce the long-term radiotoxicity of the high-level wastes by up to three orders of magnitude, both the duration of the radioactivity and the storage time in an ultimate disposal site could be reduced from geological to historical periods of less than one thousand years.

Safety of final repository sites

It is envisaged that all radioactive wastes will ultimately be disposed of in deep geological formations. The objective is to securely emplace the wastes and isolate them from the biosphere over the long term. Helmholtz Association scientists are working to establish the foundations on which proof of chemical and geochemical long-term safety can be based. In addition to the long-lived fission products, their efforts focus on the actinides, which determine the potential radiotoxicity of high-level wastes over hundreds of thousands of years – in other words, after most of the fission products have decayed. The scientists study the physical and chemical processes that could be used to effectively retain the radionuclides in an final repository facility.

In order to predict the mobility of radionuclides over long periods of time, it is necessary that the relevant processes are understood at the molecular level and are thermodynamically determined. The work involved combines basic studies of the chemistry of the actinides and long-lived fission products with application-oriented studies under natural conditions, for example in underground laboratories. Scientists in Germany are investigating salt and other formations, particularly clay formations, to determine their suitability for use as final disposal facilities for nuclear wastes. In addition to the purely geochemical interactions involved, the many effects of biological systems must also be taken into account – for example, the reaction of bacteria or fungi to the presence of radioactive substances.

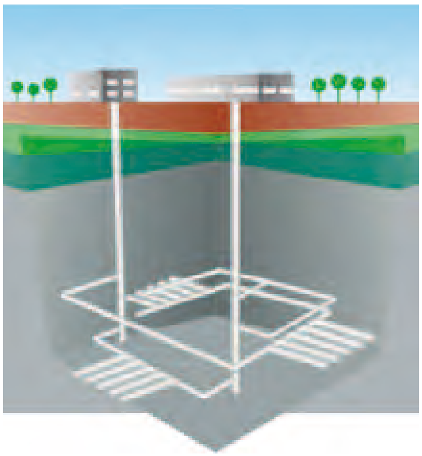


Diagram of an final repository facility for radioactive waste.
Helmholtz Centre Dresden-Rossendorf

RADIONUCLIDES

Radionuclides are unstable types of atoms. Their nuclei undergo radioactive decay to form further unstable or stable nuclides. Ionising radiation is produced by this process. Every radionuclide has a characteristic radioactive half-life, which determines how long the material will remain radioactive. The long-lived radionuclides include the actinides – 14 elements from thorium (Z=90) to lawrencium (Z=103), which follow actinium in the periodic table of the elements.

Looking down into the pilot vitrification plant (left).
Karlsruhe Institute of Technology

Radiochemistry: Safe working in the glove box (right).
Helmholtz Centre Dresden-Rossendorf

Test facility for high-temperature heat stores using salt media (left).
German Aerospace Center

Different materials can be studied using the high-temperature heat-store test stand HOT-REG to determine their suitability for use as heat stores (right).
German Aerospace Center

Storage technology

ENERGY ON DEMAND

Energy stores are key components of a sustainable energy economy. They will be essential if the widespread utilisation of renewable energy sources is to become a reality. The Helmholtz Association develops electrochemical, chemical, electrical, thermal and mechanical energy stores.

The increasing use of renewable energy sources will pose a series of major challenges for the energy system. Only some of the renewable sources can provide energy continuously; others – such as solar and wind – fluctuate depending on the season, time of day and weather. The large-scale use of renewables will only be possible if these fluctuations can be cushioned – in other words, if supply and demand can be balanced. Stores will play a key role in achieving this goal.

Energy stores can also be used to optimise the operation of power plants, especially in the case of smaller decentralised power plants providing combined heat and power. To achieve higher efficiency and maximise the proceeds from the sale of electricity, it is frequently useful to decouple generation and consumption. In addition, energy stores increase efficiency in many areas; for example, they make it possible for a large number of industrial processes to be optimised.

Electrochemical energy storage

The demands on energy stores depend partly on the form of energy to be stored and partly on the area of application. Stationary stores must be capable of storing large quantities of energy that is ready for use; for mobile stores the charging time, weight and size are important characteristics.

As far as the development of electrochemical storage is concerned, the Helmholtz Association can draw on the outstanding expertise it has accumulated from materials research and fuel cell development. One focus of work in this area is lithium-ion batteries, which are suitable for use both as stationary energy stores and in mobile applications. In their efforts to increase the energy density and lifetime of such batteries, scientists are also working on new electrode materials. Here, for example, they are investigating ceramic materials with three-dimensional nanostructures. Electrodes made with these types of structured materials can incorporate significantly more lithium than conventional electrodes and thus store considerably more energy. Charging is also faster. With liquid metal batteries a completely new concept is under investigation, too.

Short charging times, high capacity and cyclic stability – the term refers to the number of charge-discharge cycles that a cell can survive – are particularly important properties for batteries in electric vehicles. It is conceivable that such vehicles will not only be used to provide mobility in future, but will also facilitate management of

the power grid's load. For example, as intermediate stores they will be capable of absorbing excess power, which it will be possible to feed back into the grid on demand.

Chemical and electrical energy storage

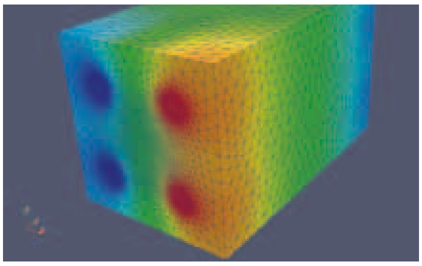
The activities of the Helmholtz Association in the area of chemical energy stores are wide-ranging. With regard to hydrogen, they range from processes related to the production, storage and use of hydrogen to questions concerning its safety. Other work addresses the use of synthetic fuels and fuels produced using solar energy as energy stores. The researchers are also developing new types of double-layer capacitors (supercaps) as short-term stores for electrical energy. These are characterised by their high capacity, short charging time, high number of charge-discharge cycles and excellent efficiencies.

Thermal and mechanical energy storage

In the area of thermal energy storage, the Helmholtz scientists have, among other things, developed new solutions for storing low-temperature heat from solar collectors. At present, the focus is on innovative technologies for high-temperature stores in solar thermal power plants as well as industrial processes and concepts for the seasonal storage of thermal energy in aquifers. In addition, the scientists are also developing innovative numerical methods and software for simulating thermodynamic processes in porous media.

Together with partners from industry, the Helmholtz Association is working on a new compressed air store for balancing the grid. When a power surplus arises, electric compressors compress air, which is fed into underground salt caverns. As soon as there is a demand for power, the cavern store is emptied and the air is used to drive turbines. Such so-called adiabatic compressed-air stores are significantly more efficient in operation than conventional facilities. This is because the heat generated during the process of compressing the air is stored and used to heat the compressed air to high temperatures before the latter is discharged via the turbine.

Research is carried out by the German Aerospace Center (DLR), Forschungszentrum Jülich, the Helmholtz Zentrum Berlin for Materials and Energy, the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), the Helmholtz Centre for Environmental Research – UFZ in Leipzig, the Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences in Potsdam, the Karlsruhe Institute of Technology (KIT) and the Max Planck Institute for Plasma Physics (IPP) into the various areas of energy storage.



Simulation of the water pressure distribution in a solid-state heat store.
Helmholtz Centre for Environmental Research – UFZ

ENERGY STORAGE

Stores hold energy that is ready for later use. They can be classified according to the form of energy stored. Some examples:

- Electrochemical: galvanic cell (battery, rechargeable battery)
- Chemical: hydrogen, synthetic fuels
- Electrical: capacitor, superconducting magnetic energy store
- Thermal: heat store, district heat store
- Mechanical: flywheel, spring, pumped storage power plant, compressed air store

The form of energy used in the charge and discharge processes can be different from the form of the stored energy. For example, a rechargeable battery is charged using electrical energy, which is converted into chemical energy. The latter is converted back into electrical energy when a consumer is connected.

PLUG-IN POWER

Electrically powered vehicles can help promote the use of renewable energy sources and reduce our dependence on fossil fuels. They therefore offer us an opportunity to preserve motorised individual mobility even as the demand for such mobility rises. The Helmholtz Association is working on the development of batteries, fuel cells and systems capable of supplying hydrogen to electric cars.

Electric vehicles can utilise completely different types of energy sources – especially renewable ones. Electric cars integrated into the power grid as mobile energy storage units can also be used to compensate for grid fluctuations. Such benefits are currently still offset by the relatively high cost of electric cars, their limited range and the expenditure and effort required for the establishment of the appropriate infrastructure. The extent to which electric mobility can become firmly established will depend heavily on the further development of energy storage units in terms of battery recharging time, capacity, weight, reliability, service life and, last but not least, cost.

Along with battery improvements, research and development is focusing on optimising power trains, building charging stations, setting up charging management systems, designing grid-vehicle interfaces and developing concepts for billing systems. Activities here need to take into account the entire energy supply chain – from power conversion and storage to distribution and consumption. Electric vehicles also have to be designed with their actual purpose in mind and integrated into the conventional transport system environment.

Electric mobility development activities at the Helmholtz Association are geared mainly towards energy conversion, storage and safety in fuel cells, batteries and hydrogen supply systems. To this end, Helmholtz researchers have various test stands, laboratories and technical equipment at their disposal. The Helmholtz Association also employs systems-analytical approaches in order to holistically address the possibilities for electric mobility, as well as their impact. The goal here is to examine and assess technologies, concepts and management approaches for all modes of transport.

Longer-lasting fuel cells

Fuel cell development benefits from the Helmholtz Association's extensive expertise regarding electrodes, electrolytes, real-time diagnostics during operation, and component integration into mobile systems. A major focus here involves the examination of the aging processes that gradually lead to a decline in performance. Knowledge of these degradation mechanisms makes it possible to improve concepts, structures and components in a targeted manner and to

extend the service life of fuel cells. Helmholtz researchers also work on systems for the onboard production of hydrogen using fuels already widely available on the market. They do this so that fuel cells can be used to make the onboard electricity supply cleaner and more efficient in those vehicles that will continue to require conventional liquid fuels in the future.

In addition, to produce hydrogen, Helmholtz researchers are designing closed thermochemical processes that split water vapour with the help of concentrated solar radiation. Another way to make hydrogen available is to reform middle distillates to create a hydrogen-rich gas mixture. Helmholtz scientists are also examining techniques for storing hydrogen, whereby safety issues play a major role.

New generation of batteries

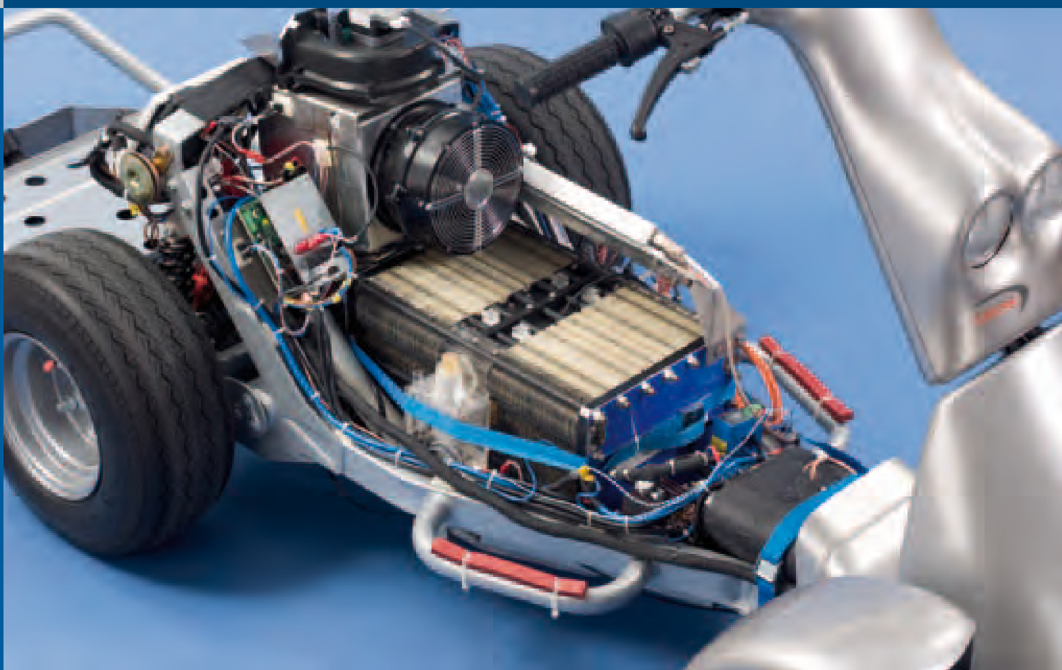
Expertise in fuel cell electrochemical processes can also be put to good use in next-generation battery development. The Helmholtz Association is extensively involved in the northern and southern German consortia “electrochemistry for e-mobility” that are being funded by the German Ministry of Research. The networks also include several universities and research institutes. The goal is to develop powerful, safe and affordable batteries based on lithium technology, for example, with a focus on speeding up recharging times, improving storage density and extending service life. Other issues being addressed include new concepts for the hybrid operation of fuel cells, batteries and double-layer capacitors (supercaps) that charge quickly and deliver high output for short periods.

The Helmholtz Association’s electric mobility projects are based at the German Aerospace Center, Forschungszentrum Jülich and Karlsruhe Institute of Technology.

ELECTRIC CAR

Electrically powered automobiles offer an individual motorised transport alternative to diesel- or gasoline-driven vehicles. There are different ways to supply energy to an electric drivetrain. The most common method is to use either rechargeable batteries or fuel cells that generate electricity from chemical fuels such as hydrogen or methanol. Hybrid-electric vehicles are powered by at least one electric motor and an additional energy conversion device.

Electric cars can also be used as mobile energy storage units. The idea with this application is to integrate the vehicles into a smart grid. In this way, they can store energy that is not needed at a given moment, which can subsequently be returned to the grid when it is required. In other words, electric mobility can offset load fluctuations and promote the use of energy from fluctuating renewable sources like the sun and the wind.



Modular vehicle concept as the basis of sustainable individual mobility (left).
Karlsruhe Institute of Technology

The electric motor in the JuMOVe prototype is powered solely by a fuel cell (right).
Forschungszentrum Jülich

Studying the energy mix of the future (left).
Karlsruhe Institute of Technology

Network of lights across Europe at night (right).
NASA

Technology, Innovation and Society

THE BIG PICTURE

What might the energy mix of the future look like? Which new technologies will establish themselves over the long term on the supply and demand sides – and why? What can society expect from research? Energy systems analysis is concerned with these questions.

The direction energy system development will take depends not only on energy research and technologies but also on other important disciplines such as materials research and nanosciences. External factors such as demographic change and the demand for and acceptance of new systems by industry and society also play a role. In order to obtain a holistic view of the situation, researchers from the Helmholtz Association examine the entire energy process chain – from the production and conversion of energy to its storage, distribution and final use. In doing so, they analyse the ecological, economic, political, social and ethical implications of new technologies.

The Helmholtz Association's "Technology, Innovation and Society" programme aims to assess individual technologies and energy systems according to the principles of sustainable development, create innovation strategies, help shape public opinion, and support the decisions of government and industry by providing competent scientific advice. The programme's projects are carried out at Karlsruhe Institute of Technology, the Helmholtz Centre for Environmental Research in Leipzig, the German Aerospace Center and Forschungszentrum Jülich.

Helmholtz scientists are working intensively on possible energy futures – in other words, forecasts, scenarios, visions and strategies that are relevant to the energy systems of tomorrow. The key questions here are how specific possible futures might come about and how they will influence decision-making. The researchers identify the epistemological foundation of statements regarding the future in order to ultimately assess the form a specific future might take according to sustainable development criteria. The goal here is to make social decision-making and design processes more transparent. The research is conducted in an interdisciplinary manner, whereby engineers and economists work together side by side with philosophers and social and political scientists.

Systems-analysis approach

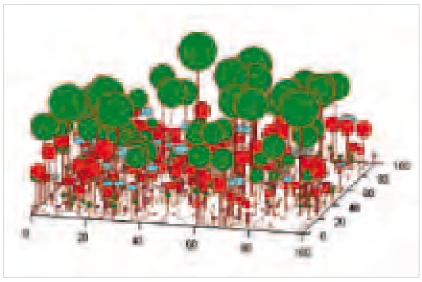
Systems-analysis work on energy issues currently focuses on biomass, microalgae, electrochemical energy storage, carbon management, cross-cutting and efficiency-enhancing technologies, highly efficient fossil fuel power plants and CO_2 separation, nuclear waste disposal and the integration of renewable energy into the power supply system. For example, scientists are studying technologies that can produce fuel from biomass and comparing them with competing techniques such as those used for fossil fuels.

Microalgae are viewed as a promising future source of biomass. These organisms do not require high-quality soil, can be continuously harvested and yield high levels of oil and protein. The nutrients needed to cultivate them can in some cases be obtained from secondary sources such as waste water or waste from power plants. Helmholtz researchers analyse various methods for producing energy from and with microalgae, and also develop guidelines for sustainable microalgae process chains and products.

Work on electrochemical energy storage focuses on the respective lifecycles of future storage media in order to obtain a comprehensive overview of the impact of ecological sustainability. At the same time, Helmholtz researchers are studying the potential risks and opportunities associated with innovations in this field.

Research into cross-cutting and efficiency-enhancing technologies currently focuses on thermoelectric power generation and micro-process engineering. Scientists are also looking at technologies that improve the energy efficiency of buildings and entire communities. Work on fossil-fuel power plants addresses methods that will ensure that future decisions will encompass the energy efficiency of new materials on the one hand and the costs and environmental impact on the other. After all, the most energy-efficient solution isn't always the most environmentally sound one. In the area of nuclear waste disposal, Helmholtz Association researchers use sociological methods to study social conflicts and negotiation-focused conflict management techniques. The aim here is to facilitate a constructive settlement of social conflicts related to this issue.

Helmholtz Association scientists also examine cost-optimised methods for integrating large amounts of energy from renewable sources into a future electricity supply. Their approach here takes into account a combination of solar thermal power plants in the Mediterranean region, wind power plants in the North Sea, and pumped-storage hydroelectric facilities in Norway. They use the results of this analysis to draw up pilot scenarios for the medium and long-term development of the entire German energy system. These scenarios are then used to draw up policy recommendations for the German federal government.



Simulation of biomass in a species-rich forest system.
Helmholtz Centre for Environmental Research

ENERGY SYSTEMS-ANALYSIS MODELS

In some cases, the analysis of energy systems and their interaction with technological, ecological, political, social and economic developments utilises computer-based models. These models map the relationships between technological, economic and/or environmentally relevant parameters that are important to the respective research issue being addressed. A distinction is made here between simulation models that depict possible developments in specific scenarios, and scenario-based optimisation models that identify the most favourable approaches (also in terms of costs) for achieving predefined goals under a variety of constraints. Both techniques reveal specific energy futures that play a major role in scientific, political and public debates regarding the future energy supply.

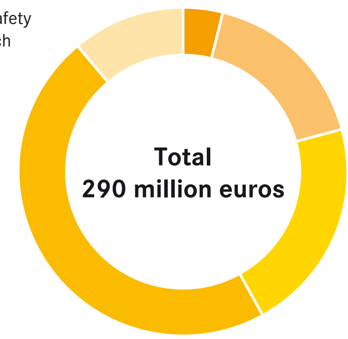
THE HELMHOLTZ RESEARCH FIELD ENERGY

Facts and Figures

Five strategically aligned research programmes
(funding period 2010–2014)

- Renewable Energies
- Efficient Energy Conversion
- Nuclear Fusion
- Nuclear Safety Research
- Technology, Innovation and Society
  (together with the Research Field Key Technologies)

The Structure of the Research Field Energy
Senate recommendation for core-financed funding 2010:
290 million euros
(including the proportional programme-bound research)



Core-financed costs	**290**
Renewable Energies	**50**
Efficient Energy Conversion	**61**
Nuclear Fusion	**137**
Nuclear Safety Research	**32**
Technology, Innovation and Society	**10**

Total personnel, including infrastructure personnel, corresponding to 3,807 fte (full-time equivalents)

Scientists corresponding to 1,106 fte, of whom 773 core funded, 333 externally funded

424 supervised doctoral students

1,061 publications in ISI-cited journals (Institute for Scientific Information)

77 patents granted

819 cooperation projects with science

540 cooperations projects with industry

(Status 2009, unless otherwise stated)

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Karlsruhe Institute of Technology, Institute of Product Development (page 30 bottom)

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