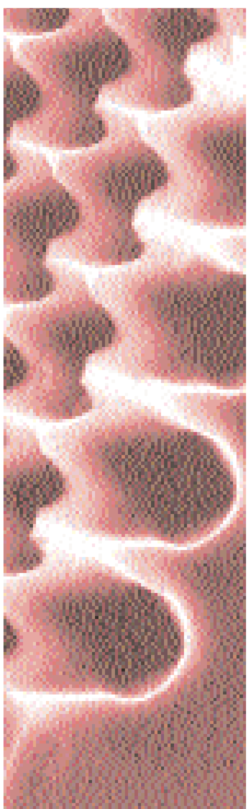
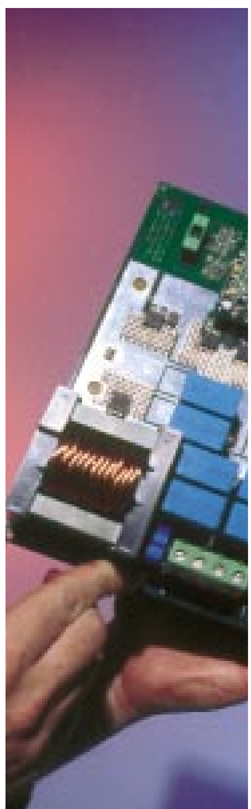
Fraunhofer Institut Solare Energiesysteme

Annual Report 2004

Achievements and Results





left
Surface texture of the multi-crystalline solar cell with an efficiency value of 20.3 %, the current world record. The scanning electron micrograph reveals the structure of the surface. It greatly improves the absorption of incident light. The psychological barrier of a 20 % efficiency value was overcome with the help of this surface structure and a newly developed solar cell process. (See article on p. 34.)

centre
New development of a bi-directional DC/DC converter to connect fuel cells and electrolysers to battery systems.
In comparison to conventional converters, the innovative component and circuit concept is distinguished by a significantly higher efficiency value and a high spatial power density. The control unit, which is implemented with a digital signal processor (DSP), also allows flexible application as a uni-directional converter, e.g. as a PV charge controller or as a power controller for electrolysers and fuel cells.
(See article on p. 54).

right
Micrograph of a membrane-electrode assembly for a polymer-electrolyte membrane fuel cell. The image was taken with an environmental scanning electron microscope (ESEM), which allows measurements to be made in an atmosphere containing water vapour. This procedure can be applied to investigate the hydrophilic (areas with large water drops) and hydrophobic (areas with small water droplets) properties of the catalyst and the membrane.

The Fraunhofer Institute for Solar Energy Systems ISE conducts research on the technology needed to supply energy efficiently and on an environmentally sound basis in industrialised, threshold and developing countries. To this purpose, the Institute develops systems, components, materials and processes for the following business areas: buildings and technical building components, solar cells, off-grid power supplies, grid-connected renewable power generation and hydrogen technology.

The Institute's work ranges from fundamental scientific research relating to solar energy applications, through the development of production technology and prototypes, to the construction of demonstration systems. The Institute plans, advises and provides know-how and technical facilities as services.

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All around the world, the growth of the photovoltaic industry is unprecedented. In Japan and Germany, growth rates well above 100 % per annum are being achieved at present.

Accordingly, the German industry in particular has increased its demand for production-relevant R & D at Fraunhofer ISE. In this context, it is extremely important for us that we were allocated a very large investment project in this field by the German Ministry for the Environment, Nature Conservation and Nuclear Safety at the end of 2004. At a press conference in Freiburg, the Minister, Jürgen Trittin, personally announced that a Photovoltaic Technology Evaluation Centre (PV-TEC) costing over eleven million euros will be established at Fraunhofer ISE. A complete experimental solar cell production line will be installed as part of PV-TEC. With a laboratory floor area of 1200 m^2, we aim to co-operate with industry to develop highly innovative processing steps and production equipment for photovoltaics to an even greater extent than previously within short timeframes.

The schedule for PV-TEC is very ambitious. The entire, highly flexible production chain is to be installed by the end of 2005. We want to have PV-TEC available for the industry at the end of the first quarter of 2006. This presents a major challenge to the core project team, consisting of Gerhard Willeke, Daniel Biro, Ralf Preu, Stefan Glunz and Thomas Faasch. The Fraunhofer Headquarters and all of ISE will also advance this key project with high priority and the greatest enthusiasm. A well-qualified industrial advisory board is accompanying the project.

For various reasons, including this new major activity, we hope to continue our growth course convincingly in 2005. In 2004 - the period covered by this report - our operating budget increased by about 8 %, as in the previous years. Our commissions from the industry represent about 35 % (8.2 million euros) of the total.

Parallel to the increasing commercial success of solar technical components, durability analysis is gaining rapidly in significance. In some market sectors, guaranteed service lifetimes exceeding 20 years are expected. Thus, in 2004 we gathered our diverse activities in this area together in the group entitled "Solar Facades and Durability Analysis", so that this field of work can be developed still better strategically. Tilmann Kuhn and Michael Köhl will intensify their work in this area. The durability analysis will focus on solar components for building envelopes, materials for solar thermal energy conversion and photovoltaic modules.

As every year, we hope that this Annual Report will give you a good overview of the complete spectrum of our R & D activities. (The photovoltaic semiconductor field discussed above represents "only" 30 % of the total.) From the diversity of results achieved in 2004, I would like to select four here as examples to demonstrate the performance of Fraunhofer ISE in applied and industrially relevant research:

- Optically selective absorber coatings for high-temperature applications in solar-thermal power plants have proven themselves in the first practical tests.

- As part of our development of direct methanol fuel cells, we achieved current densities of 55 mA cm^{-2} at a power of 30 W.

- In our work on developing power electronics for fuel cell systems, we achieved conversion efficiency values of 97.5 % in the kW power range.

- We demonstrated that multi-crystalline silicon material can also be used to achieve solar cell efficiency values exceeding 20 %, applying processes that can be transferred to industrial production. Until then, it was considered that the magic threshold of 20 % could not be sur mounted.

Concerning patents and licences, we reached an important milestone in 2004. For the first time, our income from licences exceeded the annual expenses for patents. Furthermore, we broke another internal ISE record: 16 patents were awarded in 2004, and 14 new claims were filed. We are currently occupied with developing a focussed and more efficient strategy for patents, particularly with regard to their marketing.

Foreword

Often, complete R & D solutions for our clients cannot be offered by Fraunhofer ISE alone - we then need excellent partners working in complementary fields and well-functioning partnerships. With this aim in mind, our success in founding the "Energy Association" within the Fraunhofer Gesellschaft represents major progress. Ten Institutes - which already earn income of 45 million euros in the energy sector (with 50 % of it from the commercial sector) - are co-operating increasingly closely within this new structure. The Association is co-ordinated by Prof. Hauser (Fraunhofer IBP, Deputy Spokesman), Tim Meyer (Head of Department at Fraunhofer ISE, CEO of the Association) and myself (Spokesman).

The success of our Institute is based on many pillars. This year, I would like to emphasise one in particular: our large number of excellent undergraduate and postgraduate students. As in previous years, on average there were around 45 undergraduate students and 55 postgraduate students at Fraunhofer ISE. This is possible only because many of the scientists at Fraunhofer ISE are active in teaching (and some also in research) at universities and technical colleges. Apart from myself, these are: Roland Schindler, Gerhard Willeke, Volker Wittwer, Dietmar Borchert, Bruno Burger, Andreas Gombert, Sebastian Herkel, Jens Pfafferott, Christel Russ and Heribert Schmidt. Many thanks for this significant contribution - made in addition to all activities at Fraunhofer ISE - in the academic world!

Finally, It is important to me to emphatically thank all members of the Institute staff here for their achievements in 2004. Their creative, highly motivated and successful work deserves undisguised admiration! I am especially grateful to our clients and supporters in industry, ministries and the European Union. It is ultimately their interest and trust which makes our work possible.

Prof. Joachim Luther

Since 2002, the organisational structure of Fraunhofer ISE has had two parallel, mutually complementary main components: departments and a grouping according to business areas. R & D marketing, external presentation of the Institute and above all, our strategic planning are structured according to the five business areas the Institute addresses.

The four scientific departments are responsible for the concrete organisation of work and laboratory operation. Most scientific and technical staff are based in the individual departments.

The photos show the Heads of the scientific departments, the Institute Director and the Business Manager of Fraunhofer ISE.

Portraits right, from left to right:
Joachim Luther
Volker Wittwer
Gerhard Willeke
Christopher Hebling

Portraits below, from left to right:
Wolfgang Wissler
Tim Meyer

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Institute Profile

The Fraunhofer Institute for Solar Energy Systems ISE conducts research on the technology needed to supply energy efficiently and on an environmentally sound basis in industrialised, threshold and developing countries. To this purpose, the Institute develops systems, components, materials and processes for the following business areas: buildings and technical building components, solar cells, off-grid power supplies, grid-connected renewable power generation and hydrogen technology. Further expertise - beyond solar technology - includes micro-structured functional surfaces, seawater desalination and purification of drinking water.

The Institute's work ranges from fundamental scientific research relating to solar energy applications, through the development of production technology and prototypes, to the construction of demonstration systems. The Institute plans, advises and provides know-how and technical facilities as services.

Fraunhofer ISE has been certified according to DIN EN ISO 9001:2000 since March, 2001.

The Institute is integrated into a network of national and international co-operation. Among others, it is a member of the Forschungsverbund Sonnenenergie (German Solar Energy Research Association) and the European Renewable Energy Centres (EUREC) Agency. There is particularly close co-operation with the Albert Ludwig University in Freiburg.

Research and Services Spectrum

The Fraunhofer Institute for Solar Energy Systems ISE is a member of the Fraunhofer-Gesellschaft, a non-profit organisation, which occupies a mediating position between the fundamental research of universities and industrial practice. The Institute finances itself to more than 80 % with contracts for applied research, development and high-technology services. Whether it concerns a major project lasting several years or brief consultancy work, the working method is characterised by its clear relevance to practice and orientation toward the wishes of the client.

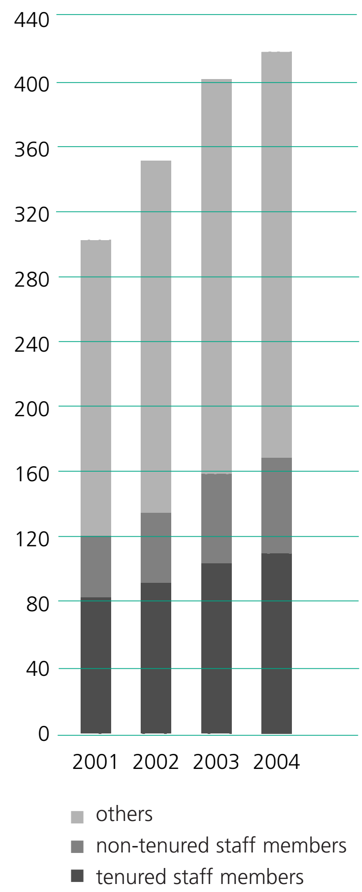
Networking within the Fraunhofer-Gesellschaft

Fraunhofer Institutes or Institute Departments working on related topics co-operate within Associations or Alliances and are represented jointly in the R & D market.
Fraunhofer ISE has the following memberships:
- member of the Institute Association on "Materials, Components" (materials research)
- guest member of the Institute Association on "Surface Technology and Photonics"
- member of the Thematic Association on "Energy"
- member of the Thematic Association on "Nanotechnology"
- member of the Alliance on "Optically Functional Surfaces"

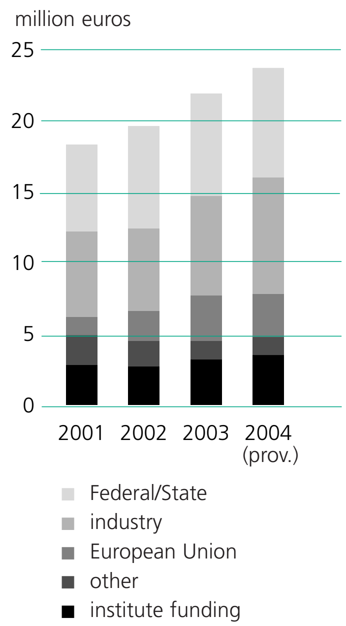
International Clients and Co-operation Partners

The Fraunhofer Institute for Solar Energy Systems has co-operated successfully for years with international co-operation partners and clients from a wide range of business sectors and company sizes. You can find a list of our partners at www.ise.fraunhofer.de/german/profile/index.html

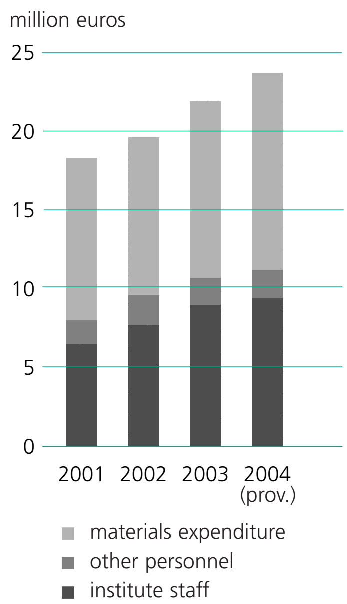
Personnel development



Income



Expenditure



The "other" staff members are an important pillar of the institute, who support the work in the research projects and thus contribute significantly to the scientific results obtained. In December 2004, 53 doctoral candidates, 75 undergraduate students, 6 apprentices, 115 scientific assistants and 1 other assistant were employed at the Institute. In this way, Fraunhofer ISE provides essential support to the education system.

In addition to the expenditure documented in the graph, the Institute made investments of 3.1 million euros in 2004.

Research and Development

- selective absorber coatings for parabolic trough power stations prove themselves in the first practical tests

- gasochromic window systems tested for the first time in larger demonstration facades

- nano-structured functional surfaces produced over an area exceeding 1 m^2 for the first time

- newly developed sun-shading slat systems accepted widely in the market

- complete cooling units based on sorptive materials developed to the prototype series stage

- new evaluation criteria allow user acceptance of sun-shading and glare-protection systems to be predicted better

- world record efficiency value (20.3 %) achieved for 1 x 1 cm^2 multi-crystalline silicon cell

- silicon concentrator cell achieved an efficiency value of 25 % with an optical concentration factor of 100

- 18.1 % efficiency value achieved for 180 µm thin monocrystalline silicon solar cells with an area of 125 x 125 mm^2, screen-printed front contacts and LFC back contacts

- 17.1 % efficiency value for a Cz Si solar cell with an area of 125 x 125 mm^2, screen-printed contacts and high-resistance emitter (film resistance 60 W/sq)

- successful low-defect silicon epitaxy with a unit for continuous in-line deposition of silicon with a throughput of 2.9 m^2/h

- 1.6 x 2.4 cm^2 MIM PV elements (monolithically integrated modules) with 25 V developed on the basis of GaAs

- quintuple-junction solar cell with 5.2 V cell voltage developed for space applications

- bi-directional DC/DC converter for fuel cells or electrolysers developed with a power of 1.2 kW and a peak efficiency value of 97.5 %

- autonomous hybrid PV system for a hikers' inn operated and analysed in a field test with a fuel-cell auxiliary generator

- new flasher enables precision measurements of PV modules over an area of 4 m^2 to an accuracy better than ± 2.5 %

- energy management system developed at Fraunhofer ISE successfully controls distributed generators and storage units in a low-voltage grid in Stutensee near Karlsruhe

- diesel reformer to generate synthesis gas for a 20 kW_{el} molten-carbonate fuel cell developed and successfully tested for 500 h of continuous operation

- 2 kW_{el} fuel-cell combined heat and power plant with a natural gas reformer developed at Fraunhofer ISE in operation since March 2003 without any breakdowns

- direct methanol fuel-cell stack achieves a power density of 55 mW cm^{-2} at 75 °C. The cell voltage is 350 mV, the fuel is a 1M methanol solution. The complete stack consists of twelve single cells and has a power of 33 W.

- passive cold start at -20 °C demonstrated with a weather-resistant, portable fuel-cell system (20 W)

- miniature electrolyser for use in gasochromic windows demonstrated at the Glasstec Trade Exhibition: technology transfer from Fraunhofer ISE made the first industrial pilot production feasible

University Appointments and Prizes

The Dr. Meyer-Struckmann Science Prize 2003 of the Brandenburg Technical University, Cottbus was awarded to Ralf Preu and Eric Schneiderlöchner in January 2003.

The "Verein Deutscher Ingenieure VDI" (German Engineering Association) for the Central Rhine region awarded the "VDI Förderpreis" to Marc Hofmann.

At the "Fuel Cells Science and Technology 2004" Conference, Michael Oszcipok was presented a Poster Award.

Board of Trustees

The board of trustees assesses the research projects and advises the Institute directorate and the Executive of the Fraunhofer-Gesellschaft with regard to the working programme of Fraunhofer ISE.
Status: 31st December, 2004

Buildings and Technical Building Components

Solar Cells

Off-Grid Power Supplies

Grid-Connected Renewable Power Generation

Hydrogen Technology

Special Areas of Expertise

Service Units

Buildings and Technical Building Components

Sustainable buildings not only protect the atmosphere, but are also easier to market. Buyers and tenants can be found more readily for real estate with built-in solar energy features and energy efficiency. This applies equally for new buildings and for building renovation, for commercial buildings and family homes, as energy costs have long since become a "second rent". In addition, sustainable buildings offer more user comfort: an abundance of natural lighting without glare, comfortable temperatures throughout the entire year, fresh air without draughts.

Legislation is supporting the trend toward sustainable building. Thus, from 2006 on, legally specified limits for the primary energy consumption in buildings must be observed. This will support the introduction of solar and energy-efficient conversion systems. An energy passport will make the specific energy consumption of buildings transparent to the general public.

The following statistic demonstrates the importance of this subject. Today, more than 40 % of the end energy consumption in Germany is used to operate buildings. It is used for heating, cooling, ventilation, illumination and many other purposes. The rational use of energy reduces the amount of energy consumed for these services and often improves the user comfort at the same time. A general principle applies in all cases: The lower the remaining energy demand, the larger is the share which renewable energy can usefully supply.

At Fraunhofer ISE, buildings and their technical services represent a central area of activity. We are always the right partner to contact when completely new solutions are sought or if particularly high demands are to be met. We develop concepts, turn them into practicable products or processes and test them in demonstration buildings. We design sophisticated building complexes with simulation tools we have developed ourselves. The topics are treated at all levels, ranging from fundamental development to market introduction of completed systems.

These tasks rely on co-operation between many disciplines: materials research and thin-film development, rational use of energy, simulation, planning, monitoring, development of components such as windows or walls, and of solar systems for heat and electricity. The importance of miniature heat pumps is growing. In future, decentralised energy converters such as small fuel cells and Stirling engines will assume a major role as suppliers of heat and electricity in the building sector.

We apply comprehensive measurement technology to characterise materials and systems. Monitoring is used to analyse the practical operating experience in selected buildings, improving our concepts and those of our clients. We accompany national demonstration programmes with extensive analyses.

Working in a team together with architects, professional planners and industrial representatives, we plan the buildings of today and develop the buildings of tomorrow. We help to define the international boundary conditions for solar air-conditioning, solar building and the long-term durability of components by participating in programmes of the International Energy Agency IEA. This ensures that we are always informed about the current technical standards. Together with our international contacts, it means that we can support our clients optimally in market introduction.

Our work includes both the further development of simulation programs to optimise materials and systems and also user acceptance studies on architectural innovations.

We are constantly developing our equipment and measurement procedures further. Some examples include:

- large laser exposure benches, to produce microstructures over areas of up to 120 cm x 120 cm
- vacuum deposition system for quasi-industrial production of large-area (140 cm x 180 cm), complex coating systems on glass, polymer films and metals
- optical laboratories for characterisation and analysis in materials development
- test laboratories to determine physical and technical properties of collectors, thermal storage tanks, windows, building envelope systems and PV modules
- measurement technology for on-site quality control in buildings.

The more complex buildings and systems become, the greater the importance of controls. With the development of our own software and hardware, we are working toward the goal of operating complete systems optimally according to economic and / or ecological criteria.

Buildings and Technical Building Components

The s_enn® sun-shading system, which was developed together with the company, clauss markisen Projekt GmbH, has gained widespread recognition on the market. Shown here is the view through a facade that has been equipped with s_enn® at the University of Brixen. The component rods are designed to block out direct sunlight whenever the sun is more than 20 ° above the horizon. The minimised energy transmission allows the air-conditioning costs to be reduced. Visual contact to the outdoors is always retained. The system is also extremely wind-resistant. (See article on p. 25.)

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Photochromic Window System for Use in Building Envelopes

Photochromic systems react to the illumination level by colouring and bleaching reversibly. However, previously known systems, such as have primarily been used for sunglasses, are not suitable for building envelopes as they are too unstable and colour only weakly at higher temperatures. By combining electrochromic tungsten oxide and a dye solar cell layer, we have succeeded in producing a photochromic window system which is particularly appropriate for glazing applications in buildings or vehicles.

Anneke Georg*, Andreas Georg

* University of Freiburg, Freiburger Materialforschungszentrum FMF

In the Annual Report for 2003, we already presented the photo-electrochromic window system with polymer ion conductors that we had developed. It colours when illuminated and can be bleached again at any time with the help of a switch. Now we have succeeded in modifying this system to form a simpler photochromic window element, which is characterised by deep colouring even at elevated temperatures. Although this system can no longer be switched arbitrarily, it is much simpler to produce.

When illuminated with sunlight, the photochromic window sample darkens from a visible transmittance of 60 % to 4 %. Figure 2 shows the principle of a photochromic multi-layer system. Under illumination, dye molecules are excited and inject electrons via the titanium dioxide TiO_2 into the tungsten trioxide WO_3. The WO_3 colours blue as a result. Charge neutrality is maintained by two processes: positively charged lithium ions from the electrolyte are intercalated into the WO_3 and simultaneously, negatively charged iodide ions donate electrons from the electrolyte to the dye molecules, oxidising the I^- ions to I_3^- ions. The reverse process also occurs when electrons, primarily from WO_3, flow to the I_3^- ions in the electrolyte. This reverse reaction is originally very slow but can be accelerated greatly by adding a catalyst such as platinum (Pt). Appropriate adjustment of the catalytic activity is essential for a marked photochromic effect. Stronger catalytic action accelerates the bleaching process but reduces the equilibrium coloration depth. The optimisation depends on the specifications for each particular application. Figure 3 shows how the concept can be implemented as a single-layer system.

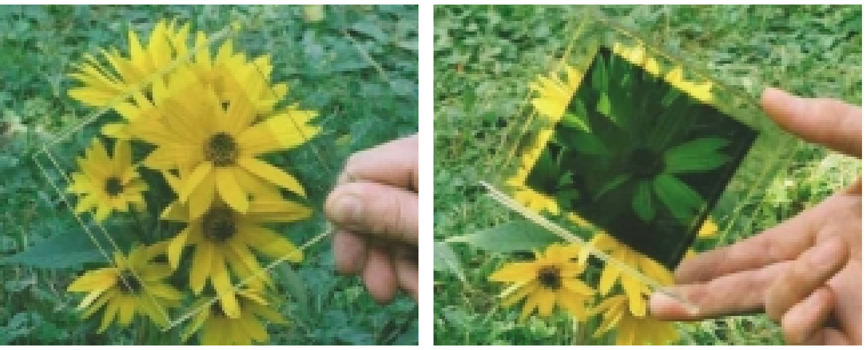


Fig. 1: Photochromic window element before and after coloration by illumination with sunlight.

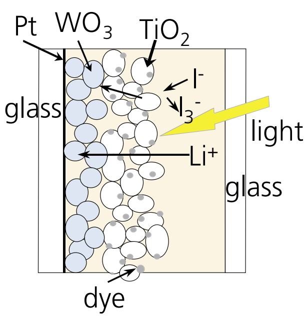


Fig. 2: Operating principle of the photochromic window system, illustrated with a multi-layer configuration. A substrate is coated with a catalytic platinum layer, followed by nanoporous layers of WO_3 and TiO_2. The TiO_2 surface is covered with dye. An electrolyte containing Li^+, I^- and I_3^- ions is located in the pores.

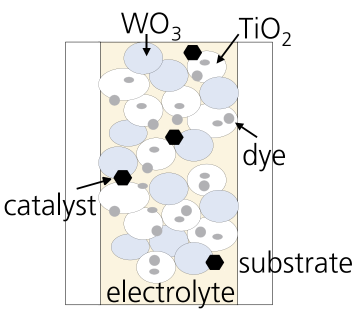


Fig. 3: Single-layer photochromic system. The catalyst is homogeneously distributed over the nanoporous surface of the oxide layers. In principle, the dye can also be deposited directly onto the WO_3 in all systems.

Visibly Switchable Mirrors

Certain metals are transformed from a metallic, reflecting state to a semiconducting, transparent state when hydrogen is intercalated. Alloys of magnesium and nickel are particularly interesting examples, as they consist of inexpensive materials and are characterised by good optical properties. Visibly switchable windows provide useful protection against overheating and glare, particularly when combined with light-redirecting structures.

Jürgen Ell, **Andreas Georg**,
Wolfgang Graf

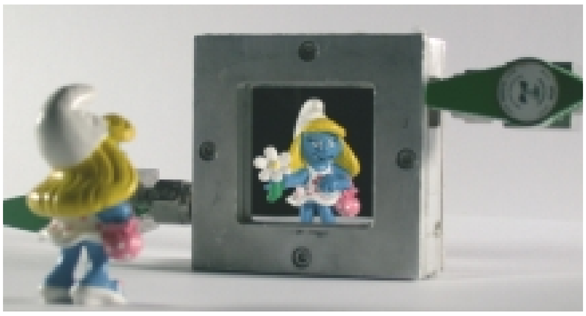


Fig. 1: Nickel-magnesium coating in the reflective state in air. The reflected image of the figure in front of the measurement cell can be seen.

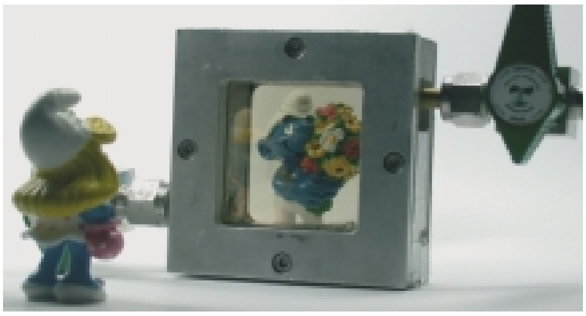


Fig. 2: Nickel-magnesium coating in the transparent state in a gas atmosphere containing diluted hydrogen. The figure standing behind the measurement cell can be seen through it.

Figures 1 and 2 show nickel-magnesium films in the reflecting state in air and in the transparent state in a gas atmosphere containing diluted hydrogen. The visible transmittance values can be switched typically from 0.2 % to 40 %. The coatings are thus particularly suited to applications relating to glare protection. The reflectance changes in parallel from approximately 75 % to 20 %.

The main focus of our investigations is on improving the stability of the coatings. To achieve this, the mechanism of the hydration reaction was studied, i.e. the insertion of hydrogen for the transition to a transparent semiconductor, and also the reverse process of hydrogen extraction (Fig. 3). The metal film is covered with a catalyst coating of palladium. As well as acting as a catalyst for gas dissociation, it also functions as a protective layer, i.e. it reduces the degradation of the metal film. The degradation first becomes evident in lower switching rates. By comparison with other cover layers, we determined that specifically the palladium/metal boundary layer plays an essential role in the kinetics and operation of the system. This strongly limits the potential for including additional layers for stabilisation. In addition, analysis of the switching processes revealed that a nucleus layer forms on the substrate, where the phase transition from the metal to semiconductor is particularly rapid. Thus, the phase transition from metal to semiconductor begins with hydration at the substrate and then proceeds continuously through the coating to the surface. Increasing the nickel content improves the stability of the coating.

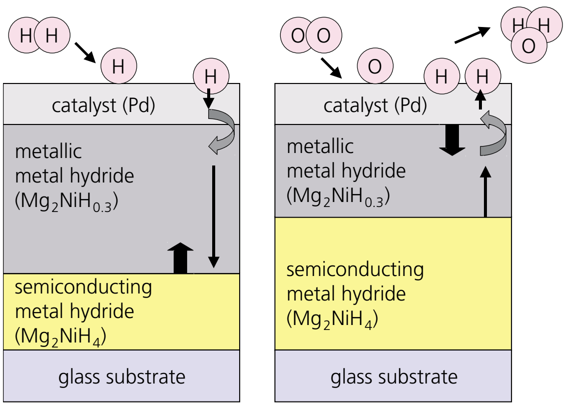


Fig. 3: Mechanism of hydration of the nickel-magnesium coatings in an H_2 atmosphere and hydrogen extraction in O_2. Hydration (left): Hydrogen molecules are dissociated on the palladium film and diffuse through the metal layer. The phase transition from metal to semiconductor begins at the substrate. The interface between the two resulting layers, a metallic and a semiconducting layer, migrates continuously toward the surface. During the hydrogen extraction process in O_2 (right), this interface moves from the surface to the substrate.

Building Materials with Integrated Latent Heat Storage

Over the past few years, we have co-operated with our project partners to develop building materials with integrated phase change materials (PCM) to increase the heat capacity of lightweight buildings. In the next step, building components are being investigated, where fluids can be pumped through integrated piping structures. This allows them to be connected to any type of cooling source and makes more effective cooling feasible.

Peter Schossig, Thomas Haussmann, Stefan Gschwander, Harald Rogg, **Hans-Martin Henning**

Fig. 1: The PCM plaster is applied like conventional plaster. The thinness of the coating and its low weight combined with a high thermal storage capacity are particularly advantageous in renovation projects. The capillary tube mats, which are visible on the ceiling, can be connected to any type of cooling source, such as an evaporative cooling tower or underground water.

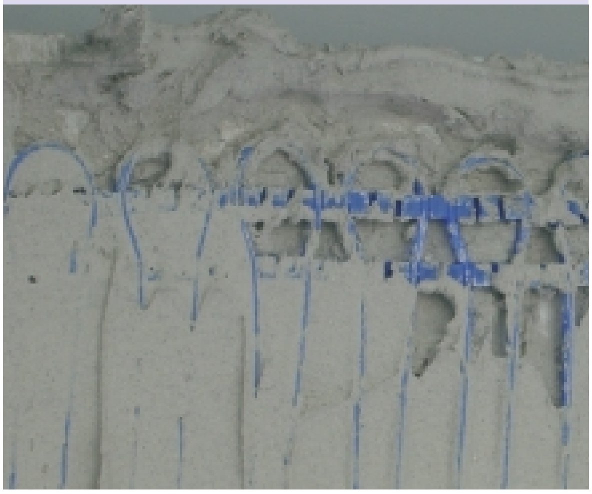


Fig. 2: The closely spaced capillary tubes, through which water is pumped, provide very good thermal coupling to the surrounding plaster. Thus, the ceiling can be cooled quickly, even if the temperature differences are only small. This feature, and the thinness of the plaster coating enable the system to react quickly compared to e.g. conventional cooling ceilings, despite the high thermal storage capacity of PCM's.

The first building materials with integrated phase change materials (PCM) for passive building cooling have been developed to commercial maturity and became available on the market in 2004. In their purely passive form, i.e. simply incorporated into building materials, these storage materials are subject to two fundamental restrictions: firstly, the heat transfer between the air and the wall limits the maximum storage power within a day/night cycle; secondly, the passive application is fully dependent on the outdoor temperature of the night air as a heat sink. In some building types or under certain climatic conditions, these restrictions appreciably limit the applicability of such materials.

One possible solution is to integrate piping for heat-transfer fluids into these heat-storing building materials: by dimensioning the piping appropriately, very good heat transfer to the PCM can be achieved. This means that a cooling ceiling can react quickly, despite its high thermal storage capacity.

The fluid circulation system means that any type of cooling source can be connected, such as the earth or underground water.

The high thermal storage capacity, in combination with a very thin coating thickness and low weight, make this type of cooling system particularly attractive for renovation projects.

As the next stage in PCM building materials, we are thus developing and optimising latent heat storage systems for buildings with actively pumped heat transfer fluids. The work in a joint project with our industrial partners, BASF, Maxit and Caparol, is being supported by the German Federal Ministry for Economics and Labour (BMWA)

Heat-Transfer Fluids with Integrated Phase Change Materials

Phase change slurries (PCS) are heat-transfer fluids which consist of a carrier fluid and a phase change material (PCM). Within the melting temperature range of the PCM, a PCS achieves a very high specific heat capacity compared to conventional heat-transfer fluids. We are developing energy-efficient applications based on PCS for heat transfer in heating and cooling systems.

Stefan Gschwander,
Peter Schossig,
Thomas Haussmann,
Hans-Martin Henning

The best-known heat-transfer fluid is water. Heat can be simply stored in it, with its specific heat capacity of about 4.2 kJ $kg^{-1}K^{-1}$. As this value hardly changes over the temperature range between 0 and 100 °C, the amount of heat stored in the water increases almost linearly with its temperature: The larger the temperature difference that can be exploited in an application, the greater the amount of heat which can be stored.

Unlike water as a heat-transfer medium for sensible heat, phase change slurries (PCS) are characterised by a heat capacity which depends strongly on the temperature. A PCS consists of a carrier fluid and a phase change material (PCM). The temperature range with a high heat capacity is determined by the melting range of the incorporated PCM, which must be chosen appropriately for the intended application. The heat which can be stored during the melting process (in a temperature band covering 3 to 5 K) ranges between 100 and 180 kJ kg^{-1} for the encapsulated paraffins that we use as PCM.

As PCS have the property of storing large amounts of heat with only a small increase of temperature within their melting range, they are particularly advantageous for applications which operate within a small temperature range. Cooling technology is an example. We investigated promising materials for the temperature ranges of 5 - 10 °C and 15 - 18 °C, which are important for industrial applications and building air-conditioning.

Fig. 1: PCS are fluids which can store very large amounts of heat with small temperature differences. They consist of a carrier fluid and a PCM additive. Appropriate measures ensure that the mixture remains liquid even when the PCM has solidified.

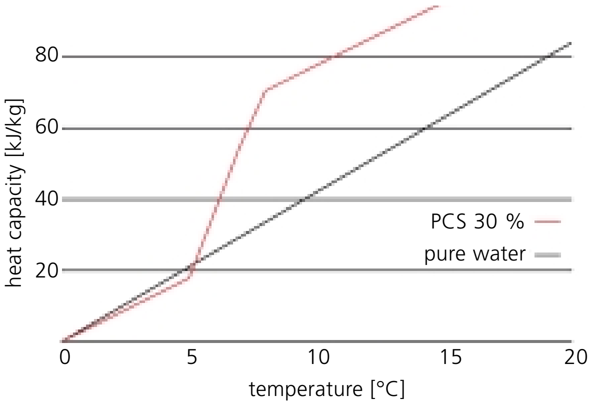


Fig. 2: The amount of stored heat in a PCS with 30 % PCM and a melting range of 5 - 8 °C is significantly higher than in pure water. The high heat storage capacity in the melting range makes this type of fluid particularly advantageous for applications operating with small temperature differences. This is usually the case for cooling technology.

Simulation of cooling networks (e.g. district cooling networks) identified the high potential for saving energy which could be achieved by replacing water or water-glycol systems by PCS. For example, the energy needed to transport the same amounts of heat could be reduced by up to 50 % by using PCS. In addition, cooling machines can be operated at a significantly more favourable operating point if PCS are used.

We co-operated with industrial partners in making these developments within a project which was funded by the EU.

Adsorption Technology for Heating and Cooling

The importance of thermally driven processes for building cooling is continually growing. Among other favourable circumstances, this has been aided by the introduction of highly efficient, decentralised combined energy systems (combined heat and power) also in the low power range. Adsorption technology is a promising approach here. We are investigating this technology at many levels, from basic principles through materials research to development of equipment.

Moritz Gerstung, **Hans-Martin Henning**, Stefan Henninger*, **Tomas Núñez**, **Ferdinand Schmidt**, Yan Schmidt, Lena Schnabel, Dirk Spreemann

* University of Freiburg, Freiburger Materialforschungszentrum FMF

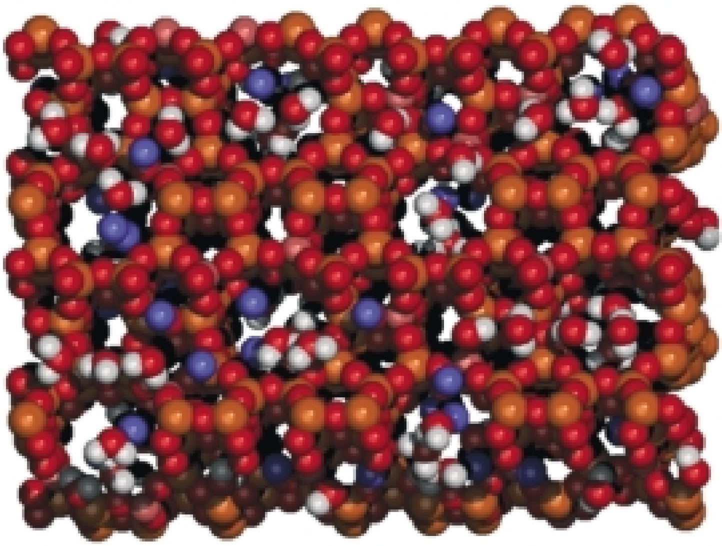


Fig. 1: "Snapshot" of a Monte Carlo simulation of a MFI-type zeolite. Zeolite structure: red = oxygen, orange = silicon, blue = charge-balancing ions of the zeolite structure, white = hydrogen. The water molecules tend to be located in pores which contain a charge-balancing ion. They rotate to a position where the partly negatively charged oxygen (red) is directed toward the positive charge of the charge-balancing ion, here sodium as an example.

Monte Carlo simulation of water adsorption in micro-pores

A large amount of heat is exchanged during the adsorption of water, i.e. the attachment of gas molecules, to the surfaces of micro-porous solids. This can be used in thermal converters. However, the adsorbents which are commercially available today were designed and synthesised to meet other goals, so that there is great potential for optimising them for use in adapted heat pumps and chillers. To achieve this, it is necessary to understand the influence of the various surface and structural properties on the adsorption isotherms at a molecular level.

Molecular computer simulations are used to study the effect of pore geometry and chemical structure on the material properties (fig. 1). Both our own specially developed Linux/PC programs and a commercially available simulation suite running under Irix/SGI (Cerius2/Sorption, Accelrys Inc.) are used for the simulations. Our work is integrated into a network project that is funded by the German Federal Ministry of Education and Research (BMBF). In this project, which is led by Fraunhofer ISE, we are co-operating with various groups specialising in synthesis.

Kinetics measurement equipment
In addition to equilibrium data, sorption kinetics play a key role for technical application. At the beginning of 2004, a test stand to measure the kinetic properties of micro-porous sorption materials was taken into operation. This allows us now to quantify the adsorption rate (fig. 2).

Heat pump test stand
To investigate the performance of thermally driven heat pumps under reproducible conditions, we constructed a suitable test stand at Fraunhofer ISE. Devices with a useful heating power (medium temperature level) of up to 25 kW can be characterised. The thermal power is supplied by a pressurised water network (20 bar, max. 200 °C).

Highly efficient, sorption-based air dehumidifier
As part of an EU-funded project, we developed a highly efficient air dehumidifier. The device is constructed as an air-to-air counter-flow heat exchanger. The basic idea is to direct the outdoor air over a surface which is coated with a sorptive material. The released sorption heat is transferred directly to the return air flowing in the opposite direction, which is cooled by continuous humidification. In this way, the air supplied to the room is both dehumidified and cooled. The high dehumidification efficiency was proven both in simulations and the first measurements.

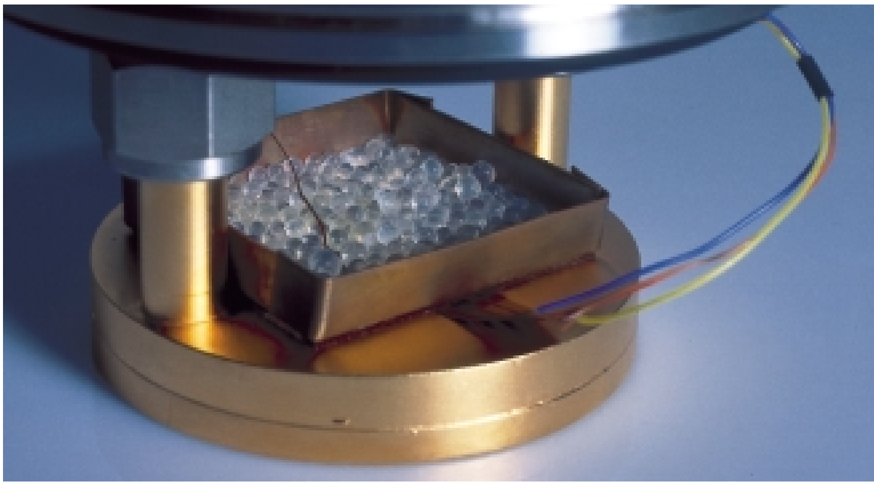


Fig. 2: Equipment to measure kinetic properties of composite systems consisting of a heat-exchanger fin and a sorptive material. The measurement can be made under isobaric conditions or with a fixed number of particles (water molecules). The dry sample (silica gel granulate in a copper holder in the photo) is placed on a temperature-controlled plate and then exposed to a defined amount of water vapour. In an isobaric measurement, the heat flow signal is analysed. In a measurement with a fixed number of particles, the pressure signal is evaluated (pressure drop due to adsorption).

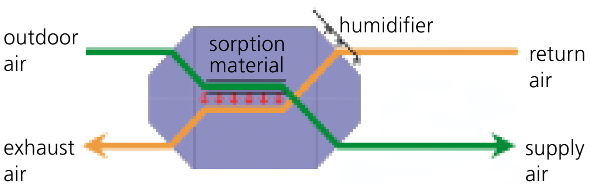


Fig. 3: Principle of the highly efficient, sorption-based air dehumidifier with indirect evaporative cooling (see text for operating principle). This procedure is particularly promising for air dehumidification in countries with hot, humid climates.

Solar Air-Conditioning of Buildings

The application of solar-thermal systems to air-condition buildings is a recent, promising technological approach. Our work in this field ranges from system design, through monitoring and evaluating demonstration projects, to leadership of joint international projects.

Daniel Gessner, Torsten Geucke,
Hans-Martin Henning,
Carsten Hindenburg, Mario Motta,
Lena Schnabel, Kay Tecklenborg,
York Tiedke, Edo Wiemken

Fig. 1: Plant room with the Menerga system. To the right are the two tanks for the salt solution in the foreground and the solar buffer tank in the background. The ventilation equipment can be seen to the left. Solar energy is used in summer for air dehumidification and in winter for heating.

Fig. 2: Shutter box (in the foreground) to disconnect a collector string of the solar air collector system on the roof of the Regional Chamber of Commerce (IHK Südlicher Oberrhein) in Freiburg. The thermal driving power can be regulated by disconnecting individual collector strings, allowing unnecessary heat transfer to the room air to be reduced when the inlet air flow rates are low under partial load conditions.

Solar air-conditioning with an aqueous salt solution

At the end of 2003, a pilot plant (fig. 1) of the Menerga Apparatebau company was taken into operation in Freiburg. The system provides air-conditioning for six rooms in the Fraunhofer Solar Building Innovation Center (SOBIC). An aqueous LiCl solution is used to dehumidify the air. The Menerga company provided the air-conditioning equipment free of charge. The solar collector system (17 m^2) was donated by the UFE Solar company.

Solar air-conditioning with air collectors

We monitor the self-sufficient, solar desiccant-cooling system of the Regional Chamber of Commerce (IHG Südlicher Oberrhein) in Freiburg. In addition to other detailed investigations during the fourth year of operation, we installed shutter boxes to disconnect individual collector strings (fig. 2), allowing the regeneration power to be reduced under partial load conditions.

Solar air-conditioning with closed-system adsorption-cooling technology

Since 1999, a laboratory building of the University Clinic in Freiburg has been air-conditioned with a solar-assisted system. The main components are the solar system (evacuated tubular collectors, 170 m^2) and the adsorption chiller (70 kW). The system monitoring was concluded in 2004. Detailed analysis of the operating data led to optimisation of the operation management and control.

IEA Task 25

Task 25 on "Solar Assisted Air-Conditioning of Buildings" ran from 1999 to 2004 under the leadership of Fraunhofer ISE and the participation of eleven countries within the Solar Heating and Cooling Programme of the IEA. The project played a key role in the further development of solar-thermal air-conditioning of buildings. The most important results include a handbook and a computer-aided design program for planners, and comprehensive documentation of experience with eleven demonstration systems.

The work was supported by the German Federal Ministry for Economics and Labour (BMWA), some of it on commission to industry.

New Stainless Steel Blind for Solar Control

As part of our work on solar control, we co-operated with our industrial partner, clauss markisen Projekt GmbH, to develop the "s_enn®" stainless steel blind. After its market introduction in 2003, large areas of the product have now been installed internationally in office buildings during 2004.

Tilmann E. Kuhn

Our task in developing the s_enn® stainless steel blind was to design the core element, the profile of the stainless steel rods. The aim was to achieve an optimum between reduced energy transmission and visual contact to the outside world. We introduced the boundary conditions that - except when the sun is extremely low in the sky - no glare should occur and that daylight should be directed into the room without any disturbing dazzle.

The goal was achieved:
- The profile (fig. 2) selectively blocks out certain angular segments of the sky. This results in very good solar control (effective g value of 5 - 8 %) and a transparent appearance (see photo on p. 14), although the direct sunlight is almost always completely obstructed.
- The compact profile with several folded edges is much more wind-resistant than blind slats or fabrics.
- The sharp outer lower edge of the profile blocks the sun without creating disturbing bright stripes along the inside of the blind.

In 2004, the first building projects were completed in which s_enn® was installed over large areas. In addition to the installation in Salach shown in fig. 1, s_enn® has been chosen by the architects Murphy/Jahn for the "Horizon Serona" building in Geneva. Further examples are the guesthouse of the Prime Minister of Malaysia and the VIP cube belonging to the fashion designer, Louis Vuitton, in Beverly Hills, California, USA.

In 2003, s_enn® was awarded an innovation prize at the international trade exhibition R + T, to be followed by the Bavarian State Prize and the VR Innovation Prize in 2004. Current information can be found under: www.s-enn.de

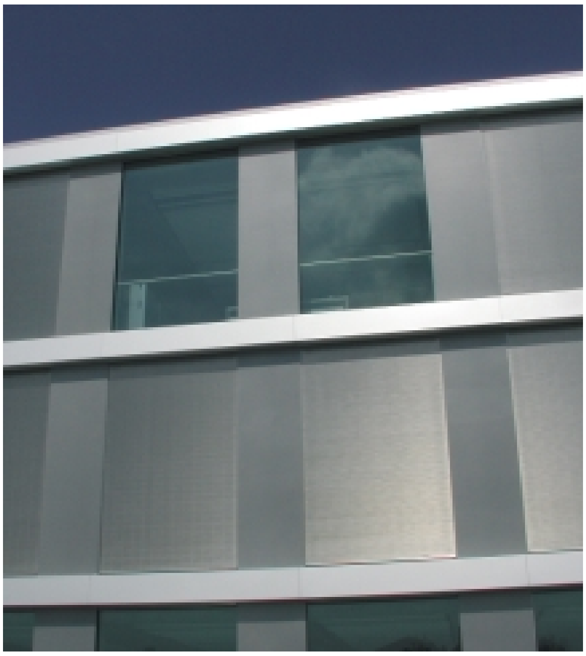


Fig. 1: Facade of the "Haus der Technik" belonging to the EMAG group in Salach, Switzerland. The stainless steel blind appears to be opaque from outside. In the upper storey, two blinds are open while in the lower storey, all blinds are closed. Architecture: Neugebauer + Rösch, Stuttgart
Photo source: clauss markisen Projekt GmbH.

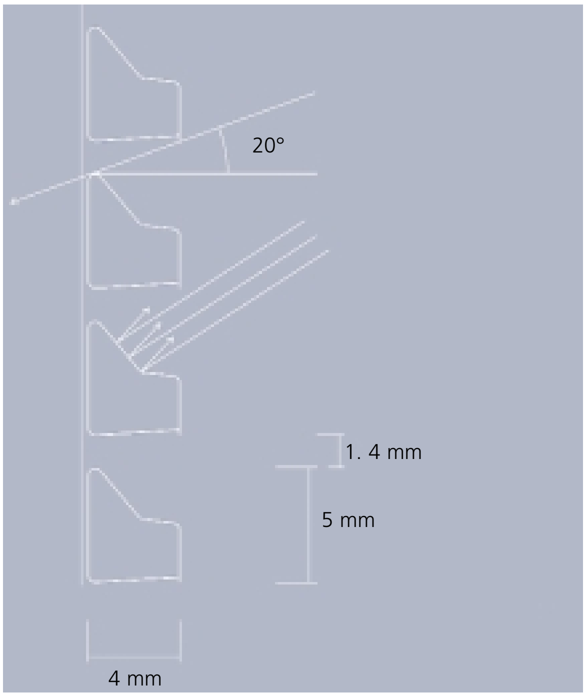


Fig. 2: The cross-section profile of the rods for the s_enn® stainless steel blind was developed by Fraunhofer ISE. The 4 mm thick blind can be rolled up like a fabric but is much more wind-resistant. Direct sunlight is obstructed for profile angles exceeding 20 °.

Development of New Criteria for Glare Protection

The importance of glare-free working conditions is increasing at a time when many buildings with large areas of glazing are being used as offices. Despite this, there are not yet any generally applicable criteria to quantify glare protection by building facade components. At Fraunhofer ISE we are thus developing new glare protection criteria as an instrument to focus technological optimisation and to achieve planning certainty concerning this aspect of facade design.

Jan Wienold, Tilmann E. Kuhn

Fig. 1: User investigations in a test room. In the identical, adjacent reference room, a high-resolution luminance camera with a fish-eye lens is located at the position corresponding to the person's head and records the complete field of view. The test persons must carry out typical office tasks and then evaluate the lighting situation with the help of a questionnaire.

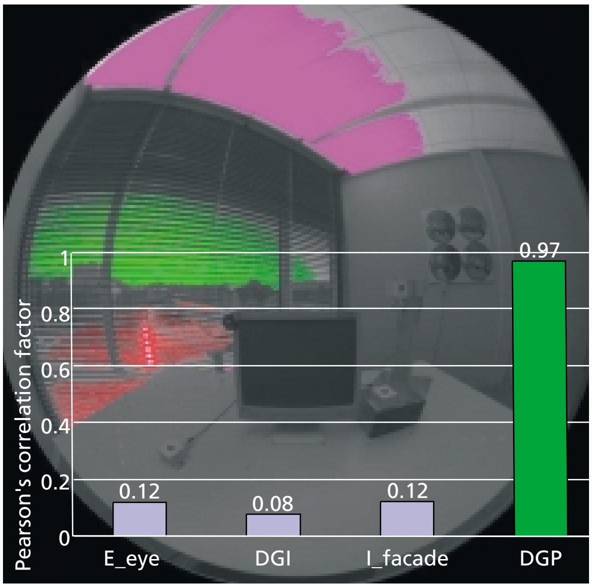


Fig. 2: Background image: Result of automatic glare source detection. The associated evaluation program is a new development by Fraunhofer ISE and is the basis for developing new glare protection criteria. Program options allow e.g. extreme glare spots to be treated separately from other sources. Apart from calculating existing and new indices, the program can generate an image in which the detected sources of glare are colour-coded. The inset graph shows the Pearson correlation factor r between user assessment and glare analysis procedures. Existing indices (e.g. daylight glare index DGI, facade luminance I_facade) and simple measured quantities (vertical illuminance at the eye E_eye) show very low correlation factors, as they do not take account of the variation among users. Significantly better correlation is obtained with the new evaluation procedure (DGP), which determines the probability of disturbance.

Within our work on new glare protection criteria for daylit offices, we are carrying out user tests in a rotatable test room (fig.1). The lighting conditions are documented in a second, identical, adjacent test room with sophisticated instrumentation. While carrying out typical office tasks, each test person is exposed to at least three different facade configurations (25 %, 50 % and 90 % glazed area in the facade) with a given glare protection system.

In order to cover the broadest possible range of potential glare situations, we conduct the tests with three very different systems (white indoor venetian blind, Indoor venetian blind with a highly reflective front surface and a grey back surface of the slats, vertical blind consisting of polymer film strips with a visible transmittance of 2 %).

To analyse the luminance images, we developed a new software tool, which allows possible glare sources to be identified. It is based on the image format of the RADIANCE lighting simulation program and thus allows glare protection to be evaluated during the building planning process. Results from more than 75 test persons show that existing glare indices correlate only weakly with user assessment (see fig. 2). In particular, the non-correlation (r = 0.1) should be noted between the user responses and the facade luminance, which is currently used as a criterion in standards and guidelines.

With the aid of the new evaluation program and statistical parameter optimisation, we are developing an assessment procedure which gives the probability that a user will be disturbed by glare as the result. This new glare evaluation formula, the "Daylight Glare Probability DGP" takes the detected glare sources into account and is distinguished by very high correlation (r > 0.95) with the user responses.

Solar Buildings in Practice

We analyse "lean" office buildings in cross-sectional comparisons and develop new tools for their operation management based on long-term monitoring.

We are responding to global challenges by providing locally appropriate concepts to the Chinese building market, which is the fastest-growing in the world.

Sebastian Herkel, Jens Pfafferott, Jan Wienold

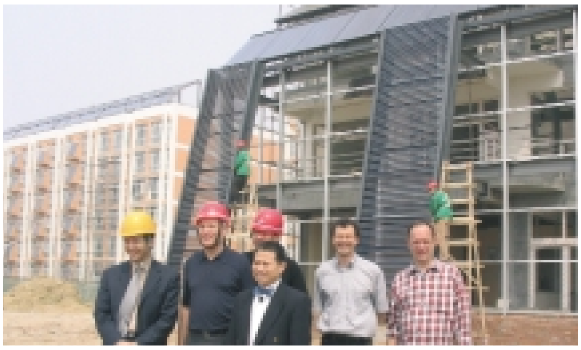


Fig. 1: Low-energy building in Dezhou, China. Fraunhofer ISE is developing locally appropriate solutions for energy-optimised buildings and their energy supply.

EnBau:Monitor

The operation management of non-residential buildings is decisive in meeting planning goals concerning energy consumption and indoor comfort. The long-term monitoring instrument which we have developed, based on the Internet and correlated to the local climate, enables faults to be detected quickly and the operation to be optimised. Cross-comparison of 25 buildings revealed that comfort and energy consumption goals have been achieved in the large majority. The comprehensive results will be published at the beginning of 2005 in the book, "Zukunftsfähige Bürogebäude - Konzepte, Analysen, Erfahrungen".

We are co-operating with the Universities of Karlsruhe and Wuppertal, and the Solidar architectural office in Berlin. The scientific support project for new buildings is funded within the programme for energy-optimised building by the German Federal Ministry for Economics and Labour.

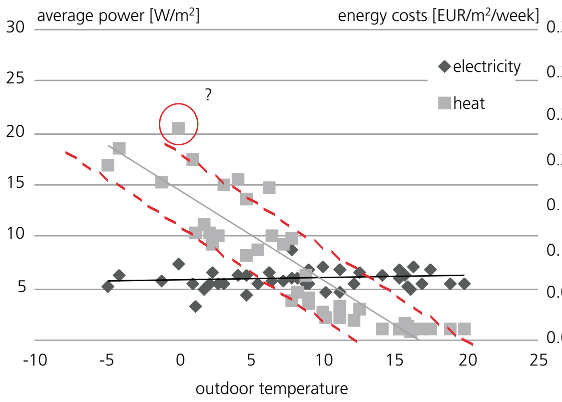


Fig. 2: Results of the weekly readings for the energy consumption of the Bonn Rhein Sieg University of Applied Sciences for 2003. The heating energy consumption decreases with increasing outdoor temperature, the electricity consumption remains almost constant, being effectively independent of the weather. One weekly value, indicating atypically high consumption, is marked in red. By plotting the weekly energy consumption as the average specific power versus the average outdoor temperature, the building operation can be controlled with little time delay. The red lines mark the maximum allowable deviations from the predicted values. Possible disturbances can be quickly detected. When the weekly values are entered via Internet, they are also used directly for an economic analysis. This creates a set of instruments which gives the operating staff much more information than just the annual consumption figures.

Lowest-energy building in China

In 2004, more than 25 % of the global cement production will be incorporated into buildings in China. This boom in the building sector is accompanied by enormous growth rates in energy consumption. We are advising building contractors in China and developing concepts for lowest-energy residential buildings. The aim is to construct the first zero-emission building. The integration of thermal solar energy to support space heating is the main feature in our co-operation with a Chinese collector manufacturer.

For the State of Baden-Württemberg, we are co-ordinating a demonstration project for multi-storey residential buildings in Liaoning Province. The goal is to reduce the energy demand by 50 % and to introduce German technology.

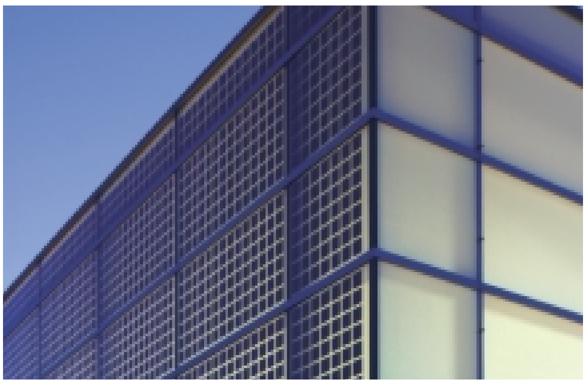


Fig. 3: Facade-integrated photovoltaics in a gymnasium in Burgweinting. Fraunhofer ISE is supporting the planning process and quality assurance during construction by integrated planning of the indoor climate and daylighting.

Optimising Buildings together with the User

Many aspects are taken into account when commercial buildings are planned, built and operated. The final judgement is delivered by the people who work in them. At the same time, users react to their surroundings and influence the comfort level in their office. We develop models to integrate user behaviour into the planning and operation of energy-optimised office buildings with reduced ventilation and air-conditioning technology. We evaluate buildings with the help of user surveys. The results are taken into account when the thermal building performance is characterised. The goal is reduced energy consumption and improved comfort.

Elke Gossauer, **Sebastian Herkel**,
Jens Pfafferott, Jan Wienold

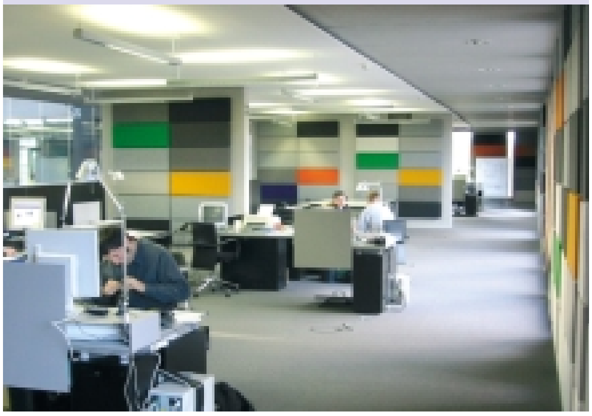
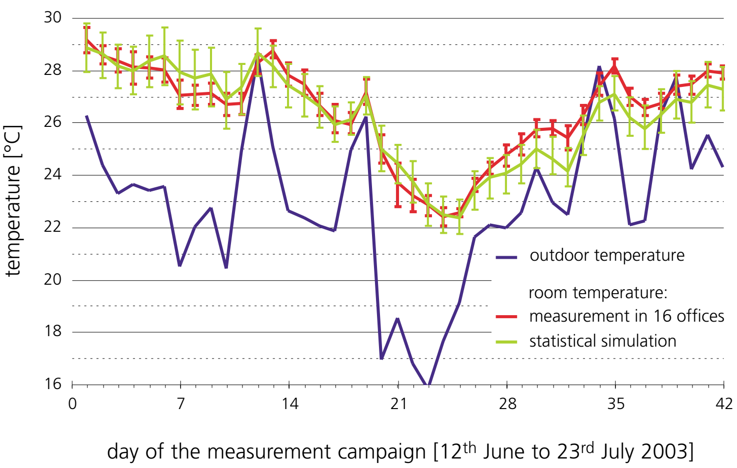


Fig. 1: The administration building for Pollmeier Massivholz GmbH in Creuzburg was consistently designed as a low-energy building with reduced installation of building technical service systems. The building is not equipped with an active air-conditioning system, so that the users strongly influence their thermal comfort in summer by manual operation of windows and sun-shading devices.



Over the past few years, several low-energy office buildings that we had planned have been taken into use. As well as analysing the building according to energy and comfort criteria, we are now turning our attention to the users themselves as a new focus. Statistical analysis of our comprehensive measurement campaigns provided the first models for user behaviour. For planning and operation management purposes, these take account of occupant presence, window opening and sun-shading as functions of typical, independent input quantities such as outdoor temperature, season, time of day or day of the week.

In general, the effects of architectural constructions on the people who work in them are not followed further. Just as the acquisition of measurement data in buildings can lead to objective knowledge and thus to improved working conditions and reduced energy consumption, so can the subjective impressions of the users contribute decisively to a process of improving the quality of working conditions.

Since February 2004, we have co-operated with the University of Karlsruhe within the SolarBau:Monitor project to conduct parallel user surveys and indoor climate measurements in seven buildings to date. Analysis of the surveys allows specific weaknesses and strengths to be identified.

Investigations based on questionnaires can reduce the need for measurement technology and could even replace it in future, assuming that the results of the subjective user surveys correlate strongly with the objective measurements. Planners conceiving new buildings or renovations profit from the experience gained by comparative evaluation of energy-saving buildings and user satisfaction.

Fig. 2: The room temperature in 16 identically constructed offices is statistically analysed at Fraunhofer ISE. In accordance with user behaviour, the average room temperature varies from office to office. If a statistical user model is used for the simulation, the measured and simulated values lie within one standard deviation from the daily average value.

Building Technical Services for Sustainable Residential Buildings

Sustainable residential buildings have an optimised building envelope, offer a very high level of thermal comfort and enable a very low consumption of primary energy. Together with our industrial partners, we are developing new, innovative equipment for space heating, domestic hot water and ventilation within such buildings. In doing so, we combine solar energy with heat pumps, biomass utilisation, ventilation including heat recovery systems and decentralised electricity generation to produce intelligent technical service units.

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Together with our clients, we develop optimised equipment to supply technical services for residential buildings. Our main tasks are simulation studies, advice on the choice of components and the design of system configurations and test devices. We also advise on the development of controls and the measurement of the first units with our test stand and in field tests. We pay particular attention to high energy efficiency, low production costs and the possibility of coupling appropriate system components with solar technology.

Compact ventilation units with exhaust-air heat pumps for passive and lowest-energy houses have been a major focus of our developments. For these units, we have developed new heat pumps with higher efficiency values and optimised both the integration into the ventilation units and the controls. Great care was taken to optimise a power reserve according to primary energy criteria, so that as little use as possible is made of existing electric power reserves.

Another main aspect of our work is the development of combined heat and power systems in the very low power range (micro-CHP) for decentralised application in residential buildings. Particularly those buildings with a very low heating demand make it feasible to dimension the performance such that not only domestic hot water but also almost all of the required

Fig. 1: Exhaust-air heat pump in an opened compact ventilation unit (required floor area: 0.5 m²). It uses the sensible and latent heat of the exhaust air as a heat source and meets the entire demand for space heating and domestic hot water in a passive house. Conversion to refrigerants without greenhouse gases (FHC) is a goal of our development work.

space heating can be provided simultaneously with the electricity generation. This makes the peak-load boiler redundant, with its poor primary-energy performance.

In addition to internal combustion engines, we see particular potential for developing low-power CHP systems with fuel cells and small Stirling motors. The latter have the specific advantage that they can be operated directly with biomass, without sophisticated fuel treatment. In co-operation with our partners, we are developing new micro-CHP systems and optimising component integration and operation control.

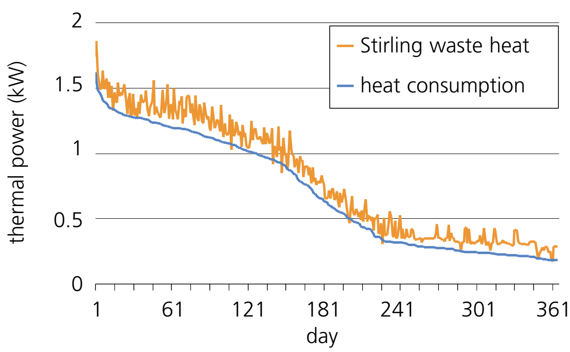
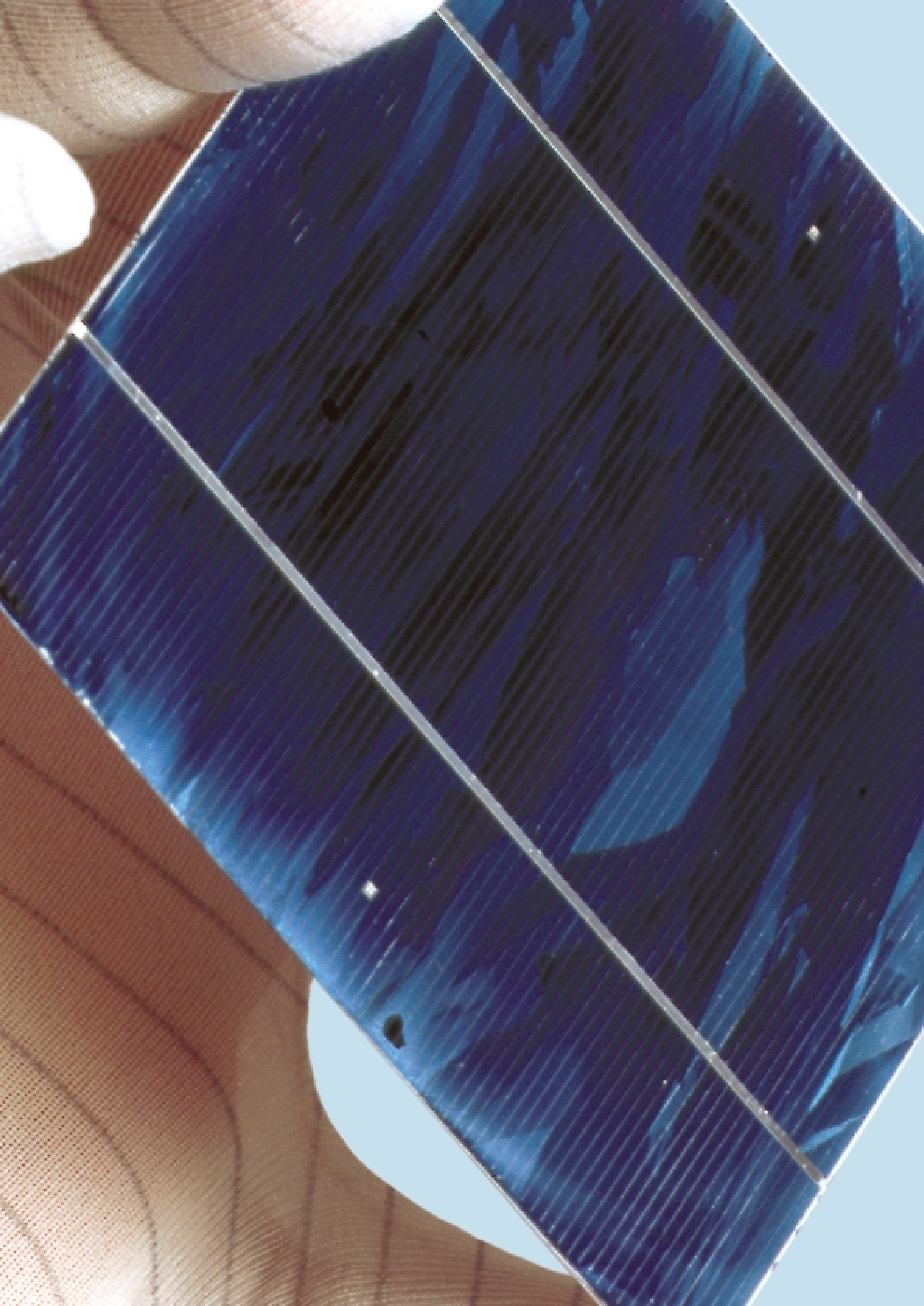


Fig. 2: Simulated annual operation duration curve for a 1 kW_{el} micro-CHP system based on a variable-power Stirling motor to provide heat for a lowest-energy house. The total useful heating consumption amounts to 6066 kWh p.a.. The heating-led system provides 7015 kWh p.a., so also covers tank losses. In simulation studies, the effect of different operation management strategies (e.g. taking the household electricity consumption or a local electricity exchange into account) was calculated and compared.

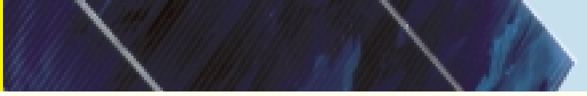


Solar Cells

Photovoltaics is experiencing a real boom all over the world, with growth rates of more than 100 % per annum.

More than 90 % of solar cells are manufactured of crystalline silicon. The price-to-performance ratio, long-term stability and reliable predictions for further cost reduction indicate that this peak performer in terrestrial photovoltaics will continue to dominate the market for at least the next ten years. More than 50 % of the market is supplied by multi-crystalline silicon solar cells. Thus, we are particularly proud that this year, our research group was the first in the world to produce a solar cell of this material with an efficiency value exceeding 20 %. Knowledge gained in this research directly benefits industrial applications.

In order to reduce consumption of the expensive raw material, the silicon wafers are becoming thinner and thinner. Despite this, we still achieve constantly high efficiency values by appropriately adapting the cell structure. We are leading the way in producing high-performance solar cells of extremely thin, flexible 40 µm wafers, which can already be processed completely in our pilot line. We are also working on processes to produce these thin wafers directly from crystals.



Concerning the crystalline thin-film solar cell, we have intensified our research on the concept of a wafer equivalent. A high-quality thin film is deposited from gas containing silicon onto inexpensive substrates. The result looks like a wafer and can be processed into a solar cell in exactly the same way in conventional production lines. The silicon-containing gas is available in practically unlimited quantities. The experimental results are extremely promising.

The second type of material we investigate is the III-V class of semiconductors such as gallium arsenide. At present, it is still associated with a special market that can be summarised by the keywords, space, optical concentrators and special applications. We are working on radiation-resistant tandem and triple-junction cells for extra-terrestrial applications. For terrestrial use, we are developing concentrator cells for the highest optical concentration factors.

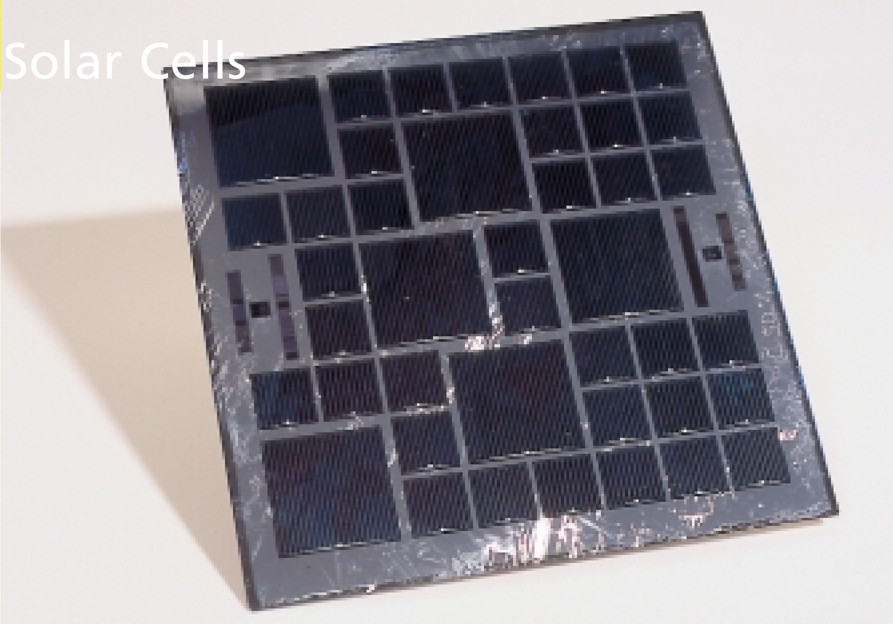
Dye and organic solar cells represent a third class of materials. In particular, the technology for dye solar cells has developed well beyond the laboratory scale over the last few years. However, long-term stability and the upscaling of this technology to module areas exceeding 0.5 m^2 must still be demonstrated. Organic solar cells are currently at the stage of application-oriented basic research.

Solar cells must protected against the environment by encapsulation with durable materials, an area which still exhibits considerable potential for raising the quality and reducing costs. Here, we are working on more stable polymers and new module concepts which completely avoid the use of polymers.

In the "Solar Cells" sector, we support materials developers, system manufacturers and producers of solar cells and modules in the following areas:

- development of new cell structures
- evaluation of novel processing sequences
- optimisation of production procedures for solar cell materials and modules
- production of small series of high-performance solar modules and customised test objects
- characterisation of semiconductor materials and solar cells
- development of semiconductor characterisation procedures
- conduction of photovoltaic studies

Solar Cells



Highly efficient 1 cm^2 and 4 cm^2 solar cells on a 100 cm^2 multi-crystalline silicon wafer. By adapting the solar cell structure and processing sequence specially for multi-crystalline material, we achieved efficiency values of up to 20.3 %. This is the current world record for multi-crystalline silicon solar cells. The average efficiency value of all cells on the wafer illustrated here is 18.1 %. Transferring the cell structure to large wafers areas is thus the next logical step and is the subject of our current research. (See article on p. 34.)

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High-Efficiency Solar Cells of Multicrystalline Silicon

Today 55 % of the solar cells produced globally are made of multicrystalline silicon. In comparison to monocrystalline silicon, with a market share of just on 35 %, the multicrystalline material is less expensive but is characterised by many more defects such as grain boundaries or dislocations. For this reason, the efficiency values of solar cells made of this material have remained below 20 % to date - in contrast to monocrystalline silicon. By specifically optimising the cell structure and the manufacturing process, we have succeeded for the first time in exceeding this psychologically important limit.

Stefan Glunz, Jan-Christoph Goldschmid, Franz J. Kamerewerd, Daniel Kray, Harald Lautenschlager, Antonio Leimenstoll, Elisabeth Schäffer, Eric Schneiderlöchner, Oliver Schultz, Sonja Seitz, Siwita Wassie, Gerhard Willeke

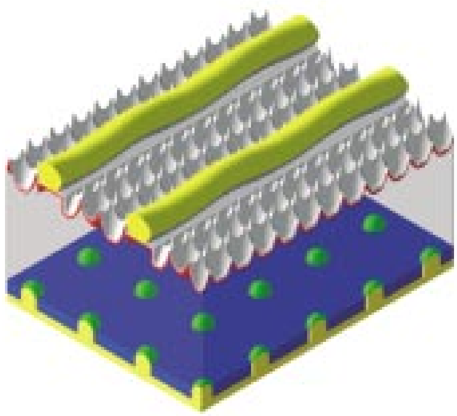


Fig. 1: Structure of the high-efficiency multicrystalline silicon solar cell (see text). The pronounced texture on the front surface of the cell is clearly evident (see also fig. 2). The additional anti-reflective coating is not represented for graphical clarity.

Multicrystalline silicon differs from monocrystalline silicon in two essential aspects: Firstly, it consists of silicon crystallites with differing orientations, with a configuration resembling a patchwork rug. Secondly, it features a high density of crystalline defects such as dislocations and grain boundaries. Many metal impurities aggregate at these defects during the crystal production. These two circumstances prevent the record-breaking processes for monocrystalline silicon, which have been established for years, from being simply transferred to multicrystalline silicon.

The fact that the multicrystalline wafer surface is composed of differently orientated crystals makes it impossible to apply the anisotropic etching step which is used to produce the typical pyramid-textured surface on monocrystalline silicon. However, as it is just this structured surface which increases the penetration of incident light and is essential to achieve high efficiency values, we developed a new process to produce it on multicrystalline material. Figures 1 and 2 illustrate this very deep and effective structure, which reduces the optical reflectance to values below 2 % when combined with a suitable anti-reflective coating.

In order to achieve efficiency values of around 20 %, it is absolutely essential to prevent recombination, i.e. annihilation of the charge carriers generated by the absorbed light. As multicrystalline material is usually characterised by a relatively high concentration of electrically active defects, which are also very inhomogeneously distributed, the diffusion lengths - the average pathlengths of minority charge carriers - are not very long. Therefore, we used relatively thin wafers, so that the distance to be travelled by the charge carriers to the pn junction was shorter.

However, the reduced wafer thickness means that the back surface of the cell becomes more significant. Long-wavelength radiation can penetrate quite deeply into silicon, so that it is particularly important in thin cells that the back surface be a good optical reflector. In addition, the generated charge carriers should not recombine on the back surface, so it should be free of electrically active defects. The aim here is to achieve good surface passivation. These specifications are met ideally with a back surface structure consisting of a silicon dioxide layer (blue in Fig. 1) and an aluminium film (yellow). Applying the laser-fired contact process developed at Fraunhofer ISE, the aluminium film is "fired through" the silicon dioxide layer at only a few points to create the electric contact.

One difficulty is presented by the production of the silicon dioxide layer: This is usually produced by oxidation at a temperature exceeding 1000 °C. At such high temperatures however, the metallic impurities located at the crystal defects are dissolved and "flood" all of the material with highly active defects. For this reason, we developed a new oxidation process, which takes place at lower temperatures on the one hand, but also guarantees good surface passivation on the other. The decisive point in the process is the addition of water vapour to the oxidation atmosphere. The oxidation rate is then also relatively high at lower temperatures and the produced oxide layers display very good properties.

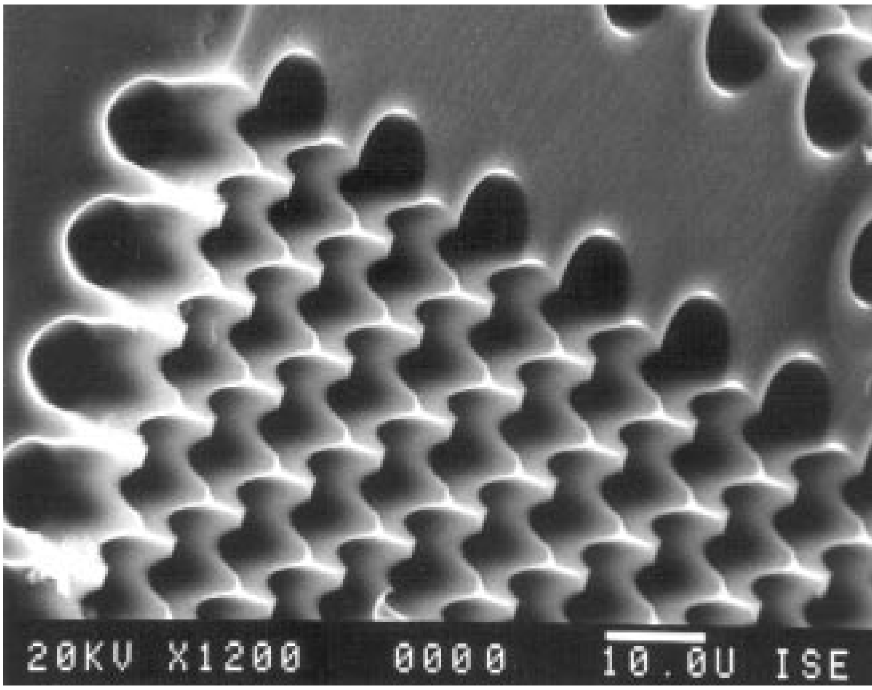


Fig. 2: Scanning electron micrograph of the anti-reflective structure. The flat area on the left serves as a platform for the contact fingers.

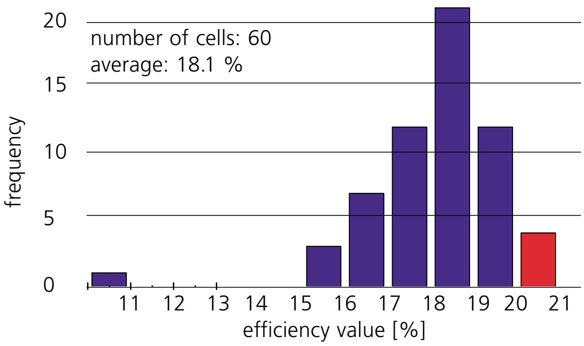
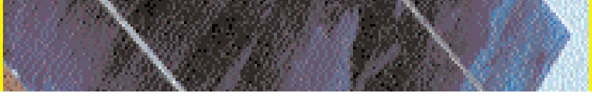


Fig. 3: Distribution of the efficiency values achieved with two wafers. In addition to the peak values around 20 %, the high average value should also be noted. It indicates that the process developed, particularly concerning the selected temperature profile, also allows high efficiency values in poorer-quality material.



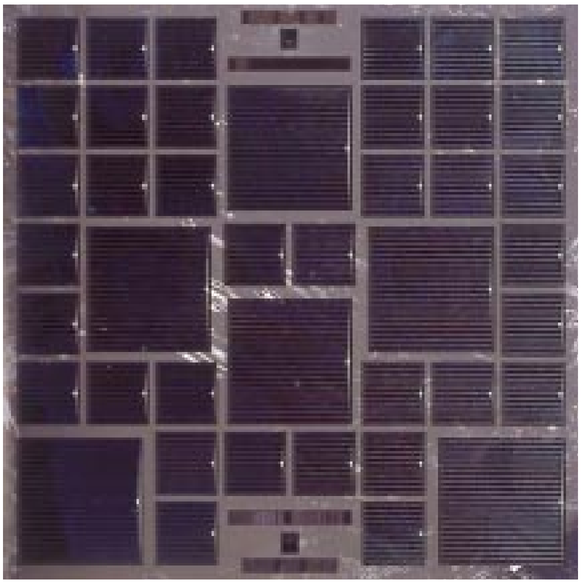


Fig. 4: Photo of a 10 x 10 cm^2 multicrystalline silicon wafer with 1 x 1 cm^2 and 2 x 2 cm^2 solar cells.

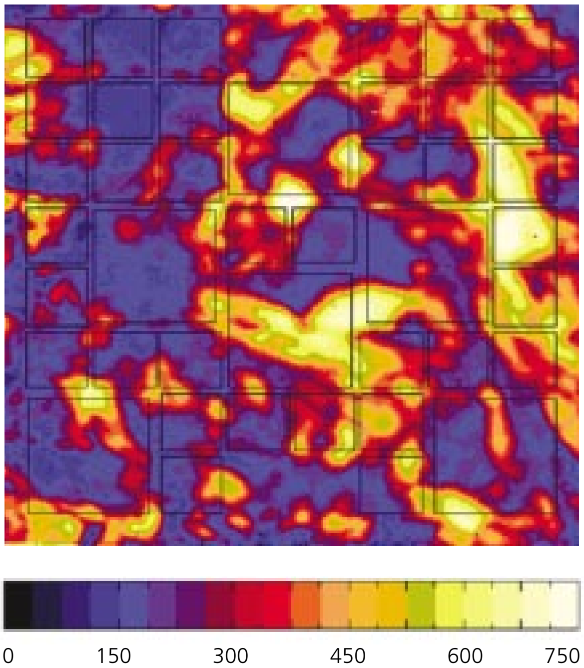


Fig. 5: Spatial distribution of the charge carrier diffusion lengths (colour-coded scale in µm) over a 10 x 10 cm^2 multicrystalline silicon wafer after phosphorus diffusion. The measurement was made with the "Carrier Density Imaging" method (CDI). The black lines indicate the edges of the solar cells with areas of 1 and 4 cm^2. Some are located in very good (yellow) regions, but others are in poor (black) material.

Applying this cell process, we produced many small solar cells from 10 x 10 cm^2 multi-crystalline wafers (fig. 4). Figure 5 shows a typical spatial distribution of the diffusion lengths over a multicrystalline silicon wafer. As can be seen, some cells are located completely in relatively poor (black) zones whereas others are in good material (yellow). The distribution of efficiency values achieved (fig. 3) shows how well the solar cell process has been adapted to multicrystalline silicon. Even the cells from poor material still feature high efficiency values of 15 - 17 %. In these critical areas, it was even possible to improve the electrical quality by the process. Of course, the efficiency values corresponding to good material are still more spectacular. As the first research group in the world, we have succeeded in overcoming the important limit of 20 %: The best efficiency value and current world record of 20.3 % was confirmed in an independent measurement by the National Renewable Energy Laboratory in the USA.

Trend toward Large-Area Silicon Solar Cells

Reacting to the trend toward large-area silicon solar cells, we are investigating the handling limits for solar cells with large dimensions. Our multi-crystalline solar cells with an area of 450 cm^2 are rectangular and supply a short circuit current of 14 A.

Dietmar Borchert, Ali Kenanoglu, Harald Lautenschlager, Isolde Reis, Markus Rinio, **Roland Schindler**

Over the last few years, silicon solar cells have become larger and larger. At present, the industry mainly uses silicon wafers with dimensions of 125 x 125 mm^2 and increasingly also 156 x 156 mm^2. Even larger wafer formats such as 210 x 210 mm^2 are being discussed. The reason for the trend toward larger areas is that the costs for handling wafers with larger dimensions are reduced in many production facilities. If the solar cells also become thinner, the costs can be reduced further due to the smaller amount of silicon material used. However, the fragility of such large and thin wafers poses new handling problems.

To test the handling limits of large-area silicon solar cells, we produced solar cells with an area of 150 x 300 mm^2 and different types of back-surface structures.

Much of the back surface of conventional solar cells is covered with an aluminium contact coating, which can lead to strain and resultant bending of the solar cell. The thinner the silicon wafer, the greater the bending, which can finally cause breakage. To reduce the bending, strain-compensating metallisation designs have to be developed. We tested this with a combination of dielectric passivation and linear contact structures. The first such solar cells, with short circuit currents of 14 A, achieved an efficiency value of 14.2 %.

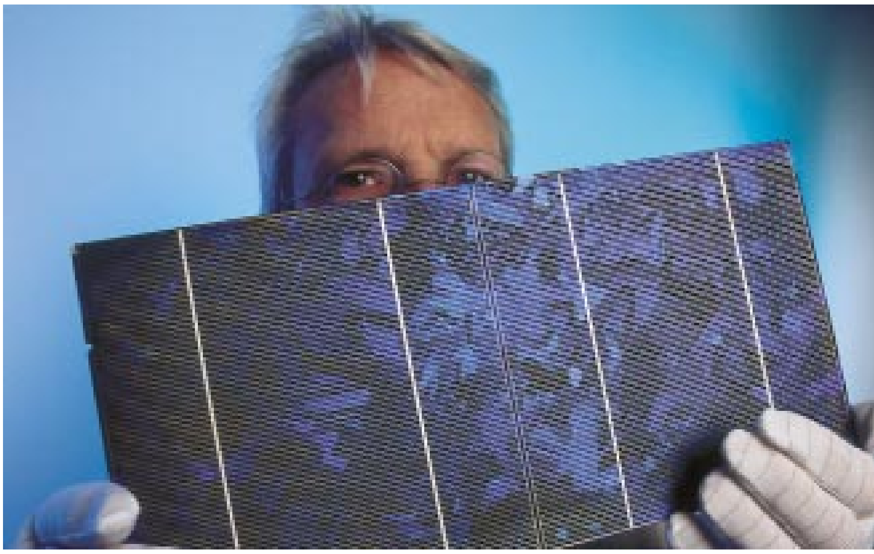


Fig. 1: Large-area silicon solar cell (150 x 300 mm^2).

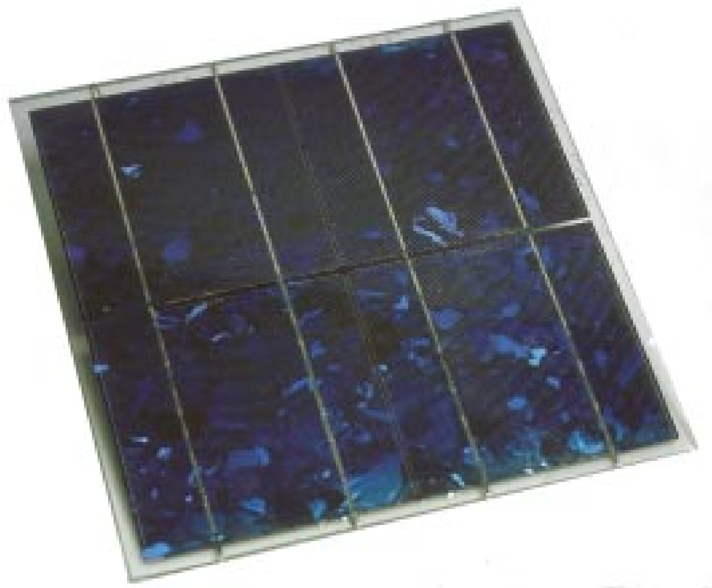
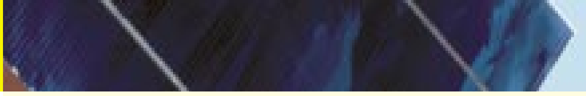


Fig. 2: Mini-module consisting of two large-area solar cells.



Technology Development for the Production of Thin and Highly Efficient Silicon Solar Cells

We have combined our LFC technology for back-surface contacting of solar cells with the screen-printing process conventionally used by the industry to produce front-surface contacts. Using this approach, we have succeeded in producing solar cells from 160 µm thin monocrystalline silicon wafers with an area of 125 x 125 mm² and an efficiency value exceeding 18 %, without bending the solar cell.

Ingo Brucker, Gernot Emanuel, Andreas Grohe, Daniel Kray, **Ralf Preu**, Jochen Rentsch, Eric Schneiderlöchner, Oliver Schultz

Fig. 1: The screen-printing process was used only to produce the front-surface contacts of these 160 µm thin silicon solar cells. On the aluminised back surface of the cell, which can be seen in the background, 10,000 contact points were created by laser radiation, each of them with an area of only 0.01 mm². Applying this process prevents the cell from bending.

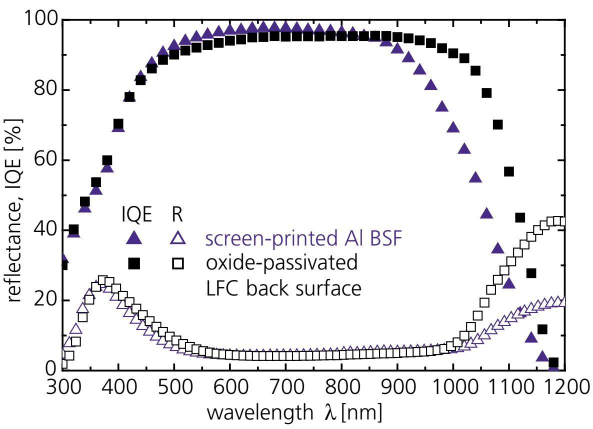


Fig. 2: Comparison of the internal quantum efficiency and the reflectance of solar cells with back-surface contacts produced by the LFC and screen-printing processes. The improved performance of the LFC cell in the long-wavelength range above 900 nm is clearly evident, which is due to its better optical and electrical properties.

We developed new production technology with the aim of reducing the manufacturing costs for crystalline silicon solar cells. Our main goals are to raise the efficiency value and reduce the thickness of the silicon wafers used. Our approach is to create the structures of highly efficient solar cells with cost-saving processes which minimise the stress applied to the material.

Most of the silicon wafers used today in the industry are more than 200 µm thick. If the wafer thickness is to be reduced to significantly less than 200 µm, novel back-surface contacting procedures must be developed, as the process used today results in the cell bending, e.g. more than 15 mm for cells of 80 µm thickness. We succeeded in retaining the industrially common screen-printing process for front-surface contacting, and combining it with the laser-fired contact (LFC) technology that we had developed for back-surface contacts, resulting in a complete solar cell process. In this process, the back surface of the solar cell is coated with a double layer consisting of a ~0.1 µm thin dielectric passivation layer and a ~2 µm thin aluminium film. Subsequently, a solid-state laser was used to create point contacts by alloying the aluminium into the silicon surface. A major breakthrough in the development was the use of a galvanometrically controlled mirror system to position the laser beam, which allows 10,000 contact points to be produced on a solar cell in 1 second (fig. 1). We have achieved an efficiency value exceeding 18 % with 160 µm thin monocrystalline silicon solar cells having an area of 12.5 x 12.5 cm². In comparison to solar cells produced with the usual industrial methods, we achieved a significant improvement in performance and also avoided cell bending. Some of the results were obtained within the FAKT Research Alliance on Crystalline Silicon Solar Cell Technology, which is supported by the State of Baden-Württemberg, and in which the Universities of Freiburg, Constance and Stuttgart are also integrated.

Heterojunction Silicon Solar Cells on Substrates with Industrially Relevant Dimensions

Heterojunction silicon solar cells represent an economically favourable alternative to achieve high solar cell efficiency values. At our Laboratory and Service Centre in Gelsenkirchen, we have succeeded for the first time in the world in producing heterojunction silicon solar cells on p-doped silicon substrates with an area of 100 cm². We achieved an efficiency value of 13.5 % on monocrystalline Cz silicon. The goal is to transfer newly developed processes from the laboratory scale to industrially relevant substrate areas in a form appropriate for production.

Nico Ackermann, Mohammed Abusnina, **Dietmar Borchert**, Antje Gallach, Andreas Gronbach, Ali Kenanoglu, Sebastian Krieger, Yaqiong Liu, Stefan Müller, Otto Müller, Markus Rinio, Björn Schäfer, Mark Scholz, Elmar Zippel

Heterojunction silicon solar cells consist of a monocrystalline or multicrystalline base material, on which e.g. one or more amorphous silicon layers are deposited. Figure 1 shows the simplest structure of such a heterojunction solar cell. In the complete production process, the temperature does not exceed 250 °C. The Sanyo company demonstrated efficiency values of more than 20 %, applying this concept to n-doped substrates. Simulation calculations indicated that these efficiency values could also be achieved with p-doped substrates. Values exceeding 17 % had already been reached for small areas.

The goal of our work was to transfer the processes that had been developed for small cell areas to industrially relevant substrate areas. In doing so, a major criterion was that the processes could be easily implemented in an industrial context.

First, we optimised the etching process to remove the damage caused during sawing. Then we developed processes with our in-line plasma system to deposit n-doped, p-doped and undoped amorphous silicon films. Furthermore, we took a sputtering target into operation for depositing indium tin oxide coatings (fig. 2), so that we could completely process the heterojunction cells in our laboratory.

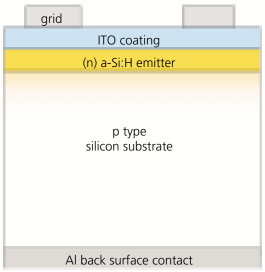


Fig. 1: Simplest structure of a heterojunction silicon solar cell. The thin emitter layer of amorphous silicon and an indium tin oxide (ITO) layer are successively deposited onto a p-doped substrate. The contacts are of silver on the front surface and aluminium on the back surface.

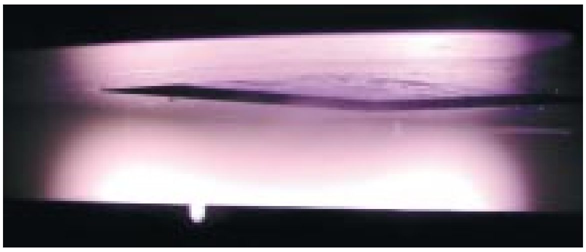
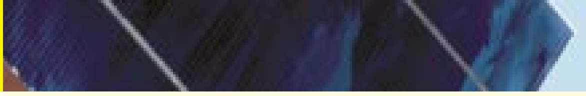


Fig. 2: Sputtering target for depositing indium tin oxide (ITO) coatings. The (multicrystalline) wafer is transported over the plasma source, so that the lower surface is coated. The ITO coating has two functions in the heterojunction solar cell: It serves as an anti-reflective coating and ensures that the transverse electrical conductivity between grid fingers is sufficiently high.

Fig. 3: Photo of a 10 cm x 10 cm heterojunction silicon solar cell on p-doped Cz silicon. The emitter is only 7.5 nm thin. The grid on the front surface corresponds to that of a screen-printed cell, but is applied by evaporation.

With this simple structure, which does not yet include specific passivation of the front and back surfaces, we have already achieved efficiency values up to 13.5 % on 100 cm² monocrystalline Cz silicon wafers (fig. 3).

In addition to their application in heterojunction solar cells, the undoped amorphous silicon films that we have developed can also be used as very good passivation layers on n-doped and p-doped silicon substrates. The "cold" heterojunction process is also very well suited for material characterisation, as the process does not cause any changes in material properties.



High-Throughput Silicon Epitaxy for Thin-Film Solar Cells

A rapid, inexpensive method to deposit silicon is central to the production of crystalline silicon thin-film solar cells, as the silicon film with a thickness of only 10 to 20 µm is the core element of this type of solar cell, regardless of the manufacturing procedure. We are developing equipment for high-throughput silicon deposition within several research projects. The centrotherm company is responsible for the implementation. The intended application is for so-called epitaxial silicon wafer equivalents.

Albert Hurrle, Mira Kwiatkowska, Norbert Schillinger, Friedrich Lutz, Harald Lautenschlager, Jochen Rentsch, **Stefan Reber**

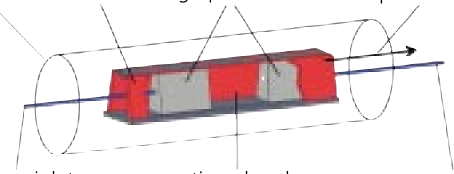


Fig. 1: Schematic diagram of the continuous CVD reactor: the processing gas is introduced into a deposition chamber, where it dissociates at 1200 °C and is deposited on the inner surfaces of the substrates as they glide past the chamber.

Trichlorsilane is the starting point of almost all silicon solar cells. The extremely pure silicon that forms the raw material for solar cells after various processing steps is obtained from this liquid chemical compound. Our thin-film technology uses trichlorsilane directly: instead of allowing blocks to crystallise and sawing them into wafers, we use the evaporated liquid directly to deposit a thin silicon layer, only 10 - 20 µm thick, on a substrate. This process is called chemical vapour deposition, abbreviated as CVD.

The foremost goal for a thin CVD film is low production costs. To achieve this, we have chosen a special construction for the reactor interior, as shown schematically in fig. 1: The processing gas is fed through a pipe into a chamber made of graphite. Here, the gas is dissociated at a temperature of about 1200 °C, the resulting molecular fragments are deposited mainly on the inner surfaces of the rows of substrates (coloured red in the diagram), causing the silicon layer to grow there. If the rows of substrates are simultaneously transported parallel to the gas flow past the chamber, very high throughputs can be achieved and inhomogeneities in the deposition process can be evened out.

Starting from this concept, we co-operated with centrotherm GmbH to develop a prototype CVD reactor, which demonstrated that our idea could be implemented. The performance specifications included deposition rates of up to 5 µm per minute over a length of 40 cm. For a 10 µm thick film, this corresponds to a throughput of just on 5 m^2 per hour, about a third of the throughput rate for a modern solar cell manufacturing line.

Fig. 2: The continuous CVD reactor in a laboratory at Fraunhofer ISE. On the left-hand side is a carrier loaded with silicon wafers, which is transported to the right through the deposition chamber and is then unloaded on the other side.

The gas curtains at the loading and unloading stations represent an essential design element in the reactor. They separate the gas volume within and outside the CVD reactor. They allow the substrate carriers to be transported continuously through the reactor, without the need for sophisticated controls. As fig. 3 shows, we were able to demonstrate the impressive effect of moving the substrates: Inhomogeneous profiles, which inevitably arise during stationary deposition and which would undermine the functionality of the wafer equivalent, are smoothed out completely when the substrates are transported during deposition. However, not only the homogeneity of the profile but also the crystalline quality is decisive. To obtain the best thin-film solar cells, the silicon films should have as few defects as possible, and must grow epitaxially, i.e. following the crystal orientation of the substrate. We were also able to clear this hurdle. Cross-sections through epitaxially grown films on multi-crystalline silicon wafers, which we use as test substrates, have shown satisfyingly low defect concentrations. Figure 4 shows eight of these 10 x 10 cm^2 silicon wafers, where the external appearance already witnesses to their good quality.

Parallel to developing the CVD reactor, we optimised the manufacturing processes for solar cells made of epitaxial wafer equivalents. They consist of thin epitaxial films, which are deposited onto inexpensive silicon substrates that cannot be used directly for solar-cell processing. The result of the work is that the wafer equivalents can be processed to solar cells and modules in the same way as "normal" silicon wafers. As fig. 5 shows, the thin-film module looks just the same as a standard module. Its efficiency value of 10.2 % is a promising starting point for a possible pilot production.

This success was possible thanks to the support in several projects from the German Federal Ministry for the Environment and the European Union.

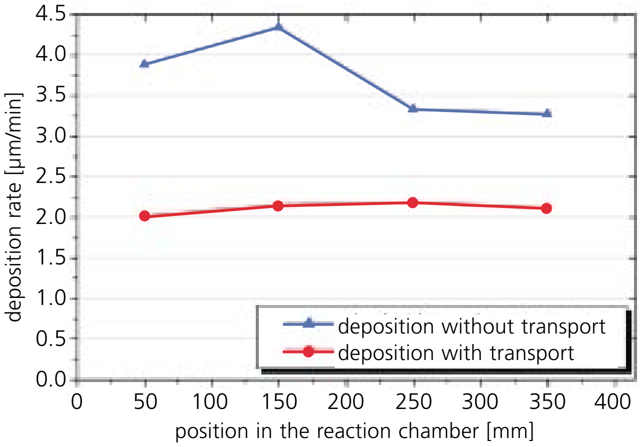


Fig. 3: Deposition rates for deposition without (blue) and with (red) transport of the silicon wafers. Clearly evident is the smoothing effect of the sample movement, which was essential to using the reactor for photovoltaic production. By optimising the process, we expect also to achieve deposition rates of around 5 µm per minute when the samples are transported.

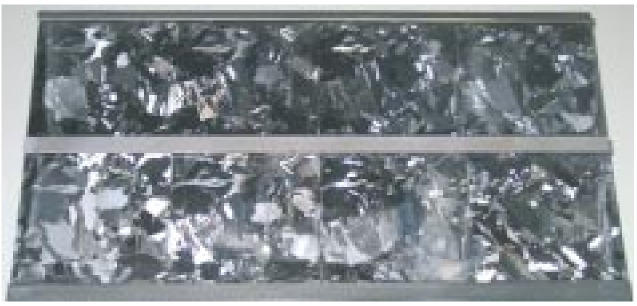
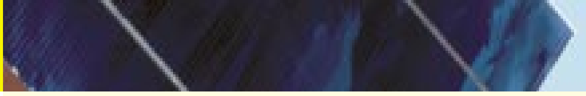


Fig. 4: A carrier loaded with test wafers of multi-crystalline silicon after epitaxial deposition of silicon. Depending on the crystal orientation in the substrate, the corresponding crystallites in the film grow at different rates, and differ clearly in their reflectance. The carrier dimensions are approximately 40 x 20 cm^2.

Fig. 5: A mini-module consisting of six multi-crystalline epitaxially prepared wafer equivalents of area 10 x 10 cm^2. Although it was processed and looks like a "normal" module, it is really a genuine thin-film module.



III-V Photovoltaic Cells and PV Receiver Modules for Optically Concentrating Photovoltaic Systems

On the basis of III-V semiconductors, we produce epitaxial structures for use in tandem cells for space applications and concentrating systems. These cells, with efficiency values exceeding 30 %, are integrated into special receiver modules for application in optical concentrator systems. One system, the FLATCON™ concept, is now ready for the market. Other developments in III-V epitaxy include customised laser power cells and thermophotovoltaic (TPV) cells.

Paul Abbott, Carsten Baur, **Andreas Bett**, Armin Bösch, **Frank Dimroth**, Ines Druschke, Wolfgang Guter, Martin Hermle, Maria Lada, Hansjörg Lerchenmüller, Rüdiger Löckenhoff, Astrid Ohm, Matthias Meusel, Severin Müller, Sascha van Riesen, Gerald Siefer, Thomas Schlegl, Jan Schöne, Johannes Seiz, Sivita Wassie

Fig. 1: Solar cell receiver modules for the FLATCON™ concentrator module that was developed at Fraunhofer ISE within projects supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). Cells with a diameter of 2 mm and suited for 500 x concentrated solar radiation are soldered onto copper plates. The copper plates are attached precisely onto a glass pane with adhesive, each at the position corresponding to the focus of a Fresnel lens.

Solar cells that are based on III-V semiconductor materials use sequences of epitaxially deposited films. Using industrially relevant equipment for metal-organic vapour phase epitaxy (MOVPE), we produce film sequences for single, tandem and triple solar cells, and more recently also for quintuple solar cells. The solar cells which are produced on the basis of these complex film structures achieve efficiency values well above 30 %. They are used on the one hand for satellites in space, on the other hand for terrestrial concentrator systems.

Figures 1 and 2 show examples of our solar cell receiver modules. In fig. 1, the base plates can be seen for the FLATCON™ modules (Fresnel lens all-glass tandem cell concentrator) developed at Fraunhofer ISE. In this configuration, we position circular tandem cells (diameter 2 mm) at the focus of a Fresnel lens embossed in silicone. Sunlight is concentrated by a factor of 500 with this lens. We are currently looking for partners for the industrial implementation of the FLATCON™ technology, which is now ready for the market.

Figure 2 shows solar cell receiver modules which we produced for the EU-funded PV-Fibre project. Here, the sunlight is concentrated by a parabolic reflector, and is then coupled into optical fibres. The light is then guided by the glass fibres to the highly efficient tandem cell. The resulting light intensity corresponds to 1000 x solar radiation. The cells are mounted on special copper-ceramic plates, which in turn are soldered to cooling fins.

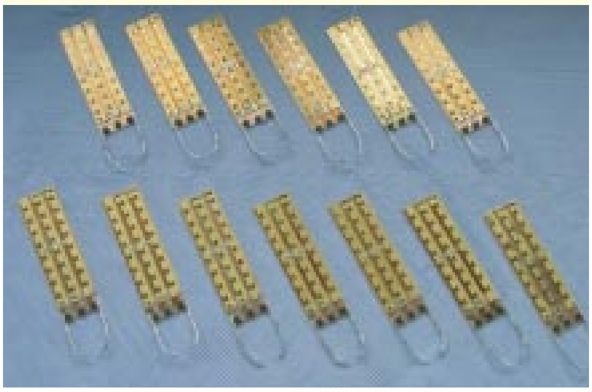


Fig. 2: Concentrator solar cell receiver module, which we developed within the PV-Fibre project. 24 tandem cells, designed for 1000 x concentration, are mounted on a copper-ceramic plate. This plate is soldered onto a cooling fin. The cells are protected with diodes.

Figure 3 shows a result which we obtained within the EU-funded HICON project. The objective is to develop technology to connect several GaAs cell units on one wafer. We succeeded in connecting 25 units in series over an area of 1.5 x 2.4 cm^2. This type of cell is used directly at the focus of a parabolic reflector or a tower power plant. Here also, the sunlight is concentrated by a factor of 1000. The series connection meant that resistance losses at the high currents could be minimised.

Another application area which draws on our III-V photovoltaic cells is that of wireless energy transfer systems. There, the PV cells transform monochromatic light to electricity with an efficiency value exceeding 45 %. This type of cell is produced according to the client's specifications. As an example, fig. 4 shows cells which are mounted in transistor housings.

In thermophotovoltaics, we apply our infrared-sensitive PV cells based on GaSb. The pn junctions for these cells are produced either by simple Zn diffusion or with MOVPE technology. We use the shingle configuration, where the cells are connected in series without losing active areas, to achieve the high coverage ratio needed for an efficient TPV system. An AlN substrate with good thermal conductivity is used as the base, as shown in fig. 5.

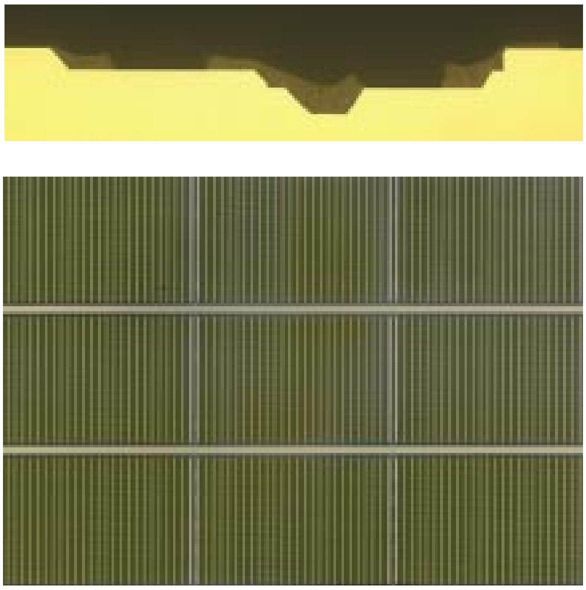


Fig. 3 (above): Cross-section through a monolithically integrated module (MIM). The interconnection groove between two cell segments can be seen. Up to 25 PV segments are connected in series and provide voltages of more than 25 V.
(below): Nine 1.6 x 2.4 cm^2 MIM cells on a 100 mm^2 wafer.

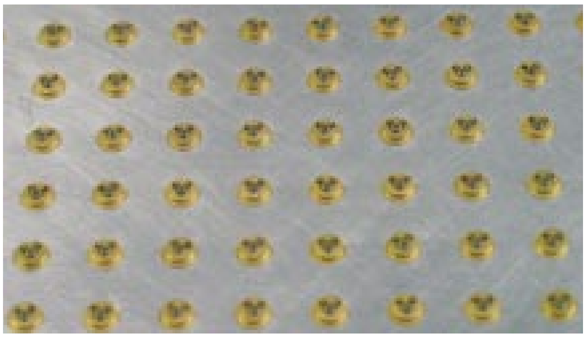


Fig. 4: Photo of laser power cells mounted on transistor housings. The cells convert light to electricity with an efficiency value exceeding 45 %.

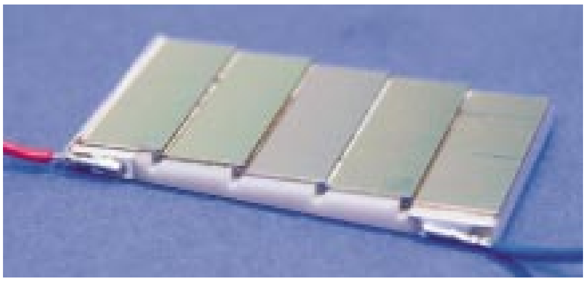
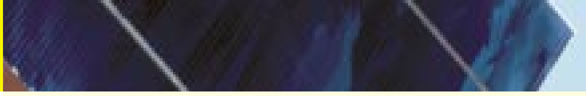


Fig. 5: The photo shows a module with shingle-mounted GaSb photovoltaic cells for use in a thermophotovoltaic (TPV) generator.



Production Technology for Dye and Organic Solar Cells

Dye and organic solar cells are based on new technology with the potential for particularly economic production and new application areas. Despite the progress made in recent years, important issues such as long-term stability, adequate efficiency values and simple production technology have not yet been sufficiently clarified. In co-operation with the industry and other research institutes, we are working on these issues at Fraunhofer ISE.

Udo Belledin*, Markus Glatthaar*, **Andreas Hinsch**, Sarmimala Hore*, Rainer Kern, Michael Niggemann, Moritz Riede*, Ronald Sastrawan*, Uli Würfel*, Birger Zimmermann

* University of Freiburg, Freiburger Materialforschungszentrum FMF

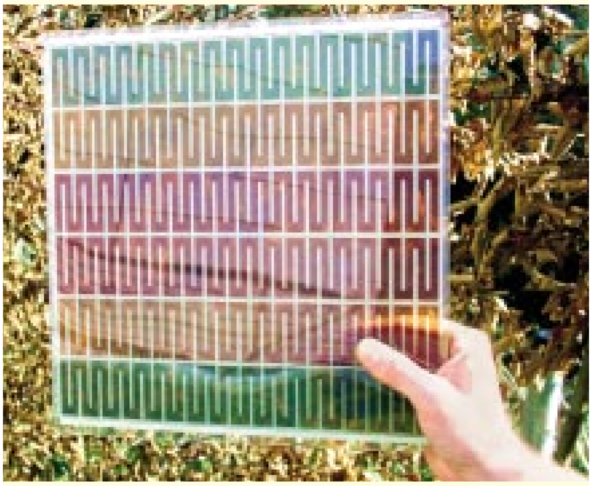


Fig. 1: Photo of a module made of dye solar cells at Fraunhofer ISE. The coloured design was achieved by using photo-active metal-organic complexes (dyes) which absorb light selectively. The module is sealed with a glass soldering technique which was developed at Fraunhofer ISE and exhibits good long-term stability.

Fig. 2: Test facility developed at Fraunhofer ISE to characterise organic solar cells automatically. Ten identically produced test cells are mounted on each of the nine substrates. This ensures the accuracy needed for comparative parameter sensitivity studies (see text also).

We see an important advantage for the market introduction of dye solar cells in the design potential which this technology offers. Our most recent work has thus been concerned with design issues. At Fraunhofer ISE, we produced modules to test the effect of different colours and graphical structures for the dye solar cells. To this purpose, we used metal-organic complexes which are known to be photovoltaically efficient. An attractive coloured appearance, such as we achieved with the example shown in fig. 1, makes this technology interesting for diverse applications in glazed facades, skylights or display boards. The coloured effects can also be obtained by use of purely organic dyes.

The main emphasis of our work on organic solar cells was in developing suitable production technology for laboratory cells and their characterisation. We developed a laboratory procedure to produce ten test cells simultaneously on a common substrate in a protective gas atmosphere. Using this procedure, we can produce a large number of organic test cells with reproducible properties (fig. 2), which serve as a basis for checking production parameters and material variations efficiently and automatically.

We established a new measurement procedure for organic solar cells at Fraunhofer ISE, electric reflection spectroscopy (ERS), which allows the internal electric field to be determined. This measurement is used to select suitable electrode materials for organic solar cells.

New Measurement Procedure for the Spatial Distribution of Defects in Silicon Wafers

Analysis of the temperature dependence of carrier lifetimes in silicon helps to characterise defects which significantly reduce the material quality. In particular, impurities and crystal defects can be identified. To this purpose, we developed the spatially resolved method of thermal defect imaging (TDI), which combines spatially unresolved temperature-dependent lifetime spectroscopy (TDLS) and spatially resolved lifetime measurement (emission carrier density imaging CDI).

Martin Schubert, Jörg Isenberg*, Stefan Rein*, Stephan Riepe, Stefan Glunz, **Wilhelm Warta**

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The detection and identification of effects which reduce the carrier lifetime in silicon is essential for the evaluation of materials and processes for solar cell production. Various measurement methods are now available for spatially unresolved lifetime spectroscopy (characterising the lifetime of minority charge carriers). Deep level transient spectroscopy (DLTS) and temperature-dependent lifetime spectroscopy are particularly important. The latter applies temperature-dependent lifetime measurements using microwave-detected photoconductance decay (MW-PCD) to determine the energy of a defect level, which is characteristic for the dominant impurity species. Under certain conditions, this allows the lifetime-reducing defect to be identified.

We have now succeeded in combining the recently developed, spatially resolved lifetime measurement technique, emission carrier density imaging (emission CDI) with the TDLS method. We constructed equipment for temperature-dependent lifetime measurements over the range from 30 °C to 270 °C, from which effective defect levels can be determined, analogously to TDLS.

The newly developed thermal defect imaging (TDI) method was validated using a silicon sample that had been deliberately contaminated with molybdenum (fig. 1). Comparison with TDLS confirmed the TDI measurement.

The significant advantage of the new measurement technique is its ability to characterise samples where the defects are inhomogeneously distributed. The measurement method is particularly interesting for multi-crystalline silicon, which is of great industrial relevance. Our first investigations of this material (figures 2 and 3) indicate an inhomogeneous distribution of defects.

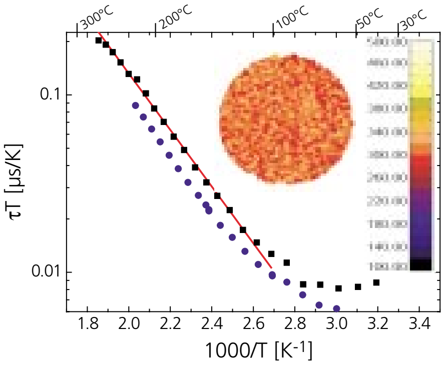


Fig. 1: Lifetime spectroscopy of a silicon sample contaminated with molybdenum. The black squares mark the averaged lifetime from the TDI measurement, the results from the comparative TDLS measurement are shown as blue circles. The energy level can be determined from the red line of best fit. Separate measurements made for each point of the image are the basis for the spatially resolved measurement shown in the graph to the upper right (diameter 2 cm, spatial resolution 350 µm), The colour-coded scale gives the calculated energy level in meV.

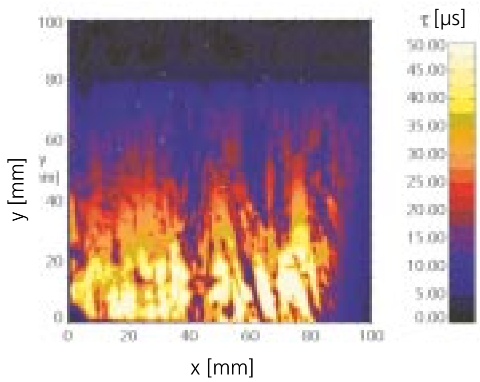


Fig. 2: Carrier lifetimes determined with emission CDI for a multi-crystalline Si sample cut vertically out of the top of a silicon block.

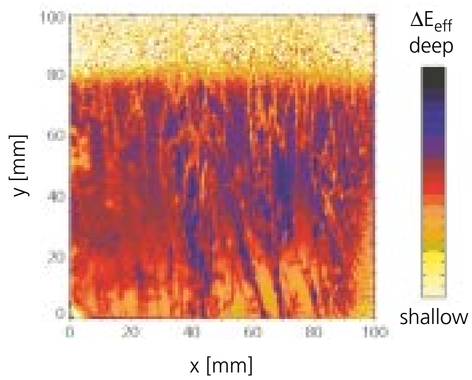
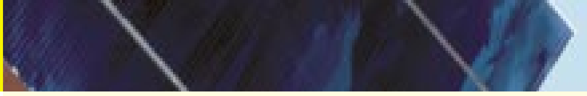


Fig. 3: Spatially resolved representation of effective defect levels in arbitrary units, measured for the sample of fig. 2 with TDI. The sensitivity limit has been reached at the upper section of the image, where the lifetimes are too short to be detected. Shallow defect levels are located closer to the band edge than deep ones.



Investigation of Module Service Life: New Test Stand for UV Exposure

Solar cells are encapsulated to protect them against environmental influences, using polymers and glass. However, the molecular structure of polymers makes them susceptible to damage by ultraviolet (UV) radiation. We are investigating the ageing performance of solar cell encapsulation by controlled exposure to UV radiation. The goal of these investigations is to extend the module service life by modifying the cell encapsulation.

Stefan Brachmann, Stefan Gschwander, Markus Heck, Michael Köhl, **Helge Schmidhuber**

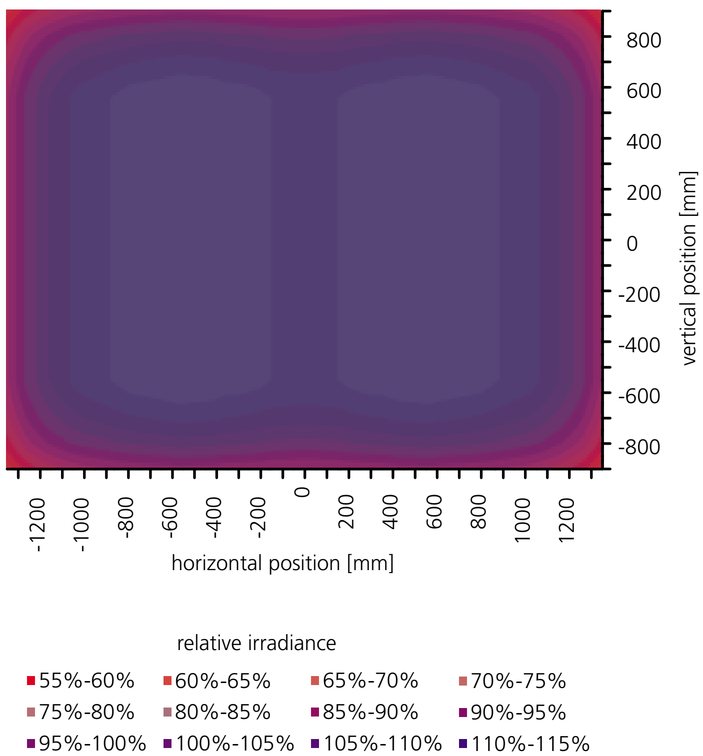


Fig. 1: Measurement of the UV-A irradiance as a function of the horizontal and vertical distance from the centre of the test plane. Blue zones represent high values and red zones represent low values of the irradiance. Radiation homogeneity of ± 15 % in the sample plane is achieved.

The international standard, IEC 61345, gives detailed specifications for a UV test facility for PV modules. For our work on extending the service life of photovoltaic modules, we have designed a new type of UV test stand which meets these specifications. It is not equipped with mercury vapour lamps like conventional test stands, but uses special fluorescent tubes. The tubes are mounted such that the radiation homogeneity in the sample plane is better than ± 15% (see fig. 1). Continuous monitoring of the UV-A and UV-B intensity and the sample and lamp temperatures ensures the quality of the tests.

An advantage of using fluorescent tubes instead of conventional vapour lamps is their limitation of the emitted radiation to the UV region and their particularly economic operation. The limited spectral radiation range means that the solar modules do not need sophisticated cooling to meet the specifications of IEC 61345. The construction of our test stand allows sample temperatures to be set both above and below the 60 °C specified in the standard. Similarly, the samples can be subjected to radiation that can be adjusted to be 3 to 7 times more intensive than the standard AM 1.5 spectrum in the UV-A range, and 30 to 62 times higher in the UV-B (fig. 2).

We use our test stand to provide quality control accompanying production and to investigate material-specific ageing behaviour. This enables us and our clients to select more durable encapsulation materials.

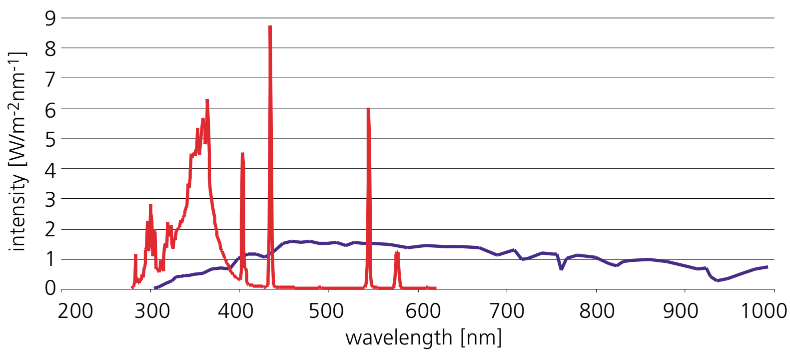


Fig. 2: Spectral intensity at a distance of 100 mm from the lamp plane (red curve) and the standard AM 1.5 solar spectrum (blue curve). The lamp radiation is 7 times more intensive in the UV-A spectral range and 60 times in the UV-B range.

Laser Soldering of Crystalline Solar Cells

Solar cells are connected to form so-called strings by soldering cell contact strips to the front and back surfaces of the cell. The quality of the contacts determines the efficiency value and is decisive for the durability performance of a solar module. We are investigating novel methods to create high-quality soldered contacts using lasers.

Gernot Emanuel, Ralf Preu,
Helge Schmidhuber

Solar cells in a module must be connected electrically with each other. This is done in almost all cases by soldering on tinned copper strips, using either radiative or contact soldering methods.

A directive issued by the European Union specifies that only lead-free solders may be used for contacting purposes from 2006 onward. In this context, we are investigating the usage of lasers to make contacts. The advantage of lasers compared to other means is that heat is transferred efficiently and controllably to the joint. This means that also lead-free solders, which melt at higher temperatures than solders containing lead, can be processed reliably and reproducibly.

To create a soldered contact, a tinned copper strip is coated with flux. This strip is positioned on the solar cell and soldered with the laser at several points (fig. 1).

Together with our industrial partners from the SOLPRO V expert panel (innovative and rational manufacturing procedures for silicon photovoltaic modules), we developed a laser process, which makes very good electrical and mechanical contacts between the connector strip and the solar cell (fig. 2).

Parallel to the technological investigations, we also co-operated with the Fraunhofer Institute for Production Technology IPT to prepare an economic feasibility analysis. The result was that laser soldering can meet the new EU standard, is technologically equivalent and does not cause additional expense.

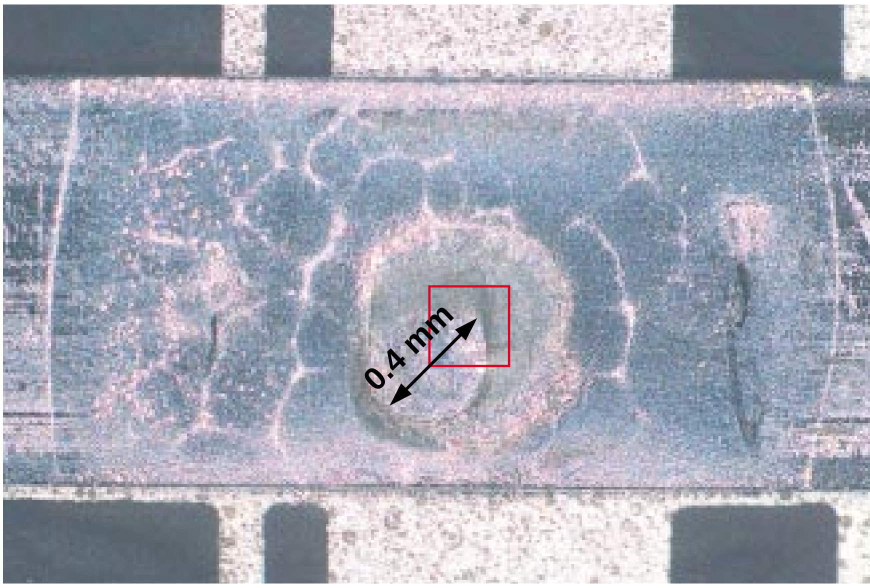


Fig. 1: Photo of a soldered contact on the back surface of a solar cell. In the centre, the zone can be seen where the laser radiation was incident. The laser spot, with a focus diameter of 0.4 mm, is moved around a square with a side length of 0.3 mm (indicated in red). The solder melts radially outward from the centre of incident energy. A mechanical and electrical contact is created between the cell connector strip and the solar cell by the solder melting and the associated activation of the flux. In this way, energy incident on a very small area can create a solder contact over a larger area. (Source: Trumpf Laser)

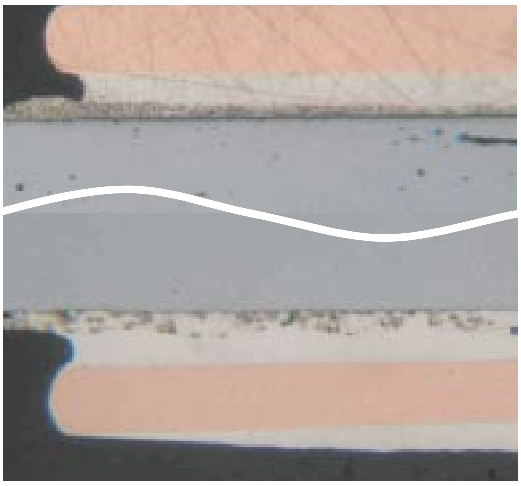
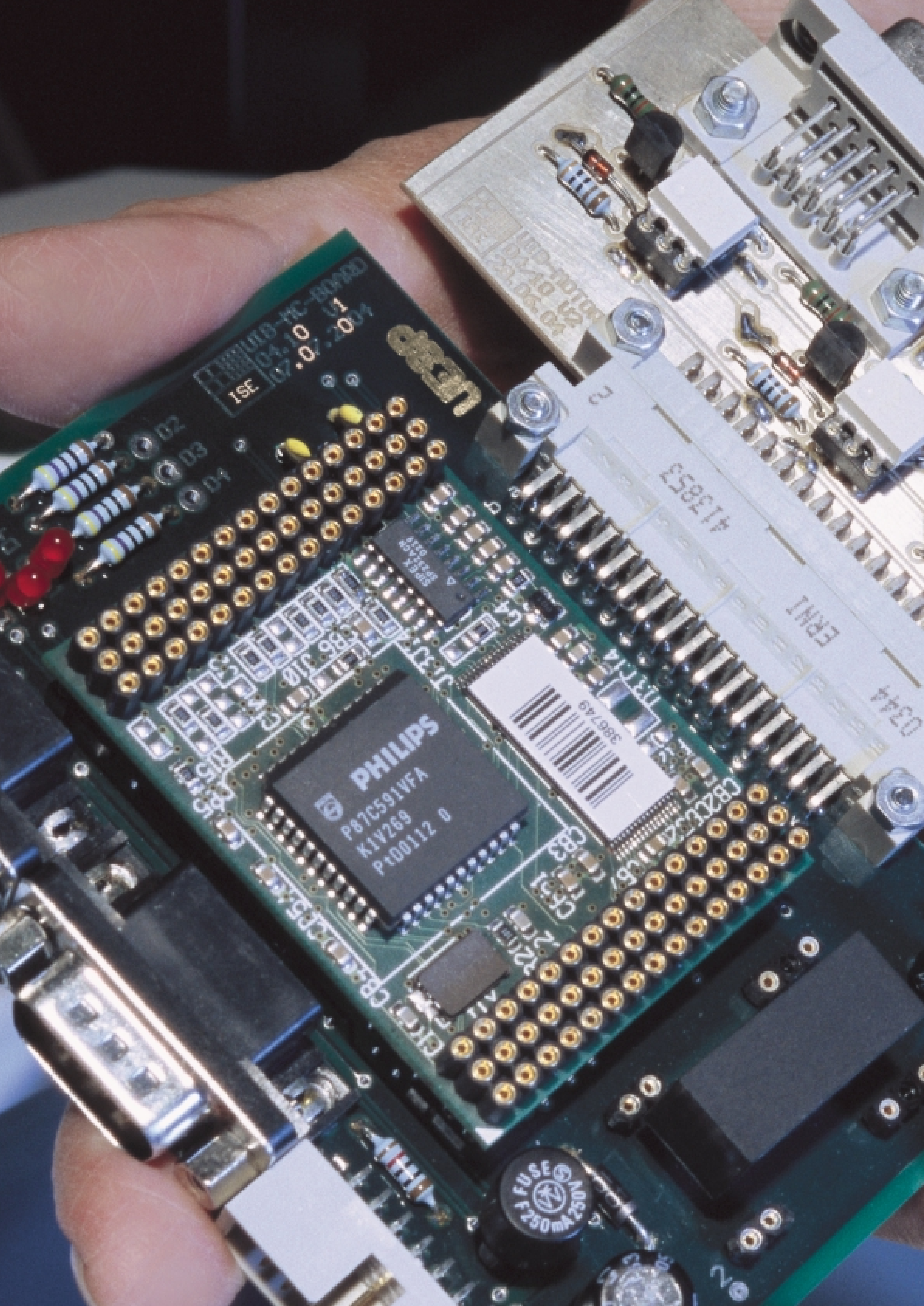


Fig. 2: Cross-section through a solar cell, with laser-soldered contacts on the front and back surfaces. The dark grey regions represent the silicon of the solar cell, which was screen-printed with a metal-containing paste for contacting. The light grey solder creates a good electrical and mechanical contact with the paste on the front and back surfaces. In addition, a very homogeneous diffusion zone has been formed on the back surface. The soldered contact was made with flux. (Source: Deutsche Solar)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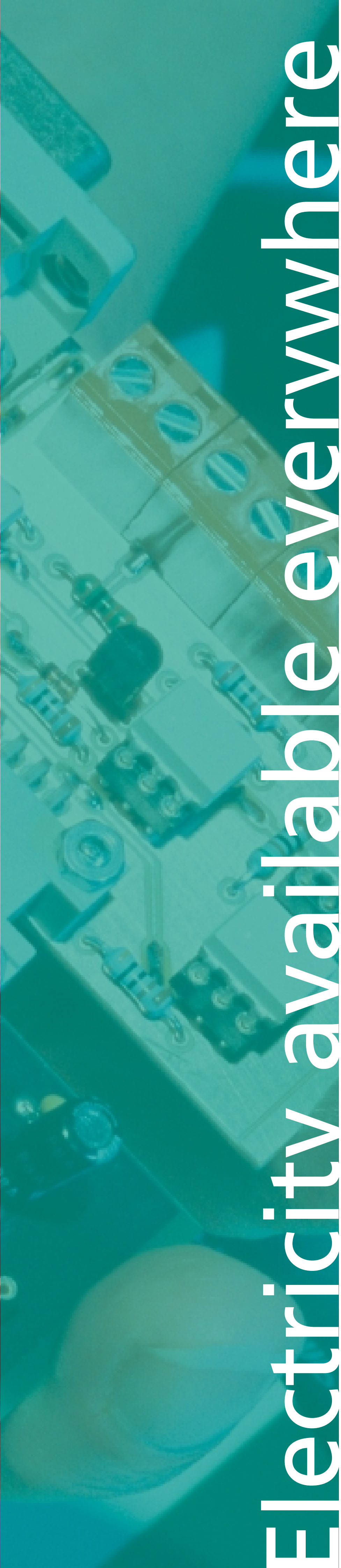

Off-Grid Power Supplies

Two thousand million people without electricity, innumerable technical power supplies for telecommunications, environmental measurement technology or telematics, and four thousand million portable electronic appliances all have one feature in common: They all require off-grid electricity. Increasingly, regenerative energy sources or innovative energy converters are being used to supply it. Around 30 % of the photovoltaic modules sold world-wide are used in these markets, some of which are already economically viable without external subsidies. In many cases, generating energy from the sun is already more economic today than disposable batteries, grid extension or diesel generators.

In addition, more than one thousand million people without access to clean water for drinking and other purposes need decentralised technology for water desalination and purification. We power these systems with renewable energy, improve their energy efficiency and reduce the need for maintenance.

Certainly, the quality of the components and the systems for both rural electrification and technical power supplies has improved notably over the last few years. However, there is still great potential for development. Thus, we support businesses in developing components, planning systems and penetrating new markets. Our special areas of competence encompass highly efficient power and control electronics, battery modelling, charging strategies, system operation management, energy management and system simulation.

Furthermore, we also offer analysis and advice on social and economic boundary conditions to aid successful market introduction of energy technology. New business models and appropriate market penetration strategies are particularly important for the companies which are involved in rural electrification. This is the only way to ensure establishment of a sustainable distribution and service network - and thus long-term operation of the installed systems

Miniature fuel cells, in particular, have great potential for portable appliances. We are developing the necessary technology for this, including the associated power and control electronics. The advantage of miniature fuel cells is the high energy density of their storage units for hydrogen or methanol. This can significantly lengthen the operating time for the appliances, while the volume or mass remains unchanged.

We support component manufacturers, system integrators, planners and service companies in the off-grid power supply sector with our expertise in the following areas:

- electronics development
- battery modelling
- small fuel cells
- system dimensioning and optimisation
- system operation management and energy management systems
- water treatment systems and technology for drinking and other water supplies
- socio-economics

The following facilities are available to us for our development work:

- inverter laboratory
- highly accurate power measurement instruments for inverters and charge controllers
- precision instruments to characterise inductive and capacitive components
- measurement chamber for electromagnetic compatibility (EMC)
- burst and surge generators
- programmable solar simulators and electronic loads
- development environments for microcontrollers and digital signal processors (DSP)
- lighting measurement laboratory
- development environments for controls based on "embedded systems"
- thermostatted test stands for multiple-cell batteries and hybrid storage units
- test stands for fuel cells operating with hydrogen and methanol
- spatially resolved characterisation of fuel cells
- calibration laboratory for solar modules
- outdoor test field for solar components
- pump test stand
- testing and development laboratory for drinking water treatment systems

Off-Grid Power Supplies

This widely applicable interface for the Universal Energy Supply Protocol UESP is the result of joint development with eight industrial partners. In stand-alone photovoltaic hybrid systems, it allows the individual components such as batteries, auxiliary power generators and loads to communicate with each other and the central energy management system. The advantages offered by the new development include greater flexibility for system dimensioning and extension, higher operating reliability and improved economic feasibility due to cost-optimised operation management. (See article on p. 57.)

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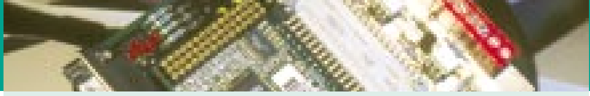


Monitoring of Village Power Supply Systems in China

As part of the technical co-operation between China and Germany, we are planning and supporting the technical monitoring and maintenance for 120 village power supply systems in the Chinese province of Qinghai. We draw on practical experience from the project in advising on further programmes for village electrification.

Georg Bopp, Andreas Steinhüser

Fig. 1: The PV-wind hybrid system in Jangkang village in the Chinese province of Qinghai is one of seven village electrification systems which were evaluated by Fraunhofer ISE and is now included in the monitoring programme.

Fig. 2: In almost all Chinese village electrification systems, as here in Dousong village, only lead fleece batteries are operated, with a system DC voltage of 220 V. As individual cells of this battery type are prone to break down unexpectedly, the systems are monitored continuously.

By the end of the decade, China aims to supply 23 million people in remote areas with electricity from renewable sources within its "Brightness Programme". As one step, by the end of 2004 around 1000 isolated villages in the western provinces had each been equipped with a central photovoltaic system supplying 10 to 40 kW. As part of the technical co-operation between Germany and China, Fraunhofer ISE was commissioned by the Gesellschaft zur technischen Zusammenarbeit GTZ (German Development Co-operation) to develop monitoring and training programmes, which would ensure sustainable operation and functionality for 120 PV systems in Qinghai province.

Based on our many years of experience in monitoring PV hybrid systems in the Alps, and using the training tools that we have developed, we ran a course, "Train the Trainer", in 2003 for the system operators and the local maintenance personnel. We did this in close co-operation with the Zentrum für Sonnenenergie- und Wasserstoff-Forschung ZSW (Centre for Solar Energy and Hydrogen Research). After an on-site inspection in 2004, we proposed concepts for technical monitoring and long-term maintenance which drew on nearby companies. As part of these measures, we are currently preparing a maintenance handbook.

For the system monitoring, the local operator in each of the 120 villages fills out daily data sheets with generation and consumption values. In twelve villages, the data are also recorded by a data logger and analysed. The data are analysed with the support of Fraunhofer ISE and ZSW. This analysis allows faults to be detected quickly and provides a basis for optimising the systems, technically and economically.

Exploiting Renewable Energy Sources as a Basis for Regional Economic Development

Within our interdisciplinary work programme, we are developing a sociological analysis and advice package to promote the acceptance of renewable energy. This helps regional authorities and companies to determine which types of technology are likely to be well accepted, and thus are suitable to act as icebreakers for an innovative regional energy and economic strategy.

Sebastian Gölz

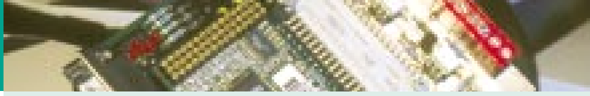
There are attractive opportunities in many regions of Europe to use renewable energy simultaneously for a sustainable energy supply and to stimulate regional economic development. Nevertheless, the different types of technology are not equally well suited to a pioneering role in an innovative economic strategy. In addition to sufficient energy potential and favourable economic boundary conditions, there needs to be agreement with the general opinion and self-image of the population. A sufficiently strong economic and political network is also necessary.

Within our interdisciplinary work programme, we are developing a sociological analysis and advice package for regional authorities and companies which want to include renewable energy in their development strategy.

For example, analysis of the Shannon region in Western Ireland revealed that exploiting the high potential for wind energy would provoke considerable resistance from the population. By contrast, the use of biomass could count on a relatively high degree of approval. Accordingly, we co-operated with local project partners to formulate an action and communication concept, which initially will prepare the establishment of networks involving authorities and companies, and exploitation of the biomass potential with demonstration projects. This procedure will promote the acceptance of renewable energy, and can later be transferred to other types of technology. The analysis and advice package is available as a service to other regions.

Fig. 1: Wind energy offers a high energy potential in the West Irish region of Shannon due to its coastal location. However, the local population is opposed to its exploitation. It fears that wind energy farms will make the landscape less attractive to tourists. Thus, increased biomass usage should first be encouraged, rather than wind energy, to support the acceptance of renewable energy.

The work was carried out within the CORE Business project funded by the EU.



Highly Efficient DC/DC Converter

The DC/DC converter for fuel cells that was newly developed by Fraunhofer ISE has a significantly higher efficiency value than conventional models. It is distinguished by an innovative component and circuit concept. At the same time, it is smaller, lighter and cheaper to produce than conventional models. The modular construction means that the converter can also be used as a PV charge controller or to feed electricity into electrolysers.

Bruno Burger, Christoph Siedle,
Heribert Schmidt

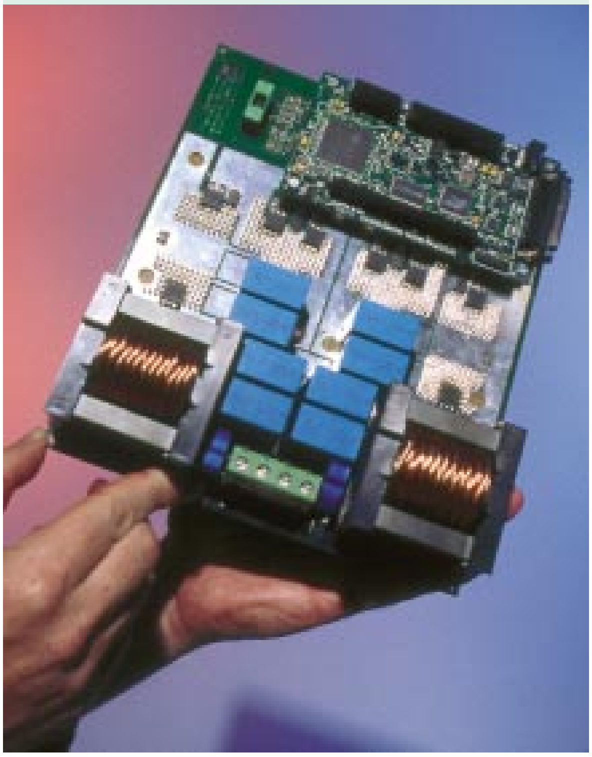


Fig. 1: The new DC/DC converter, with its small dimensions, can be easily integrated e.g. into fuel cell systems.

DC/DC converters are used to convert a variable DC voltage into a constant output voltage. Special DC/DC converters are need to connect fuel cells to batteries, which regulate the fuel cell operating point at their input and charge the battery at their output according to predefined strategies. In our demonstration system at the Rappenecker Hof (see article on p. 56), we installed a fuel cell with an industrially produced DC/DC converter in 2003. The system measurements revealed that the converter's control of the fuel cell was unsatisfactory. Also, it only achieved an efficiency value of about 75 %. We responded by developing a new converter for this system with an appreciably higher efficiency value, which is also smaller, lighter and cheaper to manufacture.

In order to achieve this goal, the converter was constructed of two step-up choppers, which operate 180 degrees out of phase. This reduces the voltage ripple at the input and output, so that film capacitors rather than electrolytic capacitors can be used. This increases the lifetime considerably. Both step-up choppers are equipped with a synchronous rectifier. This greatly increases the efficiency value. The controls are based completely on a digital signal processor, so that they can easily be adapted to different operating conditions. In addition, we provided an input for remote control. The minimal electric losses mean that cooling fins are not needed for conversion powers of up to 2 kW. The usage of SMD transistors makes simple and inexpensive assembly feasible. All the components are positioned directly on the printed circuit board, so that there is no need to wire external components such as inductance coils. The new converter is currently being tested at the Rappenecker Hof and is available for other applications.

	conventional device	new development
mass	43 kg	1,5 kg
dimensions (mm)	600 x 330 x 600	235 x 200 x 55
volume	118.8 dm^3	2.5 dm^3
efficiency value	75 %	98 %

Table: Make the large small: The DC/DC converter developed at Fraunhofer ISE has only a fraction of the dimensions and mass of the original device. At the same time, the efficiency value was improved by 23 percentage points to 98 %.

Optimal Battery Selection for Stand-Alone Power Supply Systems

The demands on batteries for stand-alone power supply systems vary greatly, depending on the energy supply, the load profile and the local conditions. To facilitate appropriate solutions, we developed an Internet-based procedure with which power supply systems are categorised according to their specifications profile. This enables planners to determine the optimal type of battery for each system. Battery manufacturers can have their batteries tested to identify the system categories for which they are best suited.

Georg Bopp, **Rudi Kaiser**

An analysis of the system and operating data from more than 140 stand-alone power supply systems in Germany, Asia and Latin America revealed that the demands on the batteries in the systems vary greatly. The climatic conditions, the energy supply, the load profile and the components used are the decisive factors.

Depending on the type and technology, the batteries in turn meet these demands - the ability to withstand deep discharge, to be cycled many times or to operate with high efficiency - to different degrees. To determine the optimal battery for a certain system, we co-operated with project partners to define six so-called stress factors. These describe the stress which a system imposes on the battery. Using the stress factors, we analysed the system and operating data and showed that stand-alone power supply systems can be divided basically into six groups, each with its characteristic load profile (fig. 1). This classification procedure for stand-alone power supply systems can found in the Internet under www.benchmarking.eu.org. It allows planners to determine the optimal battery type for their stand-alone power supply system with the aid of the data from a design and dimensioning program. In addition, it allows existing systems to be optimised.

Parallel to this classification procedure, we developed a comprehensive cycle of battery tests. Using this, battery manufacturers can have their batteries tested to determine which ones are particularly suitable for any of the six system groups, and label them accordingly. Different types of battery technology can also be compared with the test cycle. The work was carried out as part of the EU-funded project on "Development of test procedures for benchmarking components in renewable energy systems".

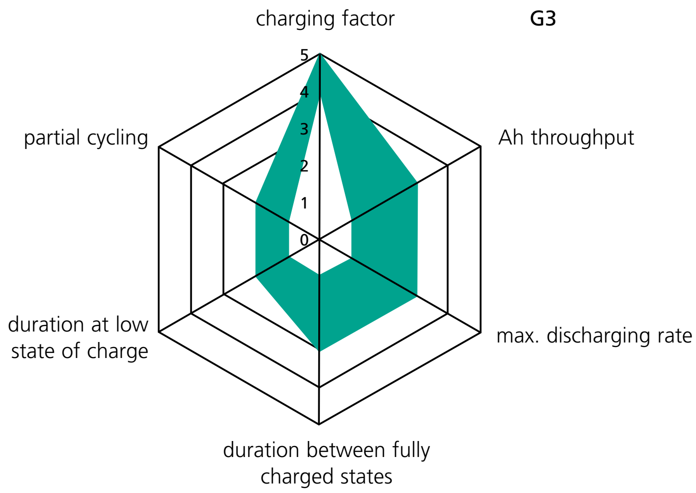
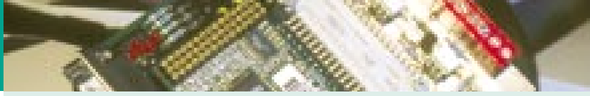


Fig. 1: Six so-called "stress factors" are used to characterise the demands placed by a stand-alone power supply system on a battery. The demand profile can then be classified into one of six groups. As an example, the graph shows the normalised demand profile for the third group, G3.



Long-Term Experience with Fuel Cells in Field Operation

Since October 2003, Fraunhofer ISE has been comprehensively testing a 1.2 kW fuel cell under field conditions in a stand-alone power supply system. The development of future PV hybrid systems with fuel cells is drawing on the experience gained. In addition, manufacturers of fuel cells profit from the knowledge gained.

Andreas Steinhüser, Felix Holz

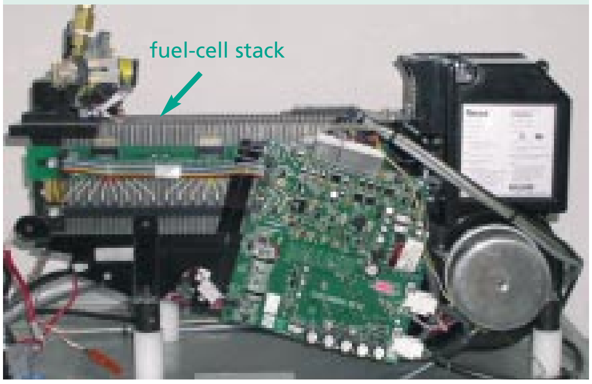


Fig. 1: This polymer-electrolyte membrane fuel cell (the stack can be seen in the background) was tested under real application conditions from October 2003 to July 2004. It achieved an operating lifetime of more than 2000 hours. In the meantime, it has been replaced by a second, identically constructed cell.

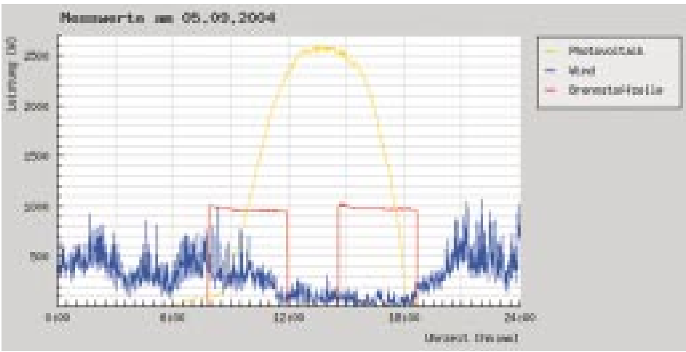


Fig. 2: Under favourable weather conditions, the photovoltaic system together with the wind generator and the fuel cell can completely meet the energy demand of the "Rappenecker Hof". During the day, the PV system contributes an increasing amount to the power supply (yellow). Towards the evening, the amount of electricity produced by the wind turbine increases (blue). During the morning and afternoon, the energy from sun and wind is not sufficient to meet the energy demand of the inn completely. During these periods, the fuel cell is switched on (red).

Since 1987, Fraunhofer ISE has been operating a stand-alone photovoltaic hybrid system at the "Rappenecker Hof", a hikers' inn on the Schauinsland mountain. The demonstration system serves to test components and systems technology under real usage conditions and provides valuable practical experience. In summer 2003, we extended the system and integrated a "Nexa" fuel cell produced by Ballard. On the long term, it is intended to replace the diesel generator as an auxiliary power supply. The performance of a series-produced fuel cell can thus be analysed under field conditions.

When systems are subjected to real operating conditions, phenomena occur which could not be encountered in a test laboratory. For example, we discovered that the internal hydrogen sensor for the system was disturbed by other gases extraneous to the system in the plant room, such as those released by solvents. Furthermore, when the operating history was analysed, it became evident that the DC/DC voltage converter used did not operate the fuel cell at the optimal working point, and also had a relatively low efficiency value. Thus, we developed a voltage converter which was specially adapted to the specifications, and can also be directly controlled by the fuel cell (see article on p. 54).

We can report a positive result concerning the lifetime. Although the manufacturer specified the lifetime as 1500 hours, we succeeded in operating the fuel cell for more than 2000 hours with only one interruption. In the meantime, the fuel cell has been replaced by an identically constructed cell. In future operation, we aim particularly to achieve a better match between the fuel cell and the voltage processing, and to further optimise the operation management.
The project was financially supported by the "Innovationsfonds Klima- und Wasserschutz" (innovation foundation for protection of climate and water) of the badenova utility in Freiburg, and by the project partners, the Riesterer family in Oberried and Phocos AG in Ulm. The hydrogen is provided free of charge by basi Schöberl GmbH und Co in Rastatt.

Innovative Energy Management System for Stand-Alone PV Hybrid Systems

In order to appreciably reduce the effort for planning, adapting and maintaining stand-alone power supply systems, we are developing the Universal Energy Supply Protocol UESP. The work on the communications protocol and on the interfaces to photovoltaic systems, batteries, diesel generators and loads was completed in 2004. Starting in 2005, prototypes of a UESP-compatible hybrid system will be tested and optimised.

Felix Holz, Hans-Georg Puls, Christof Wittwer

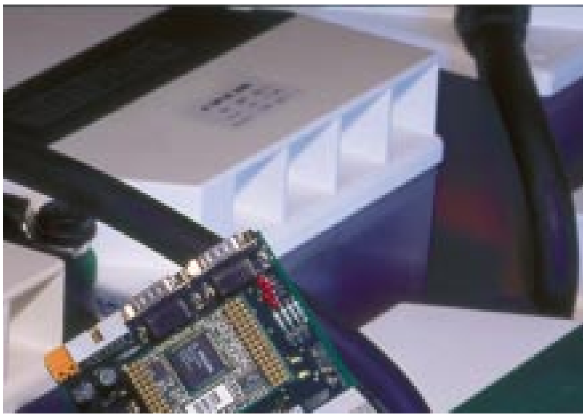


Fig. 1: Even "dumb" components without their own intelligent controls, such as batteries, can be integrated into a UESP system. To this purpose, we developed a special communication interface (UIB), which transfers operating data such as the state of charge and costs to the central energy management system.

In stand-alone PV hybrid systems, an energy management system (EMS) controls the interaction between photovoltaic modules, batteries, auxiliary generators and further components. However, in practice it often occurs that the actual power demands of the users or the usage conditions differ from those that were planned or predicted. If components are replaced or extended, the EMS must also be modified. Thus, planners and operators would welcome an innovative EMS which offers greater flexibility in system design and extension, higher operating reliability due to monitoring and more economic operation with cost-optimised operation management.

Responding to these demands, we are co-operating with eight industrial partners to develop a universally applicable energy management system, the Universal Energy Supply Protocol UESP. In accordance with the "Plug and Play" principle, UESP allows components to be disconnected during operation and new components to be connected. The management system automatically recognises the components and adapts the operation management to the new system configuration.

In 2004, we designed the protocol itself and intelligent communication interfaces (UESP Interface Boxes, UIB) for photovoltaic systems, batteries, diesel generators and a refrigerator as an example of a controllable load.

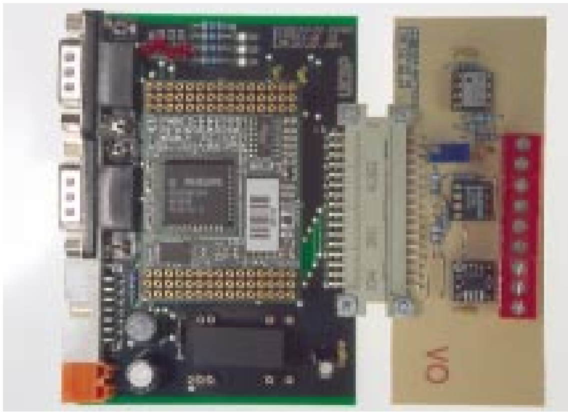


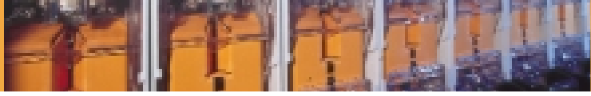
Fig. 2: The UESP Interface Box consists of two circuit boards. The first (on the left in the photo) is responsible for data exchange with the energy management system (EMS) and is identical for all components. The second part (on the right in the photo) is specific to each component and accommodates the control procedure, for a battery here as an example.

In 2005, the first UESP prototype system with these components will be operated and optimised in a demonstration hall. Further components will follow. At the end of the project duration, the protocol will be publicised. Component manufacturers can then design their own UIB's and EMS, and have them tested and certified at Fraunhofer ISE. The project is supported by the German Federal Ministry for the Environment and Reactor Safety.

Grid-Connected Renewable Power Generation

Construction of grid-connected systems is the largest global market of the photovoltaic branch today. Well-implemented market penetration programmes, particularly in Japan, Germany and some States of the USA, are ensuring high growth rates. To maintain this market growth, the costs for the systems technology - including inverters, installation and cabling systems - must be reduced continually. At the same time, expectations on the quality and lifetime of the components are increasing.

Inverters to feed photovoltaic electricity into the grid are already of high quality. Nevertheless, there is still considerable potential for improvement, which can be exploited with new circuit designs, digital controls technology, advances in power semiconductor components and passive components. To this purpose, we offer specialised know-how in the fields of circuit design and dimensioning, as well as configuring and implementing analog and digital controllers.



Quality assurance and operation monitoring of PV systems are playing increasingly important roles. Above all, project planners of large, commercial photovoltaic systems must meet expectations on investment returns, and be able to answer criticial questions from investors concerning the reliability of yield predictions, system planning and the quality of the components installed. Therefore, we are developing improved measurement procedures and more powerful simulation and information technology, which enable quality and yield assurance at all levels. We advise on system design, characterise solar modules and carry out technical assessment and performance tests of PV systems. Our yield predictions are regarded as a reference due to their high accuracy.

On the medium term, not only photovoltaic but also solar thermal power stations can make an important contribution to regenerative generation of electricity. In this field, we are conducting research on improved materials, optimising controls and carrying out system simulations.

Alternatively, optically concentrating photovoltaic systems can also reduce the price of solar electricity. Parallel to highest-efficiency solar cells, for instance, we are developing an inexpensive procedure to manufacture Fresnel lenses in concentrator modules and are testing complete modules in the field.

The liberalisation of the electricity markets and the entry of climate-protecting energy technology to the market means that the proportion of electricity generated by PV systems and other distributed generators such as combined heat and power plants is increasing rapidly. Many small generators and controllable loads will interact with each other and, in some cases, with the buildings in which they are integrated. This results in completely new demands on controls, operation management, communications and data management in electricity grids and buildings. We are working on control concepts, new simulation and management technology, and planning tools for these systems. Questions concerning costs, operating safety, supply reliability and voltage quality are major issues that are taken into account in doing so.

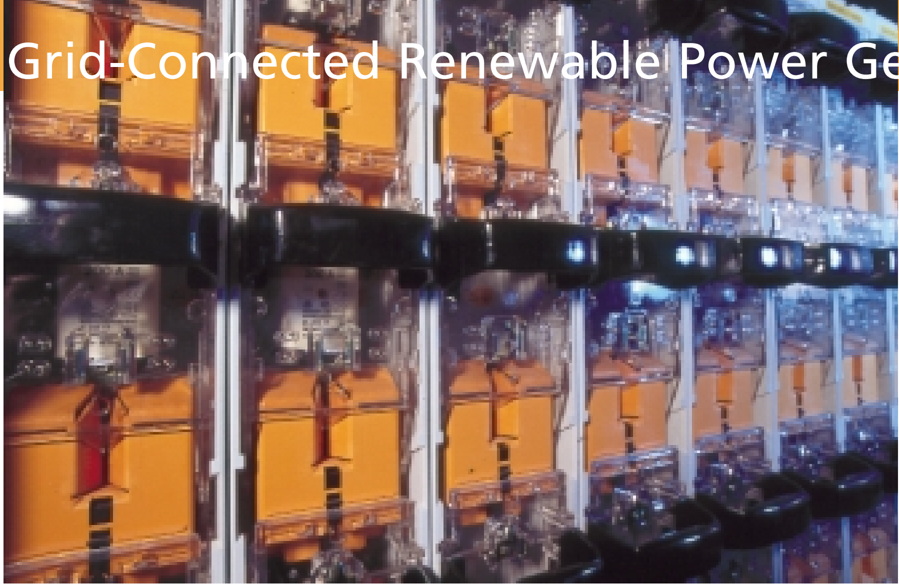
For the regenerative, grid-connected electricity generation sector, we support component manufacturers, system planners and operators, and energy utilities in the following areas:

- inverter development
- quality control and monitoring of components and systems
- investigation of concepts for distributed generation
- integration of heat and electricity generators, and storage units, into grids and buildings to optimise load flows and improve the supply reliability and voltage quality
- conception and technological development of photovoltaic and thermal power stations

The facilities we use for this work include:

- inverter laboratory
- highly accurate power measurement instruments for inverters and charge controllers
- precision instruments to characterise inductive and capacitive components
- measurement chamber for electromagnetic compatibility (EMC)
- burst and surge generators
- programmable solar simulators and electronic loads
- development environments for microcontrollers and digital signal processors (DSP)
- calibration laboratory for solar modules
- outdoor test field for solar components
- development environments for controls based on "embedded systems"
- laboratory to develop battery charging and operation strategies
- test facilities for batteries over a wide range of current, voltage and temperature values

Grid-Connected Renewable Power Generation



Increasingly often, electricity is generated in distributed power plants at the medium and low-voltage level, close to the consumer. This raises diverse questions for grid operators concerning quality and grid management. In the "Solarsiedlung Schlierberg", a solar estate in Freiburg, Fraunhofer ISE is investigating the effect of a high density of photovoltaic systems in a low-voltage grid. The photo shows the 400 V distributor field of the transformer station, where about 130 inverters feed in the electricity from approximately 330 kWp of photovoltaics. (See also article on p. 63.)

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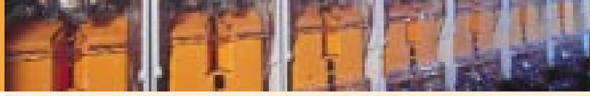


Higher Yields by Improved Dimensioning of Inverter Power

In the past, the dimensions chosen for inverters for photovoltaic systems were often too small. This meant that part of the yield was unnecessarily sacrificed. This is the result obtained with simulation calculations based on values measured every 10 seconds rather than one-hour averages. Instead of being up to 35 % higher, the solar generator power in well-dimensioned systems should be only 15 to 20 % higher than the inverter power. This recommendation by Fraunhofer ISE has been accepted by numerous inverter manufacturers.

Bruno Burger

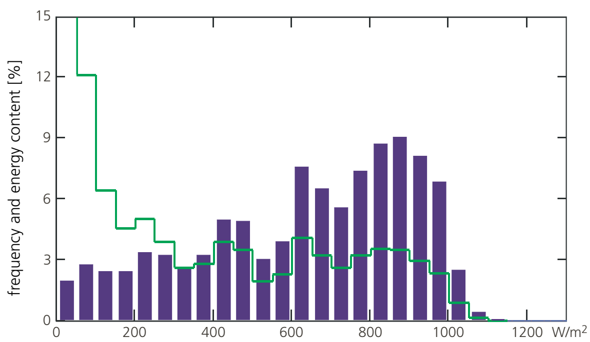


Fig. 1: Annual frequency distribution (green) and energy content of different radiation classes for calculations based on 8760 hourly average values.

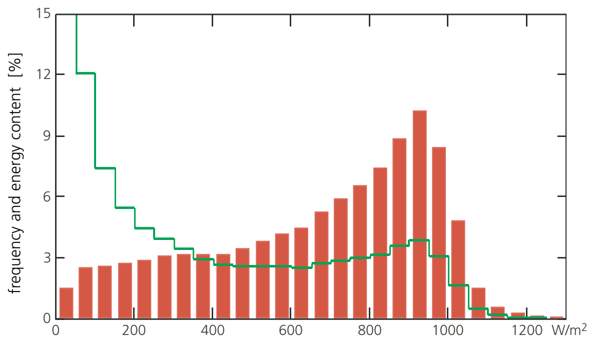
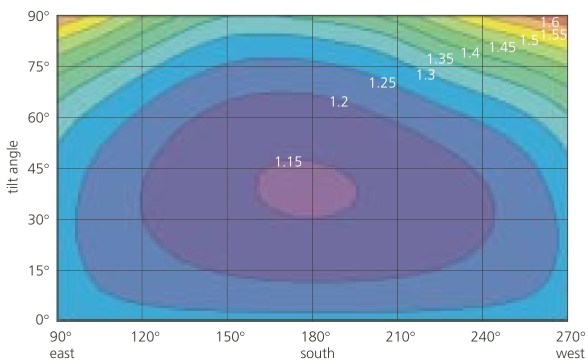


Fig. 2: If around 3.1 million "instantaneous" values are used for the simulation instead of the hourly averages, the frequency distribution (green) becomes quite different.



Up to now, the solar generator power was chosen to be 20 to 35 % higher than the inverter power, when photovoltaic systems were dimensioned. This made economic sense, firstly because a photovoltaic system supplies the peak power value for only a few hours each year, and secondly because inverters with a poor efficiency value in the lower power range thus operate more frequently in the higher power range with better efficiency. However, the disadvantage of this dimensioning ratio is that the inverter is overloaded earlier when the solar radiation intensity is high. Due to the internal power limits, energy is thus wasted.

Now that the characteristic efficiency curve for modern inverters has been improved and the module quality is better, we re-examined this dimensioning practice. In a series of simulations for one year, we used not only the usual 8760 hourly averages, but also around 3.1 million "instantaneous" values of the solar radiation measured at 10-second intervals. As presented in figures 1 and 2, the selected time base significantly changes the frequency distribution and the energy content of different radiation classes. Short-term radiation peaks are no longer averaged out when instantaneous values are used, and can thus be taken into account when the inverter is dimensioned.

This led to a clear correction in the recommended dimensions. Assuming that at most 0.5 % of the generated electricity should be lost due to the inverter's power limit, the solar generator should be overdimensioned by no more than 20 %, rather than up to 35 % as recommended previously (fig. 3). This applies to systems in Central Europe where the solar generator is oriented between 60° south-east and 60° south-west and the tilt angle is between 15° and 60°. Numerous inverter manufacturers have accepted this recommendation and integrated it into their dimensioning programs.

Fig. 3: According to the new dimensioning recommendation from Fraunhofer ISE, the ratio of solar generator to inverter power for well-orientated systems (dark blue and violet zones) should be only 1.15 to 1.2. By contrast, a ratio of 1.3 to 1.35 results if the calculations are based on hourly averages.

PoMS - an Energy Management System for Low-Voltage Grids with Distributed Generation

We are developing the energy management system, PoMS, to optimise the operation of low-voltage grids technically and economically. PoMS stands for "Power and Power Quality Management System" and is being tested in practice within the EU-funded DISPOWER project in four local grids in Germany, Italy and Spain. This will provide an important pre-requisite for the transition to distributed power supply.

Rainer Becker, **Thomas Erge**, Thomas Klose, Anselm Kröger-Vodde*, Hermann Laukamp, Hans-Georg Puls, Malte Thoma, Rico Werner, Christof Wittwer

* PSE Projektgesellschaft Solare Energiesysteme mbH, Freiburg

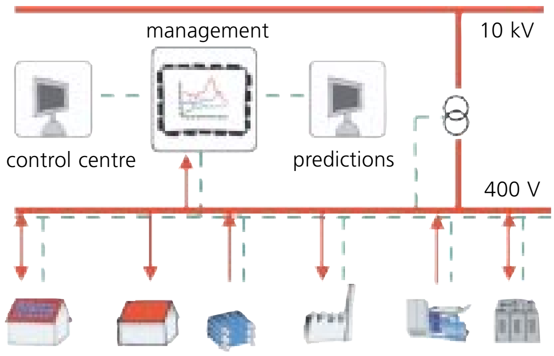


Fig. 1: Individual low-voltage grid segments (230/400 V) can be operated optimally according to technical or economic criteria with the help of PoMS. A central management system (PCU) controls grid components such as photovoltaic systems, fuel cells, CHP plants, batteries and controllable loads via an internal communication network.

A fundamental change in the power supply structure can be anticipated, driven by the liberalisation and harmonisation of the European electricity market and by the increasing application of distributed solar and wind energy systems, and combined heat and power (CHP) plants. In future, electricity will no longer be supplied exclusively from a few, large power stations, but will be generated increasingly in distributed power plants at the medium and low-voltage level, close to the consumer. This results in diverse quality and management problems for the grid operator, but also offers new opportunities. For example, distributed photovoltaic and CHP systems can improve the supply reliability and the grid quality. With appropriate tariff models, locally generated electricity can be economically attractive not only for the system operator but also for the grid operator. However, to exploit these opportunities, we need an intelligent, distributed energy management system that is tailored to low-voltage grids and which allows the grid operation to be optimised according to technical and economic goals.

Together with our project partners, we are currently developing such a "Power and Power Quality Management System", PoMS. Subsequent to laboratory tests, from the end of 2004 PoMS will be introduced into test grids of various utilities including MVV Energie in Mannheim and the Stadtwerke Karlsruhe. This will allow us to investigate in practice how distributed low-voltage grids, with a high proportion of fluctuating generators such as photovoltaic arrays, can be operated optimally according to technical and economic criteria. The optimisation criteria will be defined in each case by the utility responsible. For example, in the demonstration systems in Mannheim and Karlsruhe, the grid, auxiliary generators and

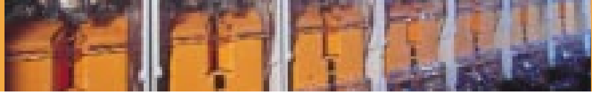


Fig. 2: The dialogue between the central energy management system and the components is maintained via the "PoMS Interface Boxes" developed at Fraunhofer ISE. They interpret commands from the central management unit and produce generation predictions for certain component types, such as photovoltaic systems.

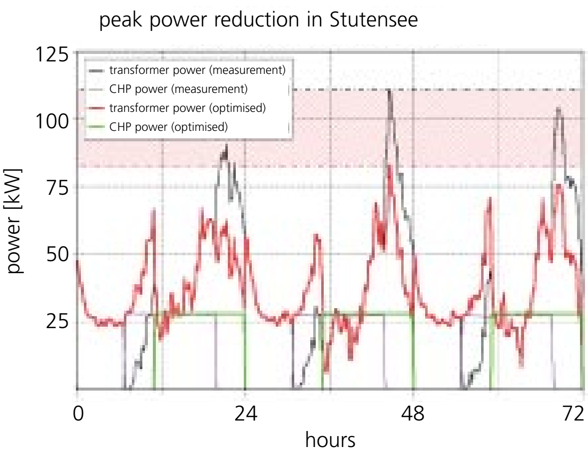


Fig. 3: Taking three days as an example, the graph shows how shifting the operating times of a CHP plant (green instead of purple curve) can reduce the peak load at the medium-voltage transformer for the settlement (black line) by 30 kW (red line). Consumption of expensive peak-load electricity can thus be reduced by optimising the operation management with PoMS.

loads are to be adapted to the operation of photovoltaic systems and larger battery banks. To this purpose, we developed suitable load and generation prediction procedures, which enable the PoMS to control the grid components optimally with flexible operating schedules. Local electricity tariffs and the parameters describing the state of each component will also be taken into account.

The technical structure of the PoMS consists of a central control unit PCU (PoMS Central Unit) and component-specific, decentrally installed, intelligent communication units, so-called PoMS Interface Boxes (PIB, fig. 2). The PCU and the PIB's are connected via their own communication network. The flexibly programmable PIB's, which we developed with the help of integrated micro-controllers (embedded systems), offer universal and innovative possibilities to control distributed generators, storage units and loads. They provide the energy management system not only with a uniform communication interface but also standardised parameters. Thus, these boxes are also suitable for intelligent communications and operation management in other applications. Implemented in a "lean" hardware design, we thus offer favourably priced system solutions for controlling components to users in the energy sector.

The work was supported by the EU within the DISPOWER project.

Guaranteed Yields from Large Solar Power Plants

As the dimensions of photovoltaic systems increase, quality assurance plays an increasingly important role, as each sacrificed percentage point of yield directly affects the returns from the projects, which are often calculated with only a small margin for error. Thus, we have developed a package of procedures for investors and system operators, which can be used to assure the quality of planning, components, construction and operation.

Thomas Erge, Wolfgang Heydenreich, **Klaus Kiefer**, Hermann Laukamp, Frank Neuberger, Christian Reise, Christof Wittwer

The increase in system dimensions and the entry of financially strong investment societies into the photovoltaic market has raised expectations on the quality assurance of photovoltaic power plants. Based on our experience with long-term monitoring programmes, we developed a package of quality assurance measures, which allow planners and system operators to meet these expectations. The measures range from professional yield prediction to monitoring of system operation.

The yield is generally predicted with quite accurate simulation models, which can calculate the yield with a total uncertainty of ± 4 %. The main source of the remaining uncertainty is the accuracy of the solar radiation values and the calculation for sloped areas. One cause of reduced yields which can be avoided is presented by ignored shading sources. Shading sources such as transmission masts are often not noticed or considered to be irrelevant, not only for roof-installed systems, but also for systems mounted on the ground. Similarly, mutual shading by rows of modules is often underestimated, above all in tracking systems. Thus, our yield prediction calculations are based on models which can simulate shading very accurately. This allows us to achieve greater certainty in yield prediction.

Fig. 1: More than 57,000 solar modules were installed on single-axis trackers in the 10 MW Solarpark Bavaria. The American project company, PowerLight Corp., commissioned Fraunhofer ISE with all stages of quality assurance, from yield prediction to monitoring.

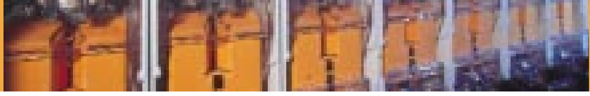


Fig. 2: The new 90 kW solar power plant on the northern tribune of the badenova Stadium in Freiburg is the first system of the 1 MW "Regiosonne" project. Here also, Fraunhofer ISE is responsible for all aspects of quality management.

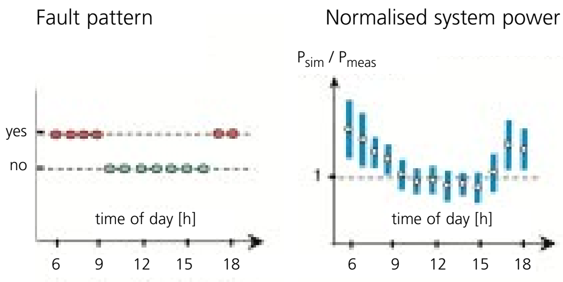


Fig. 3: The monitoring program developed at Fraunhofer ISE continually checks whether the measured power (P_{meas}) from a photovoltaic system agrees with the simulated values (P_{sim}). The ratio P_{sim}/P_{meas} should be equal to 1. If deviations are greater than the measurement error (blue bar) - as shown in the example here before 9 a.m. and after 5 p.m. - the program compares the deviations with a series of fault patterns. In this example, the deviation corresponds to that due to shading in the early morning and late afternoon.

The yield predictions are based on the specifications provided by the manufacturers of solar modules. In various test series in our calibration laboratory, we determined that the module power is usually within the guaranteed tolerance band. However, it was well below the rated value specified by the manufacturer for more than half of the tested modules. Therefore, we offer statistically representative tests of solar modules in our calibration laboratory as a service to investors and operators. This ensures that on average, the supplied modules will actually supply the power which was used to calculate the returns. After all, over an operating period of 20 years, 1 % less module power from a 1 MW system already means a loss of around € 100,000.

For quality assurance of the whole construction process, we make an authorisation inspection of the solar power plant. In doing so, we check the construction of the system according to professional and regulatory standards and also inspect the characteristic IV curves for the individual strings. This allows connection errors, faulty modules and unacceptable power deviations between the individual strings to be identified.

Finally, to ensure that the system supplies the guaranteed yields over the planned period of 20 years, operation monitoring is needed, which can detect a system fault soon after it occurs. To this purpose, we developed a monitoring procedure which not only detects a deviation of the system yield from the predicted values within 24 hours but also recognises the cause, such as inverter problems or shading. This procedure is currently being further optimised, so that deviations can be detected in real time with the help of embedded systems, and a message sent to the operator via an Internet connection.

Geometrical Optimisation of Solar-Thermal Fresnel Collectors

Fresnel collectors have the potential to reduce the cost of electricity from solar-thermal power plants. The geometrical properties of solar-thermal Fresnel collectors can be varied over a wide range. All variations affect both the collector costs and the electricity yield. We developed a simulation procedure which allows cost-optimised dimensioning of the collector and thus minimisation of the electricity generation costs.

Hansjörg Lerchenmüller,
Max Mertins*, Gabriel Morin,
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Fig. 1: Visualisation of a solar-thermal Fresnel collector array. The facetted reflector field can be seen in the horizontal plane. The reflectors track the sun individually, so that the solar radiation is concentrated onto the linear absorber tube above.

The Fresnel collector is a promising concept to reduce the electricity generation costs of solar-thermal power plants. We analysed technical and economic aspects of this collector type within a feasibility study on line-focussing Fresnel collectors. In comparison to parabolic troughs, Fresnel collectors have a lower optical efficiency relative to the reflector area. Nevertheless, lower electricity generation costs are expected due to the simpler construction and the plausible assumption of lower collector costs. This applies in particular when the potential for optimising the collector geometry is fully exploited.

We carried out detailed system simulations to determine the electricity yield of Fresnel power plants as a function of the optical properties of the collectors. Numerous geometrical parameters, such as the absorber height and the number, size and spacing of the primary reflectors, influence the optical losses due to mutual reflector shading (fig. 2). The obstruction of reflected sunlight by neighbouring reflectors and the proportion of solar radiation which does not reach the absorber are also determined by geometrical parameters. We calculated the optical performance of a collector using whole-year simulations based on hourly meteorological data. To determine the cost differences between various collector designs, cost factors were allocated to the geometrical parameters. Based on these cost factors and the whole-year simulation, we developed a procedure to optimise the collector with reference to the electricity production costs. Compared to conventional collector design for a single operating point, cost advantages of up to 15 % can be achieved with our procedure.

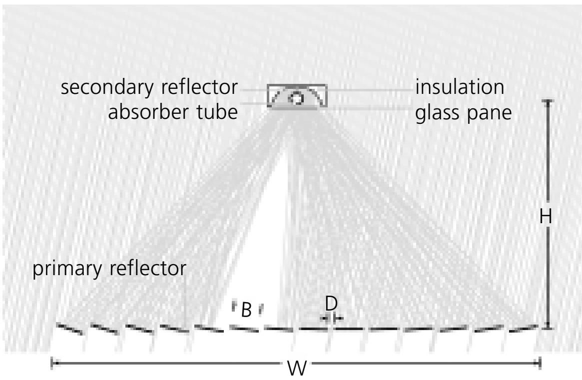
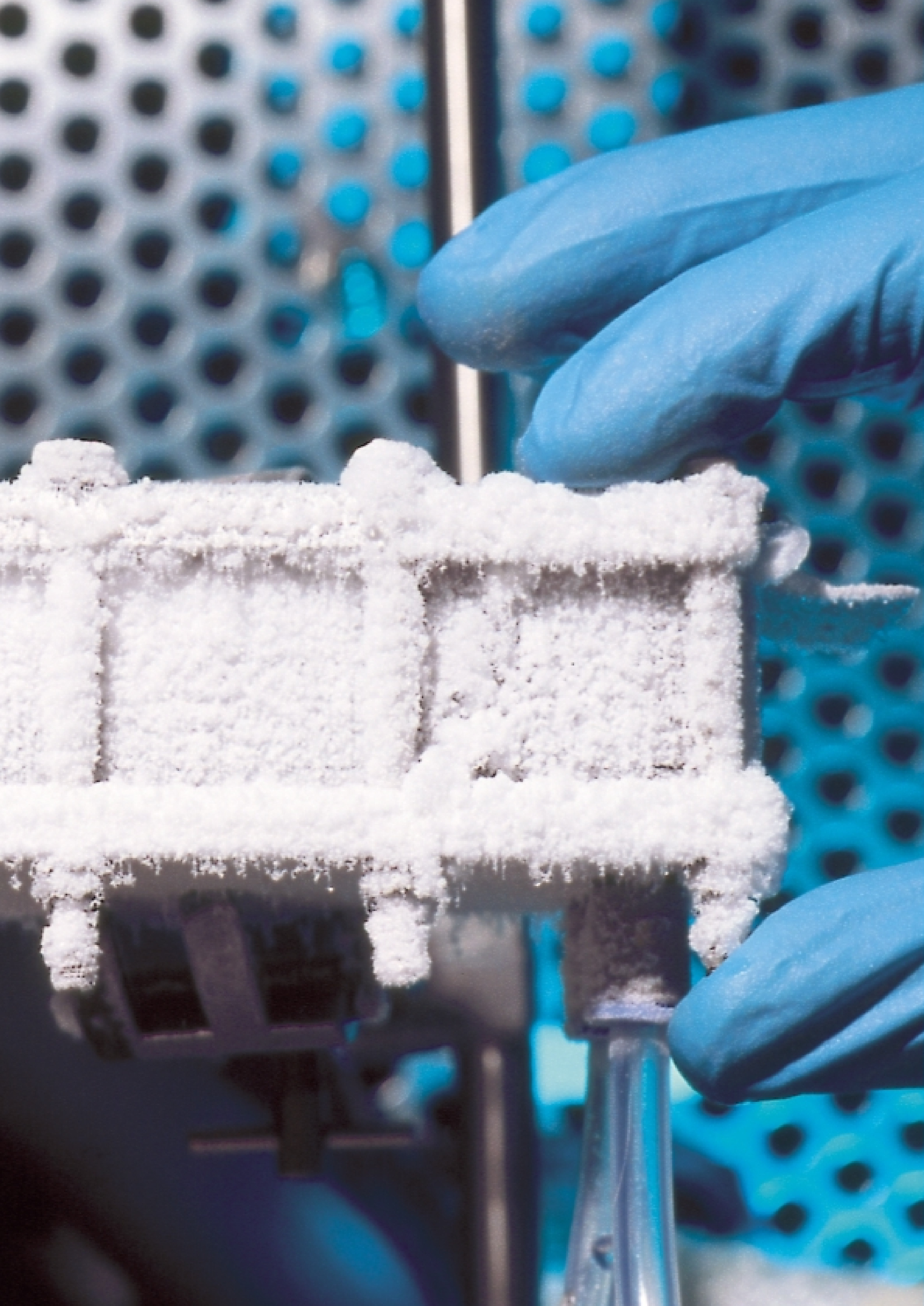


Fig. 2: Sketch of the operating principle of a solar-thermal Fresnel collector. By varying the collector width W, the reflector spacing D, the reflector width B and the height H of the absorber tube above the primary reflector field, the collector geometry can be optimised such that the electricity generation costs, as simulated for the whole year, are minimised.



Hydrogen Technology

Hydrogen releases usable energy in the form of electricity and heat when it reacts with oxygen in a fuel cell. As hydrogen is not found in its pure form in nature, it must be obtained from its diverse chemical compounds. This is achieved by applying energy – ideally renewable energy – e.g. in electrolysis with renewably generated electricity or by reforming gaseous or liquid fuels.

Although hydrogen is not a source of energy, as a universal fuel it will be an important component in the sustainable energy economy of the future. By using hydrogen, fluctuating forms of renewable energy will be processed such that all desired energy services can be provided with the accustomed reliability. Scientists and technologists are working intensively on realising this vision. The application potential of hydrogen is enormous: In distributed power supplies, fuel cells can supply heat and electricity from natural gas with a total efficiency value of up to 80 %. Fuel cells, combined with electric motors, serve in mobile applications as non-polluting engines for cars, trucks and buses. In addition, fuel cells in auxiliary power units (APU) provide electricity aboard ships. Finally, miniature fuel cells are excellent alternatives or complements to primary and secondary batteries in off-grid power supplies or electronic appliances, due to the high energy density of the fuels.

Innovative technology to obtain hydrogen and efficiently convert it to electricity and heat forms the core of our research for the hydrogen market sector. Together with our partners from science and industry, we develop components and complete hydrogen systems for an inexpensive and environmentally friendly energy economy.

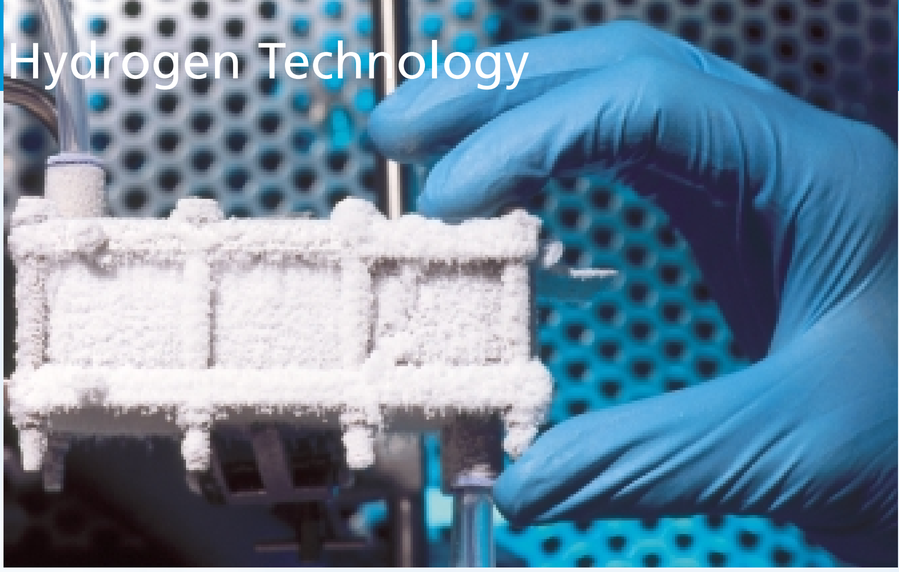
We develop reformer systems to convert liquid fuels to gas. The systems consist of the actual reforming reactor and, depending on the type of fuel cell to follow it, gas treatment to raise the hydrogen yield and reduce the concentration of carbon monoxide in the product gas. Such systems can be used in applications ranging from stationary combined heat and power plants, through marine power supplies, to portable power supplies.

To obtain hydrogen from water, we construct controlled membrane electrolysers supplying power from a few watts up to 2 kW. To gain deeper understanding of the processes occurring at the electrodes, we apply different characterisation methods, including scanning electron microscopy or cyclovoltammetry.

The membrane fuel cell, operating with hydrogen or methanol, is our favoured energy converter in power range from mW to approximately 300 W, being efficient, environmentally friendly, quiet and requiring little maintenance.

In addition to developing components and systems, we also work on the integration of fuel-cell systems into higher-order systems. We design and implement the electric infrastructure, including power conditioning and safety technology. In this way, we create the basis for a commercially viable hydrogen economy. Our offer encompasses decentralised fuel-cell CHP plants producing both heat and electricity, fuel-cell systems for power supply aboard trucks, ships or aeroplanes, stand-alone power supplies for off-grid applications, and miniature systems as portable power supplies.

Hydrogen Technology



Extending the operating temperature range of miniature fuel cells to outdoor temperatures below freezing and summer values of 40 °C presents a new challenge. The illustration shows a fuel-cell stack during a low-temperature test. The stack is to be integrated into a weather-resistant, near-production fuel-cell system for the temperature range from -20 °C to +40 °C. One possible application area is measurement and controls technology. The trend towards decentralised, off-grid power supplies for system components such as sensors and actuators offers the advantages of greater flexibility and the potential to reduce costs. (See also article on p. 74.)

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Characterisation of Fuel Cells

We characterise polymer-electrolyte membrane (PEM) fuel cells with spatially resolved measurement methods. This involves measuring the current distribution and the temperature over segmented test fuel cells. Further, we visualise the water production in the gas distribution channels. As part of our development of mathematical models, we succeeded in calculating the distribution of liquid water under dynamic operating conditions in the fuel cell.

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Spatially resolved measurement

To analyse the operating behaviour of fuel cells, we measure the spatial distribution of local current production and the temperature in test cells. This provides information on the coupling between the water and heat budgets in low-temperature fuel cells. We investigate the effect of different materials for the fuel-cell components on the operating performance. In addition, the measurement results serve to validate a spatially resolved mathematical model.

We succeeded in determining the temperature distribution, the current distribution and the water production in a test fuel cell. We were able to measure the electric impedance simultaneously on the segments of a test fuel cell.

By applying the measurement procedure, we discover which operating conditions of the test cell lead to the formation of liquid water and how water production affects the cell performance. Critical operating states of the test cell can be analysed with respect to heat generation and water production. From the spatially resolved impedance measurements in situ, we extract the protonic conductivity of the membrane as a measure for its local humidification.

We develop test fuel cells for our clients and design measurement facilities for spatially resolved characterisation. As a service, we measure and analyse the operating behaviour of fuel cells and fuel cell stacks. Furthermore, we validate spatially resolved fuel cell models.

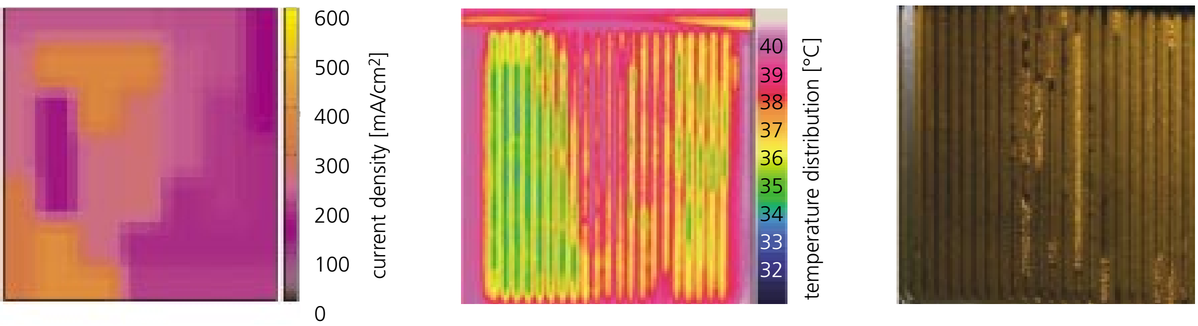


Fig. 1: Simultaneous measurement of the current density (left) and the temperature distribution (centre) of a fuel cell with meander-formed gas channels (right). The formation of water in the gas channels on the right-hand side can be seen. The condensation heat of the water has a significant effect on the temperature distribution in the test cell.

Dynamic two-phase simulation of fuel cells

We model the time-dependent behaviour of PEM fuel cells. With our mathematical models, we calculate the effect of water production and transport on the dynamic behaviour of the fuel cell. To do so, we calculate its electric and thermal properties.

Our work has two objectives: On the one hand, we develop efficient, simplified fuel-cell models for system simulation. On the other hand, we are working on a spatially resolved dynamic flow model for detailed analysis and design of fuel cells. For example, we have developed a one-dimensional dynamic fuel-cell model, which takes account of water transport in the liquid and gas phases in the porous layers of a PEM fuel cell. Figure 2 shows the time-dependent variation of current and voltage calculated with the model. The calculation was made with a time-dependent boundary condition for the electric potential at the cathode. The non-stationary current-voltage curve shows a hysteresis which was confirmed by measurements. Beyond this, the model provided the spatial and temporal distribution of liquid water in the membrane-electrode assembly (fig. 3). The model forms the basis for system simulations, in which the formation and transport of liquid water in the PEM fuel cell is taken into account.

For our clients, we develop mathematical models, for example for the Matlab and Femlab simulation environments, which are well established in the market. We carry out stationary and time-dependent simulation calculations for PEM fuel cells and offer dynamic system simulations with simplified models of the fuel cell. Flow simulations under stationary conditions in fuel cells are also included among our services. Also, we characterise the operating conditions of fuel cells by a combination of measurement and simulation.

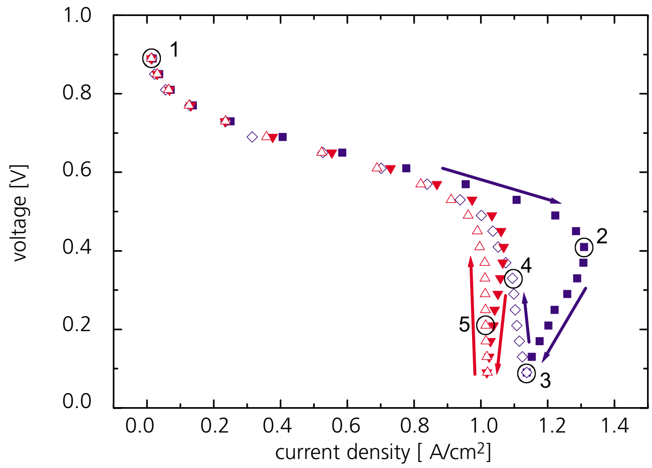


Fig. 2: Time-dependent simulation of current and voltage of a PEM fuel cell. A variable voltage (4.5 mV s^{-1}) was applied to the fuel cell. The cycle duration is 400 s. Points 1, 2 and 3 are on the forward half of the characteristic curve, point 4 is on the return half of the first cycle (blue). Point 5 is on the characteristic curve of the second cycle (red). The liquid water causes a hysteresis effect.

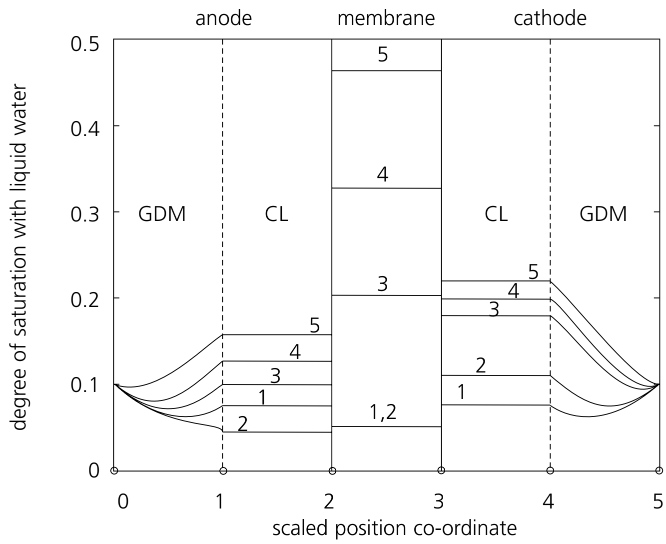
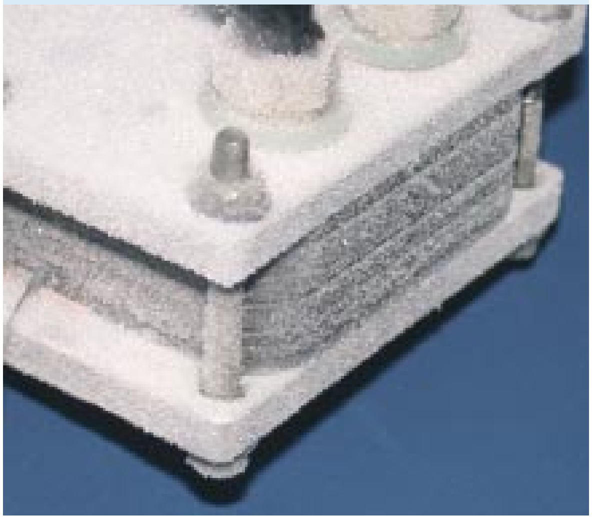


Fig. 3: Spatially and temporally resolved saturation with liquid water. The saturation degree describes the relative proportion of the pore space which is filled with water. The curves labelled 1 to 5 correspond to the operating points marked in Fig. 2 by circles. Comparison between the operating points 1 and 5 shows that the degree of saturation with liquid water has increased. (CL: catalyst layer, GDM: gas diffusion medium).

Miniature Fuel-Cell System for a Wide Temperature Range

In measurement and control technology, we can observe a trend toward distributed power supply for system components. Sensors and actuators which are independent of the grid offer flexibility and the potential to reduce costs. For this application area, we are approaching the series prototype of a weather-resistant fuel cell system for the temperature range from -20 °C to +40 °C. Our work is concentrating on investigating heating and cooling strategies, and analysing the cold-start procedure of portable fuel-cell systems in detail.

Dietmar Geckeler, Jan Hesselmann, Michael Junghardt, Michael Oszcipok, Dirk Riemann, Maik Wodrich, **Mario Zedda**



Controlling the water and heat budget of our fuel-cell systems ensures a stable and reliable power supply for electric loads. New challenges arise when the operating temperature range is extended for outdoor operation to below freezing point or to summer temperatures of 40 °C. At low temperatures, the produced water freezes in the fuel cell, whereas the membrane-electrode assembly dries out at high temperatures. In both cases, fuel-cell operation was not possible up to now. Extreme operating conditions can be imitated with the help of a fully automated fuel-cell test stand with an integrated climatic chamber (fig. 1).

With our fuel-cell stacks, a purely passive cold start, i.e. without auxiliary energy input, is already possible at -20 °C. To accelerate the cold start, we are working on a novel heating concept, which does not require additional system components. This allows us to adapt the efficiency and duration of the cold start to the application demands.

Fig. 1: A fuel-cell stack at -20 °C in the climatic chamber. If a defined load is applied under these conditions, it reaches a temperature of 0 °C within 15 minutes without any external heating. Despite the outer temperature of -20 °C, the stack temperature at the operating point is 50 °C.

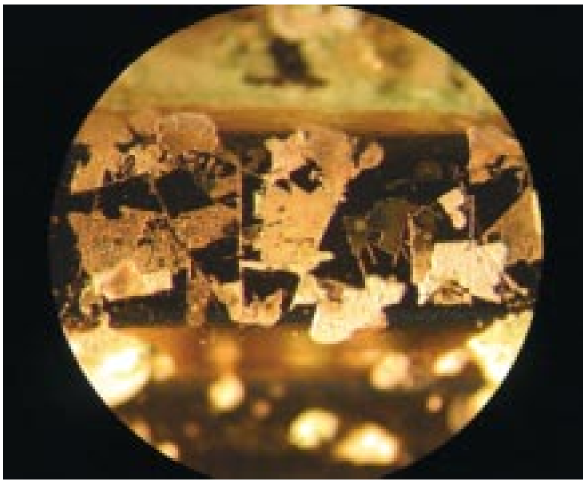


Fig. 2: Microscope image of corrosion on a metallic bipolar plate. The plates, which are only 0.1 mm thick, enable the fuel-cell stack to be heated quickly and reduce the total mass. Development of corrosion-resistant materials is still in progress.

We have successfully tested the operation of our fuel-cell system at +40 °C in the climatic chamber. A membrane humidifier that we developed uses the water produced at the cathode to humidify the hydrogen on the anode side. At the same time, we limit the temperature of the cell stack by electronically controlled fan cooling. Our innovative housing concept passively supports the system heating or cooling by its cleverly designed direction of the cold and hot air currents.

To avoid ice formation and dehydration, we manage the water budget of our fuel cells both by controlling the peripheral system components and by optimising the materials properties of the fuel-cell components. Extremely thin metallic bipolar plates, with their low heat capacity and good thermal conductivity, allow us to heat up the cell stack rapidly. Equally, the heat can be removed efficiently via the bipolar plates at high outdoor temperatures. As metallic bipolar plates can corrode in a fuel-cell stack (fig. 2), we are testing various substrate and coating materials.

Our cold-start strategies for fuel-cell systems are based on results of fundamental research on the behaviour of single-cell fuel cells under isothermal conditions. From statistically based, empirical models and experimental investigations applying impedance spectroscopy, we know which processes occur within a cell, where water is produced, in which layers ice is formed and how degradation effects can be counteracted.

We have succeeded in identifying the operating parameters which are decisive for optimising cold starts. We have transferred this knowledge to our portable fuel-cell systems to optimise their starting behaviour. Thermal models describe the dynamic heating behaviour of fuel-cell stacks and serve as a basis to analyse the efficiency of different start-up strategies.

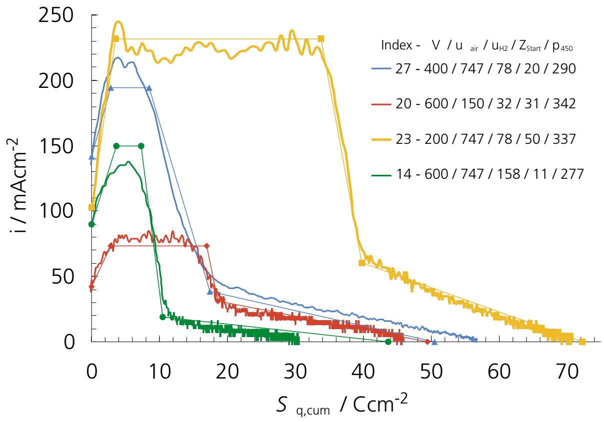


Fig. 3: Drop in the current density i during an isothermal cold start, plotted versus the accumulated charge $S_{q,cum}$. Statistical regression models describe the processes in single-cell fuel cells during a cold start at -10 °C. This gives us information on the operating parameters which are decisive for low-temperature starts, allowing us to develop optimal start-up strategies.

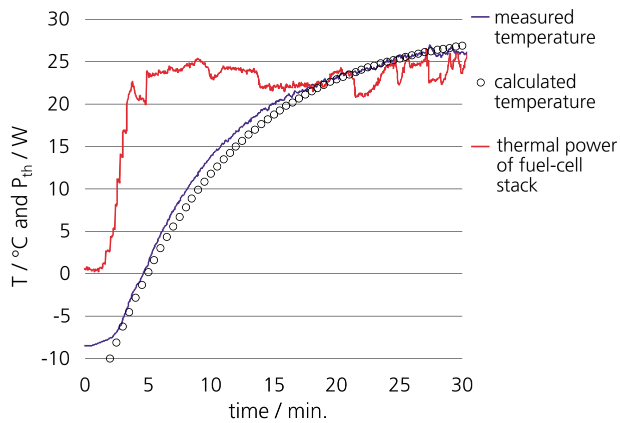


Fig. 4: Experimental results and thermal simulation of the cold start of a six-cell fuel-cell stack (15 W) in a climatic chamber at -10 °C. After four minutes, the stack temperature reached 0 °C, with an average release of 22 W heating power during operation.

Optimisation of Membrane-Electrode Assemblies for Electrolysis

The goal in developing membrane-electrode assemblies for water electrolysis is to achieve high efficiency values at low cost. A wide spectrum of characterisation methods allows us to improve the electrodes by modifying the manufacturing process appropriately. In doing so, we apply the statistical experimental design approach.

José Roberto Flores Hernandez, Stefan Klinke, Susanne Lehmberg, **Ursula Wittstadt**

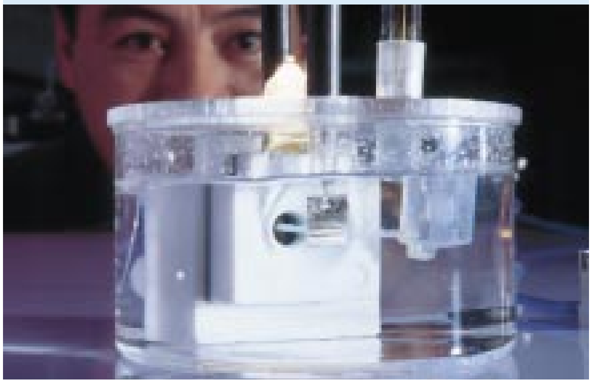


Fig. 1: Electrochemical half-cell for cyclovoltammetric measurements. We use these to determine the active area of the electrodes that have been deposited on the membrane. A silver/silver chloride electrode is used as the reference.

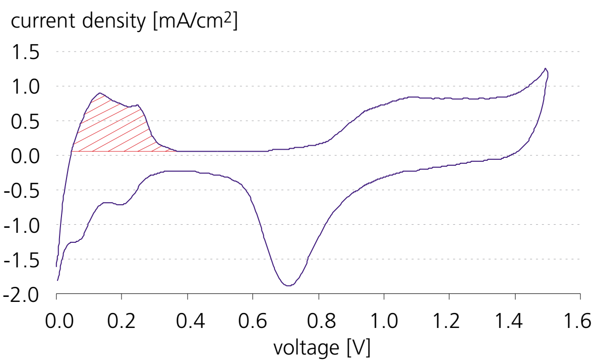


Fig. 2: Cyclovoltammogram of the platinum cathode of a membrane-electrode assembly. The catalytically active area of the platinum can be calculated from the shaded area on the graph.

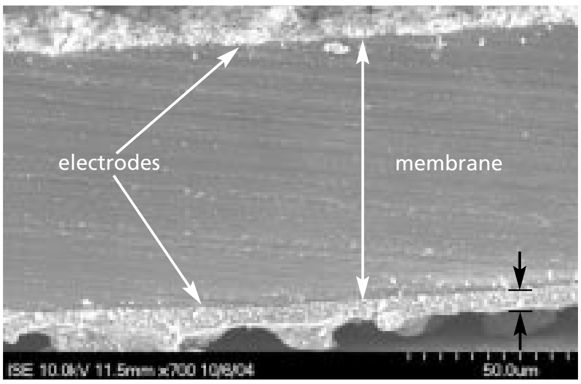


Fig. 3: Scanning electron micrograph: Cross-section through a membrane-electrode assembly. At the top, the cathode side with platinum as the catalyst can be seen; at the bottom is the iridium-coated anode. We use such images to determine the coating thickness of the electrodes.

We are developing membrane-electrode assemblies (MEA's) for water electrolysis, following the goal of improving the operating performance while reducing material consumption and costs. As part of this work, we coat proton-conducting membranes with catalysts such as platinum or iridium. An extensive range of characterisation methods is available to us for further development of the coating procedures.

During electrolysis, we characterise the MEA's in a laboratory cell that was specially developed for this purpose. Its temperature can be controlled over a wide range (5 - 100 °C). During a measurement, we record not only the characteristic current and voltage values, but also determine the amount of gas produced and its purity in real-time analysis. In combination with the current density, we thus determine the efficiency value for hydrogen generation. Using impedance spectroscopy, we are able to investigate different factors separately (e.g. mass transport or kinetic barriers) which affect the performance characteristics.

Ex situ analysis methods provide further information on MEA behaviour. When the coating procedure is varied, the electrode structure is investigated using scanning electron microscopy (SEM). We use cyclovoltammetry to characterise the active catalyst area of the electrodes that have been deposited on the membranes in electrochemical half cells.

Using these methods and the statistical experimental design approach, we are able to investigate the suitability of new catalysts and modified manufacturing procedures, quickly and simply.

Technical lifetime measurements in real electrolysis cells complement the detailed investigations and provide us with further information on the practical applicability of MEA's.

New Process to Vaporise Diesel

As diesel cannot be vaporised without formation of crusts and other residues, it must be injected as a liquid into reforming reactors via jets, which makes it very difficult to create a homogeneous mixture.

Together with a Swiss engineering consultant, we developed and investigated a new process, which allows diesel to be completely vaporised, without formation of residues. This procedure offers great advantages in reforming diesel.

Thomas Aicher

Fig. 1: New vaporiser in operation: "gaseous" diesel is visible as the white "clouds" leaving the opened outlet.

Partial oxidation is the favoured reforming process for many auxiliary power units (APU) based on fuel cells, because then water does not need to be provided aboard the vehicle, either by transporting it in tanks or recovering it in complicated processes from the product gas of the fuel cell. However, partial oxidation is a reforming process which easily creates soot, particularly if the fuel is a higher-C hydrocarbon and is not sufficiently well mixed with the reactant, air, when it enters the reactor. This is especially critical for diesel, because in contrast to other liquid hydrocarbons, it forms residues on vaporisation. Thus, up to now diesel had to be sprayed in liquid form with the help of injection jets into the reaction chamber of a reformer. This means that formation of a homogeneous mixture over a large load range becomes very uncertain.

It is exactly at this point that a novel process, which we developed and investigated in 2004 in co-operation with a Swiss engineering consultant, offers new possibilities. This patented process transforms diesel into the gas phase without creating soot or residues. In it, the diesel flows along the base of a slightly tilted cylinder, and is vaporised from above by the thermal radiation from a hot catalyst grid. The grid is heated up by combustion of a small quantity of diesel with an extremely small amount of air on the grid surface.

In the measurements, we varied the operating parameters, air and diesel flow rates, and thus investigated their effect on the catalyst temperature and the composition of the product gas. Typical results are shown in fig. 2. The volatile hydrocarbons, methane, ethene and propene, are cracking products which form during partial oxidation of diesel in the vaporiser, because some of the longer hydrocarbon chains which make up diesel are cracked.

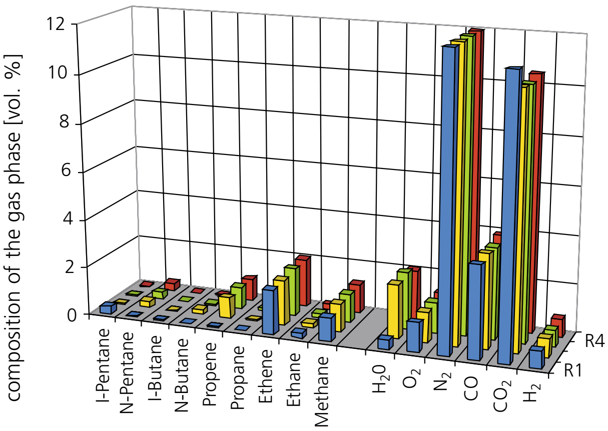
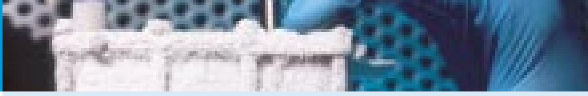


Fig. 2: Composition of the vaporiser product gas, determined experimentally by gas chromatography. The higher-C hydrocarbons (above hexane), which are also present in the product gas, were not analysed. The concentration bars for nitrogen have been truncated at 12 %; the correct values are around 74 vol. %.



Integration of a Natural-Gas Steam Reformer into a Fuel-Cell Combined Heat and Power Plant

In March 2004, a natural-gas steam reformer that had been developed at Fraunhofer ISE was successfully integrated into a fully automatically controlled, fuel-cell combined heat and power plant (FC CHP). An inverter converts the DC electricity generated by the polymer-electrolyte membrane fuel cell (PEMFC) into AC electricity and feeds it into the household circuit. The heat generated by the reformer and fuel cell is removed via a cooling-water network. Since then, the FC CHP plant has been subjected to a series of operating tests concerning load variation and its overall performance.

Thomas Aicher, **Robert Szolak**

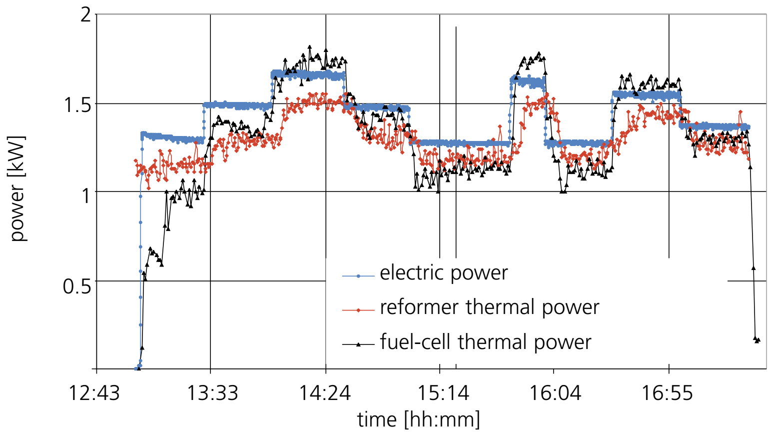
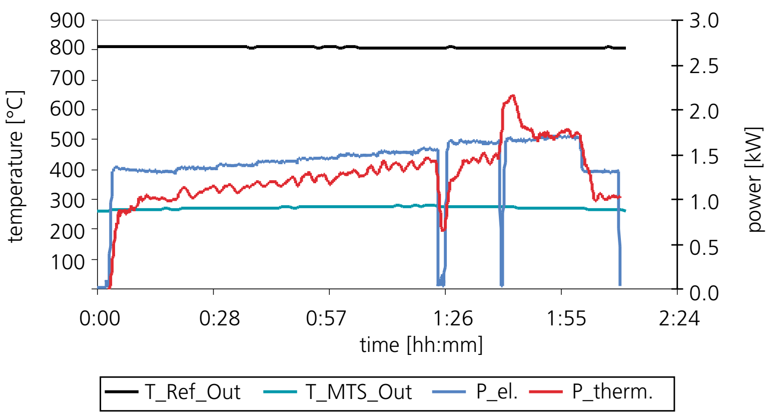


Fig. 1: The hydrogen power in the natural-gas steam reformer was varied between 21.5 Nl/min and 28.4 Nl/min. The electric power in the system follows without a time delay. The maximum measured electric power amounts to 1.7 kW_{el} for 28.4 Nl/min hydrogen. The thermal power gained from the reformer and the fuel cell amounts to 3.3 kW.



The fuel-cell combined heat and power plant (FC CHP) developed by Fraunhofer ISE and the Zentrum für Sonnenenergie und Wasserstofftechnik (ZSW) is being tested in a laboratory of the Institut für Werkstoffe der Elektrotechnik (IWE) at the University of Karlsruhe. It is fully automatically controlled by a Siemens SPS unit (programmable controller). The ProTool program allows all process-relevant quantities to be observed and modified, so the operation management can be varied, for example concerning the reforming temperature or the molar ratio of water vapour to carbon. If the values of certain parameters fluctuate beyond predefined limits - too little processing water, pressure too high - the system is brought fully automatically into a safe operating state.

The hydrogen flow rate for the reformer developed by Fraunhofer ISE can be adjusted continuously between 21.5 and 33 Nl/min. The carbon monoxide content is reduced in a gas purification step to less than 0.3 vol % (relative to the dry gas flow). To achieve this, we have developed a system in which the hydrogen-rich product gas is enriched with water before the gas purification step. Our experiments showed that the carbon monoxide concentration was reduced by a factor of 10. The heat generated during gas purification is removed by an air cooler. The water needed for the process is evaporated and superheated with integrated heat exchangers. Simultaneously, the exhaust gas from the burner and the hydrogen-rich product gas is cooled. The gas composition measured after the reformer and after the gas purification corresponds to thermodynamic equilibrium. The natural-gas steam reformer burns not only the introduced natural gas but also hydrogen from the fuel-cell anode which has not reacted (plus the remaining methane and traces of carbon monoxide). This significantly improves the total efficiency value of the system.

Fig. 2: Variation with time of the measured temperatures (reforming reactor outlet and shifting stage outlet) and the produced electric and thermal power. The load was changed stepwise every ten minutes. Again, no delay in the electric power is evident. The reformer reacts very quickly to load variation and provides the hydrogen in adequate gas quality (CO content < 0.3 vol %). The FC CHP plant displays good dynamic performance. (The electric power was interrupted twice during the presented time interval due to short disturbances to the inverter operation.)

Hydrogen Production from Diesel for Marine Electricity Generation

We operated a diesel reformer, which produces synthesis gas for a high-temperature fuel cell, for more than 500 hours. The system was developed and taken into operation last year. With the long-term experiment, we tested the ageing performance of two catalysts. Measurements of the product gas composition from the reformer indicated that the catalyst degradation was negligible. Also, the formation of soot and higher hydrocarbons was reliably suppressed by choosing appropriate operating parameters.

Thomas Aicher, Christian Siegel

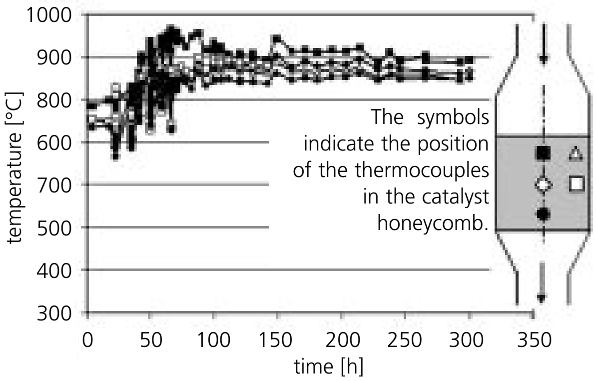


Fig. 1: Measured temperature profile in the reactor for one catalyst. The sketch at the right shows the various positions in the reforming reactor where the temperature was measured. During the first 100 hours, the operating parameters were varied to optimise the process. This explains the strong scatter of the temperatures at the beginning of the long-term experiment.

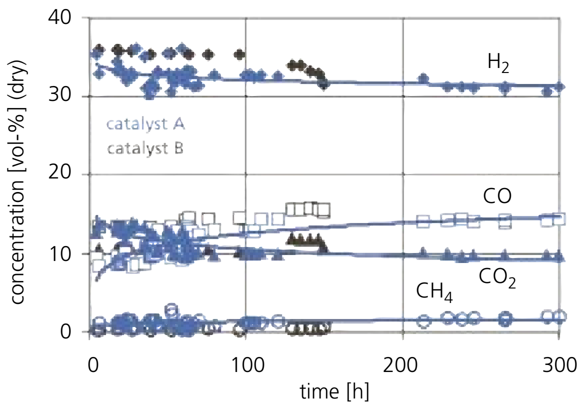


Fig. 2: Measured gas composition at the reactor outlet (dry) for two different catalysts in the long-term experiment. Measured values for hydrogen, carbon monoxide, carbon dioxide and methane are shown.

Reformer / fuel-cell systems offer several advantages compared to conventional combustion-motor / generator systems as auxiliary power units (APU) for generating electricity aboard ships. Above all, low emissions and a low noise level represent significant benefits, particularly when the ship is in harbour. Another important advantage of APU's based on fuel cells is the higher electric efficiency value. The actual ship engine is run on diesel, so this fuel is also used for the APU. As diesel cannot be converted directly in fuel cell, it must first be transformed into a hydrogen-rich gas mixture in a reformer.

In co-operation with the Italian company, Ansaldo Fuel Cell SpA (AF-Co) in Genova, we at Fraunhofer ISE developed such a reformer system to convert diesel into a synthesis gas by autothermal reforming. This pilot system has a power of 100 kW with respect to the lower heating value of diesel. The produced synthesis gas, a mixture of hydrogen and carbon monoxide, can be converted to electricity in a molten-carbonate fuel cell (MCFC).

After successfully taking the reformer pilot plant into operation, we investigated the ageing of two different commercial catalysts in long-term experiments. First, the safety features of the system had to be extended, so that it could be operated unattended. During continuous operation, we monitored the temperature profile within the catalyst honeycomb and the change of the product gas composition with time. The results are shown in figures 1 and 2. We determined that no significant degradation had occurred over periods of 150 - 300 hours (catalysts A and B). In addition, we observed that with the chosen set of operating parameters, no soot was formed in the reactor and the concentration of higher hydrocarbons ($C6^+$) in the product gas was less than 10 ppm. This is a value which is not at all critical for MCFC's.

At present, an engineering company is working together with our engineers to build a technological demonstration system, which will be combined with a 350 kW_{el} MCFC from AFCo during 2005.

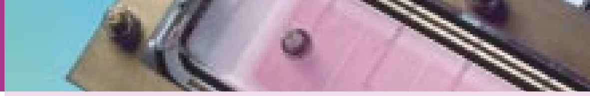
Millions of people in remote areas have neither access to hygienically acceptable drinking water nor a connection to an electricity grid. Their quality of life can be improved significantly by distributed, low-maintenance purification systems for drinking water. For small systems, it is particularly important to treat the input water, e.g. seawater, brackish water or microbially contaminated water in as few processing steps as possible. The illustration shows a flat membrane cell for water treatment with an *in situ* ultrasonic cleaning procedure, which does not require any chemicals. (See article on p. 86.)

Special Areas of Expertise

In addition to the work described in the previous five chapters, Fraunhofer ISE also applies its special expertise to research and development in non-solar sectors, or in other solar technological sectors than those covered in the previous chapters. The Institute uses this work to gain access to new strategic areas. The development of micro-structured functional surfaces, which has long been established at Fraunhofer ISE, is an example, as are the more recent areas of seawater desalination and drinking water purification.

In our work on thermal processes for seawater desalination, we have successfully constructed a small, compact, completely solar-powered experimental system. For distributed and solar-powered drinking water purification systems, we are developing low-maintenance disinfection procedures. The membranes used thereby are cleaned ultrasonically.

As an example of micro-structured functional surfaces, we present a new procedure which can be used for optical modelling of the desired properties. It is based on fast calculation methods, in which modelling approaches applying geometrical optics are used and diffractive effects are taken into account.



Optical Modelling of Micro-Structured Surfaces in the Transition Zone between Refraction and Diffraction

The micro-structuring of surfaces allows deliberate tailoring of their optical properties. We design micro-structures for large-area applications and produce prototypes. We develop fast calculation methods to design and optimise the structures, in which modelling approaches from geometrical optics are used and diffractive effects are taken into account.

Andreas Gombert, Wolfgang Hoßfeld, Peter Nitz

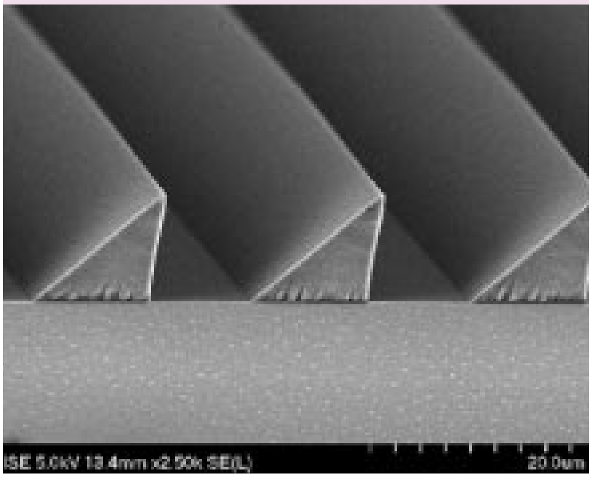


Fig. 1: Scanning electron micrograph of a prismatically structured surface. The structures are so small that they cannot be resolved by the eye. The period of the structure is 17 µm. It is thus about 30 times larger than the wavelength of light. Its optical function is thus essentially refractive.

Micro-structured surfaces present a multitude of optical functions for different applications. We can control these functions, depending on the materials properties of the surface and the structure's form and dimensions. Examples of applications include anti-reflective and anti-glare surfaces for displays, diffusers for luminaires, light-directing surfaces for architectural glazing and thermal radiation emitters for thermophotovoltaics.

We are developing interference lithography further, with the aim of inexpensively producing the tiniest structures over large areas. At present, we can prepare structures with dimensions between 200 nanometres and 50 micrometres over areas measuring up to 1.2 x 1.2 m^2. So-called master structures are prepared with the lithographic process. From these, metal copies are made by electro-forming. These copies serve as embossing dies for large-scale technical replication of the structures in polymer sheets, films or coatings on glass.

In implementing innovative applications based on micro-structured surfaces, we carry out model calculations for our industrial partners. Using these model calculations, we can optimally adjust the desired the surface properties.

One current research project concerns light-redirecting structures such as micro-prisms (fig. 1). These surface structures have periods of several micrometres. They are so small that their structure cannot be resolved by the naked eye. However, as these dimensions are still appreciably larger than the wavelength of light, their function can be understood essentially by application of ray optics. Nevertheless, diffractive effects such as diffraction at the prism edges play an important role and must be taken into account when the structures are designed. To this end, we investigated suitable modelling methods. With so-called rigorous solution methods, which numerically solve the electrodynamic Maxwell equations, the optical properties can be calculated very accurately. However, rigorous methods require very long computing times. In addition, they do not directly answer questions about the specific diffraction or interference effects which, under certain circumstances, cause the optical functionality to deviate noticeably from that predicted by geometrical optics. Approximative methods are better suited to provide quantitative understanding of these effects. They allow different diffraction and interference effects to be analysed separately, so that the structures can then be optimised accordingly.

Within the MIKROFUN II project, which is funded by the German Federal Ministry for Economics and Labour, we followed a new approach to model periodic structures in the transition zone between diffractive and refractive optics. In this approach, the wave fields are represented by superposition of the plane waves that are refracted or reflected at interfaces and the cylindrical waves originating from the edges (fig. 2). The better understanding provided by this additive approach (fig. 3) allows more specific optimisation of the microstructures.

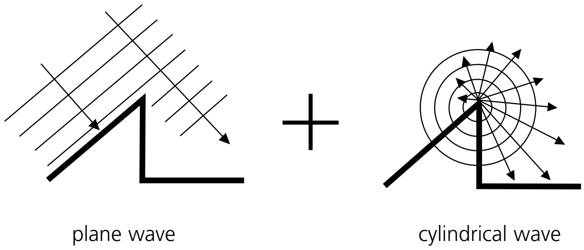


Fig. 2: In a newly developed approximative method, angle-dependent weighted cylindrical waves, which propagate from the structure edges, are added to the plane waves of geometrical optics. This represents a simple way to take diffraction effects into account and allows their effect on the optical functionality of the surface to be estimated.

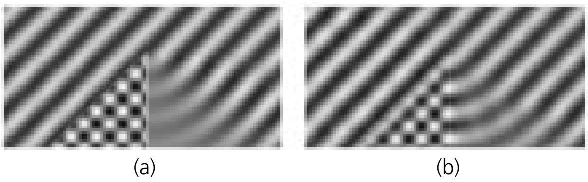
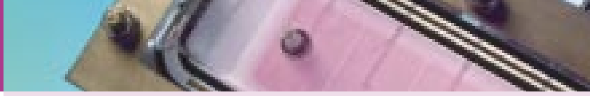


Fig. 3: Comparison of the field distribution calculated for a prismatic surface according to (a) the newly developed approximative method and (b) a rigorous method, in which the Maxwell equations are solved numerically. The checked pattern within the prisms results from superposition of the incident wave and the wave which is totally internally reflected at the perpendicular flank. Diffraction at the upper edge of the prism bends the wave which is incident from the upper left into the shaded area. Both phenomena are described sufficiently well by the approximative method.



Development of Small, Compact Systems for Seawater Desalination

With the construction of the first prototype of a small, compact, completely solar-powered system for seawater desalination, we have reached a milestone in our activities on solar-thermal seawater desalination. The system can be operated in a stand-alone mode. Thermal solar collectors provide the energy for desalination by membrane distillation. The pump and the control unit are powered by a photovoltaic module.

Robert Anti, Sebastian Basel, Joachim Koschiskowski, Heiko Rebmann, **Matthias Rommel**, Marcel Wieghaus

We develop desalination units based on membrane distillation for decentralised application in areas with little technical infrastructure (fig. 1). Membrane distillation is a thermally driven process which is particularly well suited to solar thermal desalination of water. A particularly simple system configuration is feasible, which consists of only a few components and does not require sophisticated controls. A further advantage is that there is no need for complicated initial water treatment. These are important pre-requisites for solar-driven water desalination systems intended for decentralised application in areas with little technical infrastructure. Off-grid operation of the systems is imperative. It is expected that this technology will be well suited for a system capacity ranging between 100 litres per day to about 20 m^3 per day.

We constructed a winding machine (fig. 2) in co-operation with an industrial partner for the development of spiral-wound modules for membrane distillation. This is very flexible in its application and is suitable for producing prototypes or also limited series of modules. Using this equipment, we prepared a desalination module with internal heat recovery for the first experimental compact system. With it, we achieved a specific energy demand of only 100 kW_{th} per m^3 desalinated water. This means that only a seventh of the energy needed to evaporate the water must be supplied due to the heat recovery within the desalination

Fig. 1: The winding machine which was designed and constructed at Fraunhofer ISE to produce prototypes of spiral-wound modules for membrane distillation.

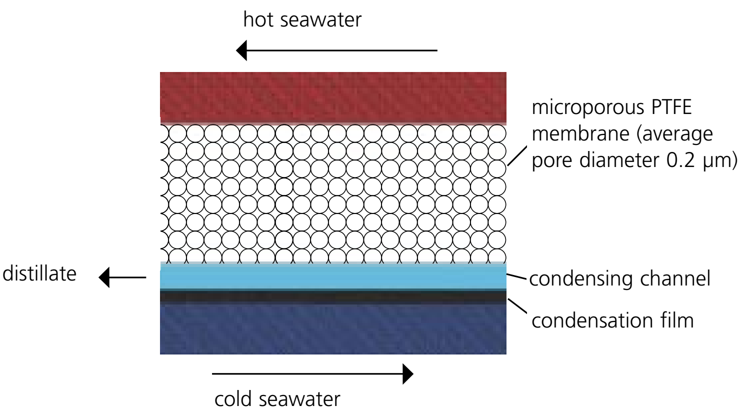


Fig. 2: Operating principle of membrane distillation: The seawater to be desalinated is located above the membrane in the illustration. Below the membrane, cold seawater flows in the opposite direction. The temperature gradient causes a difference in the water vapour partial pressure. This is the driving force for diffusion of water vapour through the membrane, which then condenses on the cold side. The condensation energy is transferred to the cold input water and pre-heats it. This heat recovery reduces the energy demand significantly.

module. In our development, we simultaneously aimed to ensure that the pressure drop in the desalination module would not be too large, so that the auxiliary energy demand to drive the system pump from the photovoltaic modules would be as low as possible. We constructed various test stands in the laboratory to aid our investigations. With our performance test stand, we can characterise our membrane distillation modules and also other thermally driven desalination units. The saltwater test stand is used to test the seawater compatibility of all system components, such as pumps, valves, gas extractor or the piping material. The test stand shown in fig. 5 is used for investigations to improve the thermodynamic performance of the membrane distillation modules, e.g. evaluation of different spacers and membranes. These facilities can also be used for other development tasks by interested partners from industry or research.

Figure 3 shows our first test model of the compact seawater desalination system that is powered exclusively by solar energy. We co-operated with another industrial partner to develop the collectors used here specially for higher operating temperatures of up to 90 °C. They have a double-glazed cover using glass panes with anti-reflective coatings. These collectors are also suitable for other process heat applications up to 120 °C.

Figure 4 shows the membrane module of the test system, which is designed for a capacity of 100 litres of distillate per day. It was installed at the test field of our project partner on Gran Canaria in December 2004. It will be followed by the installation of three further systems for our project partners in Morocco, Egypt and Jordan. The projects are funded by the EU.

Fig. 3: First test model of the compact seawater desalination system that is powered exclusively by solar energy, which was set up on the roof of Fraunhofer ISE in October 2004. Thermal energy for the membrane distillation is provided by three solar collectors. The pump and the control components are powered by a photovoltaic module.

Fig. 4: This module has been cut open to reveal the inner construction of the membrane distillation modules, with the membrane and condensation films separated by spacers. The cylindrical modules typically have a diameter of about 30 cm and a height of 40 to 100 cm.

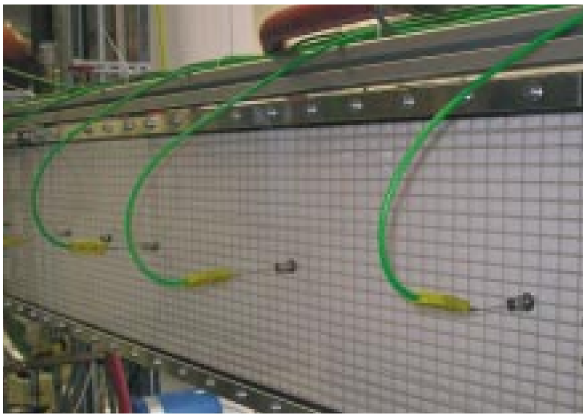
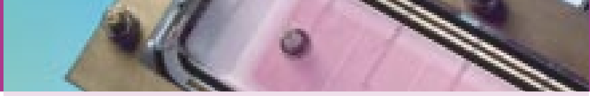


Fig. 5: Test stand at Fraunhofer ISE for investigations to improve the thermodynamic performance of membrane distillation modules (schematic cross-section in fig. 1). It can be used e.g. to evaluate different spacers and membranes. Inserted thermoelements for temperature measurements can be seen.



Distributed Drinking Water Supply in Regions Remote from the Grid

Small, solar-powered purification systems for drinking water have a high market potential to supply water safely and reliably to people in isolated regions far from the grid. We are developing low-maintenance disinfection methods for such systems, using membranes that are cleaned ultrasonically. Within a EU project, we are co-ordinating a programme to implement locally adapted desalination systems in the Mediterranean region.

Ulrike Seibert, Gisela Vogt, Joachim Went, Felix Holz

Fig. 1: To investigate the effect of process parameters for ultrasonic cleaning methods, e.g. frequency, exposure time and geometric configuration, a procedure was developed in the test stand to prepare reproducible fouling deposits with well-defined properties in a flat, transparent membrane cell.

One thousand million people live without access to either electricity or hygienically acceptable drinking water. To provide drinking water reliably to these people, the technology and usage concepts for drinking water purification must be adapted to the conditions in regions remote from the grid. In particular, small, solar powered systems with a daily capacity in the range from 0.1 to 10 cubic metres are very promising for these regions.

Technological development

For small systems, it is particularly important to treat the input water, e.g. seawater, brackish water or microbially contaminated water, in as few processing steps as possible. This is necessary if the systems are to be compact, simple and inexpensive. Fewer system components also mean less effort for maintenance and planning, as fewer components are involved in specific adaptation to the properties of the local source water. However, as the number of preparatory steps is reduced, fouling of the membrane module increases, the main purification component. Therefore, procedures to prevent fouling are an important pre-requisite to market introduction particularly of small, distributed drinking water purification systems. In the ISUS project on "In situ ultrasonic cleaning for small membrane systems in drinking water purification", we are investigating the use of ultrasonic treatment to clean the membranes. With a new physical cleaning method, we intend to develop a new, low-maintenance system, in which deposits on the membrane are removed *in situ* during operation, and which does not need added chemicals.

To this purpose, we are investigating various mechanisms to prevent fouling, based on ultrasonic treatment. With the help of a flat, transparent membrane test cell that was developed further at Fraunhofer ISE (fig. 1), we can investigate the fouling effect and the subsequent removal of the deposit by cleaning. The project is supported as part of the Innonet Programme by the German Federal Ministry for Economics and Labour.

Field tests

Within the ADIRA project, we are developing multi-disciplinary concepts for sustainable drinking water supplies for rural areas. The abbreviation stands for "Autonomous Desalination System Concepts for Sea Water and Brackish Water in Rural Areas with Renewable Energy - Potentials, Technology, Field Experience, Socio-technical and Socio-economic Impacts". Within the context of an interdisciplinary analysis, we are investigating which technical, economic, environmentally relevant, legal and socio-economic aspects are important to guarantee a reliable, decentralised water supply. By planning and constructing demonstration systems in Egypt, Jordan, Morocco, Turkey and Cyprus, we are developing practically relevant strategies for regions with differing resources and boundary conditions. We adapt water purification systems, which are already commercially available from various manufacturers, so that they can be operated with renewable energy sources. The results of the project form the input for planning guidelines, which assist authorities, companies and interested private persons in the selection, design and construction of a suitable water treatment system. The project is supported by Europe Aid.

Fig. 2: Millions of people in remote areas, as here in Morocco, have no access either to hygienically acceptable drinking water or to grid electricity. Their quality of life can be improved appreciably by distributed drinking water purification systems.

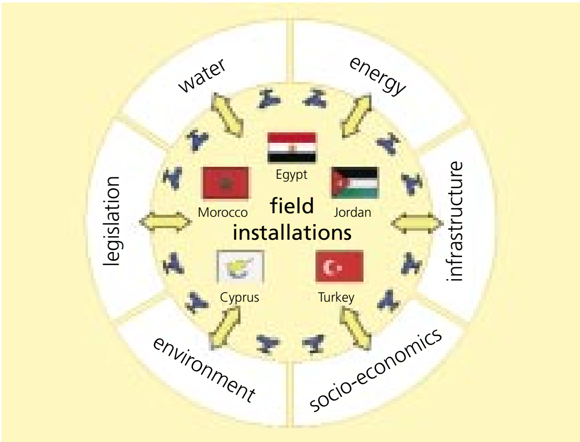
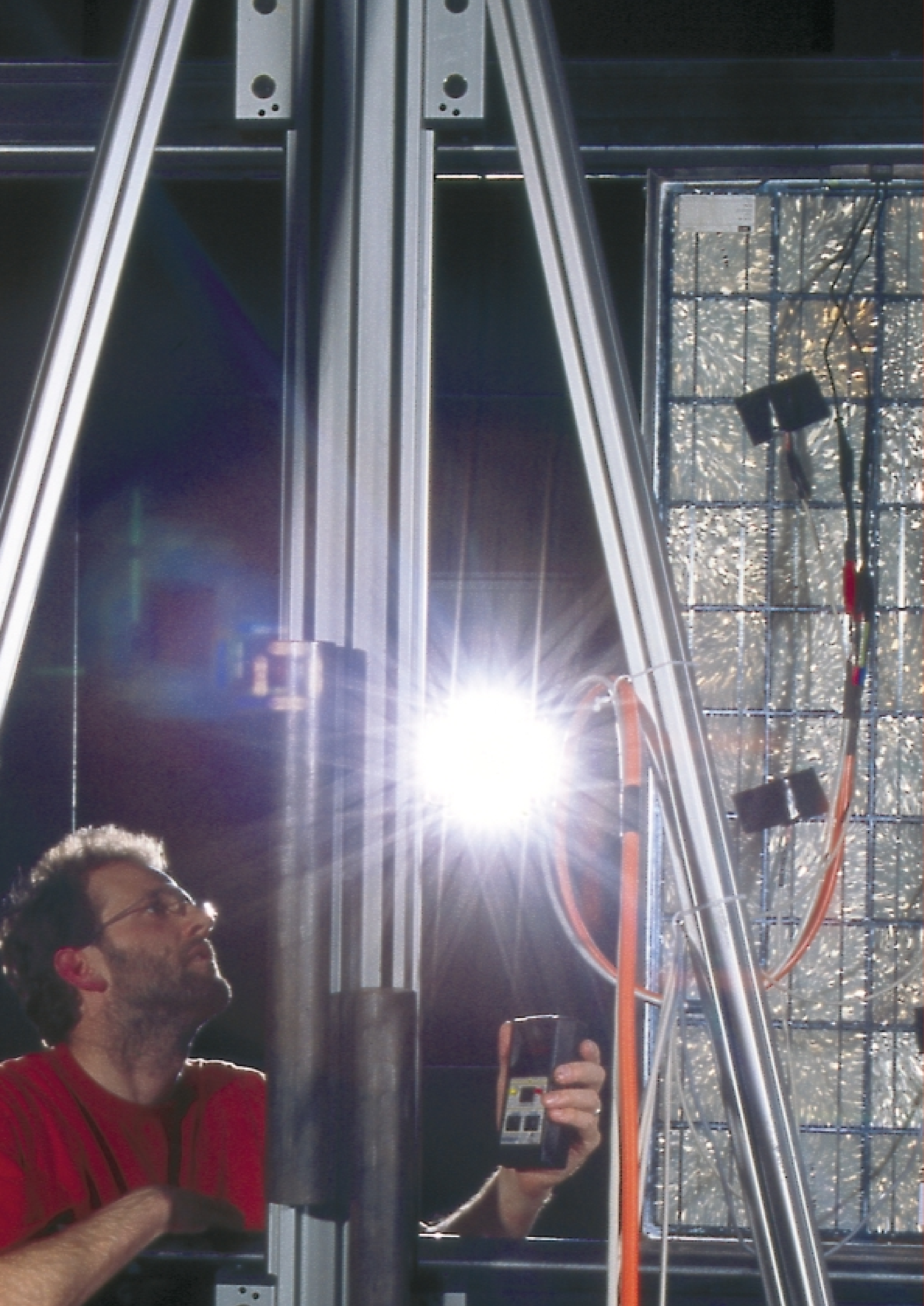


Fig. 3: To successfully establish a sustainable, distributed drinking water supply, diverse technical, ecological and socio-economic factors are taken into account in the ADIRA project. Different introduction strategies are being developed and tested with the help of demonstration systems in the participating countries.



Service Units

Quality assurance plays a major role in all types of solar energy systems. This is the only way to gain and strengthen long-lasting confidence in sustainable technology. At Fraunhofer ISE, we support our clients by evaluating products according to accepted quality criteria.

We do this by measurement, testing and evaluation, as well as calibration and certification of specifications according to national and international standards and procedures. The test objects range from individual components to complete systems. Our measurement and testing laboratories are independent and internationally recognised. We can test your products independently of the weather under standard conditions in the laboratory, or under realistic application conditions outdoors. Testing is quick, reliable and favourably priced, and the results are confidential. In some areas, we pass on our knowledge on testing and qualification procedures in training seminars.

Our spectrum of services includes a calibration laboratory for solar cells and modules, a testing centre for thermal solar systems, a test stand for compact heating and ventilation units, a thermal/optical testing laboratory, a facade testing facility, daylighting measurement rooms, an inverter characterisation unit, a battery testing laboratory, a DC testing and development laboratory, and a lighting measurement laboratory.

Contact Partners

ISE CalLab	Cell calibration	Dr Wilhelm Warta	Tel.: +49 (0) 7 61/45 88-51 92 E-mail: Wilhelm.Warta@ise.fraunhofer.de
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	Module calibration	Klaus Kiefer	Tel.: +49 (0) 7 61/45 88-52 18 E-mail: Klaus.Kiefer@ise.fraunhofer.de
		Frank Neuberger	Tel.: +49 (0) 7 61/45 88-52 80 E-mail: Frank.Neuberger@ise.fraunhofer.de
Testing Centre for Thermal Solar Systems	Indoor and outdoor test stand for solar collectors	Matthias Rommel	Tel.: +49 (0) 7 61/45 88-51 41 E-mail: Matthias.Rommel@ise.fraunhofer.de
		Arim Schäfer	Tel.: +49 (0) 7 61/45 88-53 54 E-mail: Arim.Schaefer@ise.fraunhofer.de
	Solar air collector test stand	Carsten Hindenburg	Tel.: +49 (0) 7 61/45 88-53 53 E-mail: Carsten.Hindenburg@ise.fraunhofer.de
Measurement of building facades and transparent components	Thermal-optical measurement laboratory TOPLAB	Tilmann Kuhn	Tel.: +49 (0) 7 61/45 88-52 97 E-mail: Tilmann.Kuhn@ise.fraunhofer.de
	Daylighting measurement rooms	Jan Wienold	Tel.: +49 (0) 7 61/45 88-51 33 E-mail: Jan.Wienold@ise.fraunhofer.de
	Facade testing facility FASTEST	Dr Werner Platzer	Tel.: +49 (0) 7 61/45 88-51 31 E-mail: Werner.Platzer@ise.fraunhofer.de
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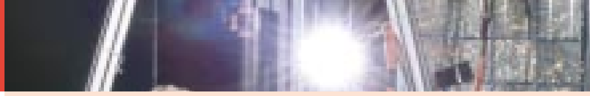
	Lighting measurement laboratory	Norbert Pfanner	Tel.: +49 (0) 7 61/45 88-52 24 E-mail: Norbert.Pfanner@ise.fraunhofer.de
	Battery testing laboratory	Rudi Kaiser	Tel.: +49 (0) 7 61/45 88-52 28 E-mail: Rudi.Kaiser@ise.fraunhofer.de

Service Units

The Fraunhofer ISE CalLab is one of the internationally leading calibration laboratories for solar cells and PV modules. Information to manufacturers and investors about the possible electricity yield of a photovoltaic system will now be even more accurate. The new flasher shown in the photo allows precision measurements to be made of PV modules over an area of 4 m^2. The homogeneity of the illumination is better than ± 1 %. The measurement accuracy of the flasher is better than ±2.5 % for precision measurements over an area of 4 m^2.



ISE CalLab - Calibration of Solar Cells and Modules

The characterisation of solar cells and modules plays an important role in research and development, as well as production. It is vital for product comparison, and quality assessment of photovoltaic systems.

Britta Hund, Klaus Kiefer,
Frank Neuberger, Wilhelm Warta

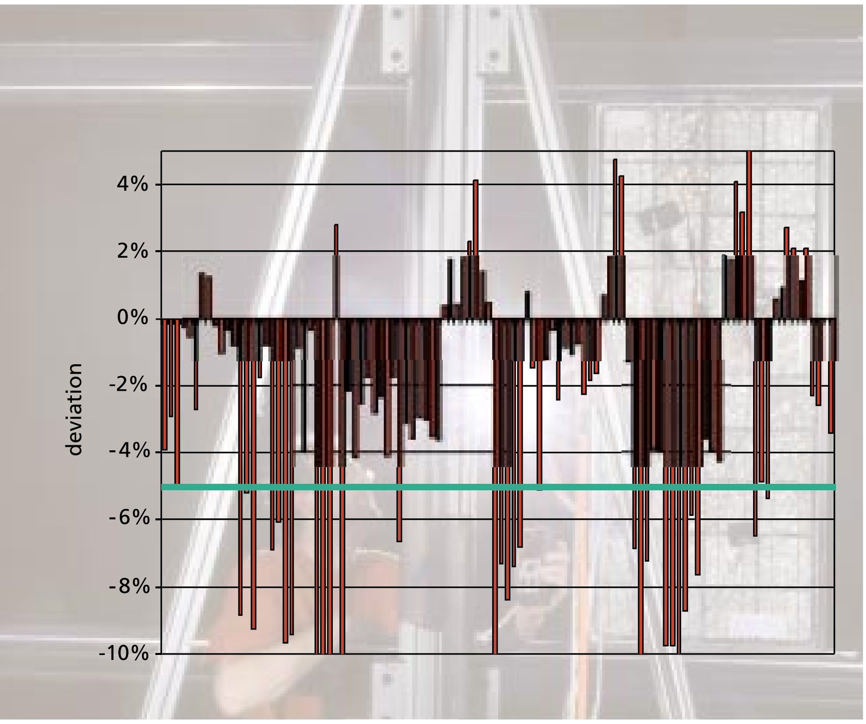


Fig. 1: Since July 2004, the performance of photovoltaic modules with an area of up to 4 m^2 can be measured at Fraunhofer ISE with a new precision pulsed solar simulator. The measurement accuracy is better than ± 2.5 % for precision measurements, and better than ± 4 % for standard measurements. A measurement test series of 100 PV modules demonstrates that quality control is important. Many modules do not deliver the rated power and even fall outside the tolerance range of -5 %. On average, the module power was 3.4 % below the rating.

ISE CalLab is one of the internationally leading photovoltaic calibration laboratories. Scientists from all over the world come to Freiburg with their new developments. Internationally renowned manufacturers and also TÜV Rheinland, the German technical authorisation body, have their reference cells measured by ISE CalLab. Our clients receive exceptional service and security, because

- we guarantee the accuracy of our results by participating regularly in round-robin tests with other internationally recognised measurement laboratories
- we observe international standards in all calibration steps and in the use of reference elements and measurement facilities
- we process clients' enquiries rapidly and without unnecessary bureaucracy, and guarantee confidentiality.

Cell calibration - references for research and industry

We undertake complete characterisation of solar cells and detectors with areas up to 15 x 15 cm^2. Our service offer includes:

- calibration of reference cells, standard solar cells, concentrator cells and tandem cells
- spectral response measurement
- determination of the temperature dependence of the output power

Module calibration - an efficient quality control method

For PV modules up to an area of 2 x 2 m^2, our range of services comprises:

- precise module measurement with a pulsed solar simulator
- outdoor module measurements
- determination of the NOCT temperature and power
- measurement of the angular and temperature dependence of the module parameters

Detailed information on our services can be found under www.callab.de.

Testing Centre for Thermal Solar Systems

We operate an outdoor test stand. Our testing centre is authorised by DIN CERTCO and fully accredited by DAP (Deutsches Akkreditierungssystem Prüfwesen). We certify solar collectors and support our clients in developing solar thermal system components. The indoor test stand with a large solar simulator has proved to be very valuable for testing and development work.

Carsten Hindenburg, Joachim Koschikowski, Matthias Rommel, Arim Schäfer, Thorsten Siems

Fig. 1: Indoor test stand with solar simulator.

Certification of solar collectors

We test solar collectors and complete systems according to national or international standards and standard procedures:

- collector testing according to DIN EN 12975, parts 1 and 2
- all relevant functionality tests
- determination of the thermal performance
- calculation of the annual energy yield
- direct measurement of the incidence angle modifier (IAM) with a tracker
- SOLAR KEYMARK label

Collector and system development

We co-operate closely with manufacturers of solar systems, both within projects or as part of individual product development. We offer:

- detailed thermographic investigations (e.g. of thermal bridges)
- determination of the collector efficiency factor F' of absorbers
- optimisation and calculation of the reflector geometry for collectors
- identification of collector heat capacity by dynamic response measurements
- characterisation of dynamic collector performance (low-flow, high-flow, matched-flow)
- parameter identification with the ColSim simulation program developed at Fraunhofer ISE

Indoor collector test stand with a solar simulator

We operate an indoor test stand with a solar simulator. Its great advantage, particularly for collector development, is the high reproducibility of the measurement conditions. This allows us to carry out targetted developmental work to improve collector constructions very efficiently and quickly.

The most important technical data are:

- test plane dimensions: 2.4 x 2 m^2. Other configurations of the test plane are possible (up to 3.5 x 3 m^2).
- irradiance: 1200 Wm^{-2} without the artificial sky, 1000 Wm^{-2} with the artificial sky
- homogeneity: ± 10 %
- lamp array tilt angle: 0 - 90 °

Test stand for solar air collectors

Since last summer, we have operated a test stand for solar air collectors. It is integrated into the indoor test stand with the solar simulator, so we can guarantee short measurement times, independent of the weather. The solar air collectors are tested analogously to DIN EN 12975. Air flow rates of 50 m^3h^{-1} to 1000 m^3h^{-1} can be measured with a maximum uncertainty of ± 1 %.

Beyond that, we offer the following services:

- measurement of the pressure loss of solar air collectors as a function of the throughput
- determination of air leakage rates
- support for manufacturers in new and further development of products
- calculation of the annual energy yield for different solar air collectors
- development of customised design software for solar air collector systems

Measurement and Testing of Ventilation Equipment

We make test-stand and field measurements for manufacturers and developers of compact ventilation units with integrated heat pumps.

Andreas Bühring, Martina Jäschke*, Christian Bichler*, Michael Schossow, Sebastian Herkel

* PSE Projektgesellschaft Solare Energiesysteme mbH, Freiburg

Fig. 1: Automated test facility with two testing stations to measure ventilation units and exhaust-air heat pumps.

Fig. 2: : Conditioning unit for outdoor air (insulation partly removed): The outdoor air flows in from the lower left through the pre-cooler/dehumidifier and the low-temperature chiller, then upwards to the ultrasonic humidifier and air heater. Two air currents can be separately conditioned as supply air and as a second heat source.

Fig. 3: Test facility in the Solarhaus of Fraunhofer ISE, Freiburg.

Test facility for compact ventilation and heating units

On commission to our clients, we support the development of compact ventilation units with integrated exhaust-air heat pumps. With our test facility, we measure the energy efficiency of both the complete units and their components. We can choose from a wide spectrum of testing conditions. The automated test stand allows dynamically changing conditions to be applied, e.g. according to the EN 255-3 standard. From the measurements, we derive recommendations to optimise the components and their interaction. We support our clients in implementing new developments, e.g. by substituting components. Skilled staff with know-how on cooling technology and the necessary technical equipment are available.

Monitoring

In numerous occupied solar passive houses, we are measuring the performance of compact ventilation and heating units from various manufacturers in practice. Based on daily data analyses, we give direct recommendations to optimise operation. Possible fault causes are identified and corrected. From these measurements, we prepare proposals to optimise the equipment and controls.

Measurements of airtightness and air exchange rate

We measure the airtightness of ventilation units under real operating conditions with the help of tracer gas chromatography, applying the constant injection method. This can be done either with the test stand or in situ in the building, for large central systems. We use the same equipment to determine the air exchange rate in buildings according to the concentration decay method. Our measurement method meets the specifications of VDI 4300, Sheet 7. It allows SF_6 to be used as the tracer gas also in occupied buildings, if the analysis is made by gas chromatography using an electron capture detector.

Measurement of Building Facades and Transparent Components

We offer developers and planners a comprehensive range of detailed and accurate characterisation for innovative building components and materials. A special laboratory is available to determine the optical and thermal properties of transparent components and sun-shading systems. Further equipment includes a daylighting measurement container and an outdoor test facility.

Ulrich Amann, Angelika Helde, Tilmann Kuhn, Werner Platzer, Jan Wienold

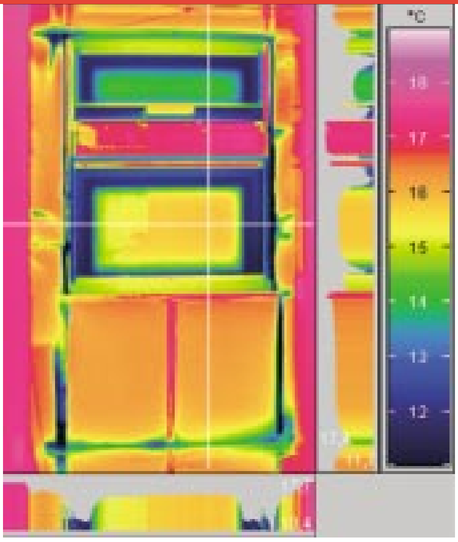


Fig. 1: Thermographic image of a facade module occupying the full height of a test cabin (viewed from indoors).

Thermal-optical measurement laboratory TOPLAB

Existing measurement procedures such as those specified in DIN EN 410 are not adequate to describe the properties of advanced glazing and facade constructions. Thus, we have developed testing procedures to characterise energy and lighting-technology effects accurately. Our equipment allows us to measure elements of more than 1 m^2 area, which have the following properties:

- light scattering and light redirection
- macroscopic structures and patterns
- angle-selective properties
- properties which change with time, e.g. photochromic, thermotropic or electrochromic
- air flow within the facade
- integrated photovoltaics.

Examples of equipment:

- solar calorimeter to determine the total solar energy transmittance of transparent components and sun-shading devices
- angle-dependent transmittance and reflectance measurements with a large integrating sphere
- thermal resistance measurements on glazing units according to DIN 52612
- measurement of the angular distribution of transmitted and reflected light with a photogoniometer

Standard testing procedures round off our range of services. We determine the spectral properties of glazing, films and surfaces for our clients with UV-vis-IR spectrometers.

Within the ISO 9001:2000 certification programme, we regularly maintain and calibrate our measurement equipment, guaranteeing high accuracy.

The German building code recognises our laboratory's determination of the g value (total solar energy transmittance). Some of the development of testing procedures was publicly funded.

Daylighting measurement rooms

The daylighting measurement rooms consist of two identical office rooms, located side-by-side in a container. They can be rotated, so that any desired facade orientation can be chosen. Meteorological data and the global illuminance on the vertical plane of the facade is measured and recorded. The following investigations have been made in the measurement rooms to date:

- glare protection tests
- user acceptance studies
- comparison of the lighting situation behind two facade systems

Facade testing facility, FASTEST

In addition to characteristic values obtained under well-defined boundary conditions in the laboratory, we measure complete facades under real climatic conditions. Eight test rooms, all with the same facade orientation, are available to us. There, we investigate the dynamic performance of the test facades and record data on the temperatures in the internal cabins and within the facade component, the operative temperature, solar and visible transmittance, heating consumption of the test cabins and other building-science parameters at one-minute intervals.

Long-term investigations provide information on the stability, switching performance and loads on the facade. The optimisation of controllers can be experimentally validated. In combination with building simulation, the measured data serve to validate facade models in programs such as ESP-r and TRNSYS.

Characterisation and Qualification Testing of Electric Components

In addition to photovoltaic cells and modules, we measure, test and evaluate complete PV systems as well as individual system components. These include inverters and DC components such as lamps, batteries or television sets.

Rudi Kaiser, Norbert Pfanner, Bruno Burger, Jürgen Ketterer, Heribert Schmidt

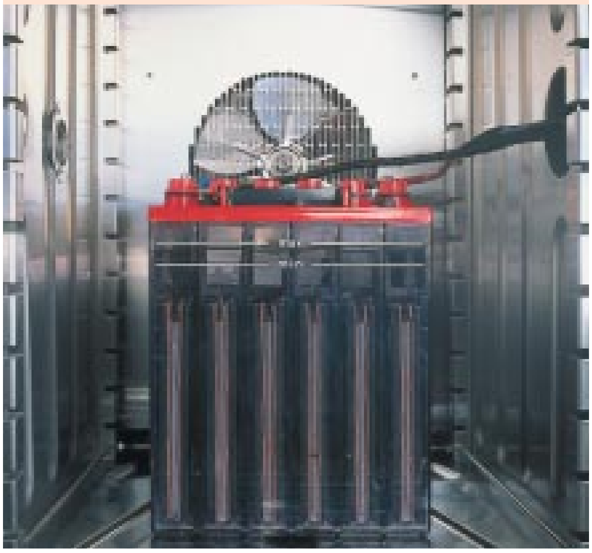


Fig. 1: In addition to efficiency and capacity, also the temperature dependence of properties such as the ageing and charging performance of storage batteries can be investigated. The photo shows the climatic chamber of the battery testing laboratory at Fraunhofer ISE.

Fig. 2: Integrating-sphere photometer to measure the luminous flux of DC lamps and light sources.

Inverter Laboratory

We characterise inverters with respect to efficiency, MPP tracking performance, electromagnetic compatibility (EMC), burst and surge disturbance, compliance with the relevant standards and user friendliness. An EMC measurement chamber is available to characterise EMC behaviour. Our staff, who work in standardisation committees, offer advice on technical questions or clarification of the standards which must be observed.

Battery Testing Laboratory

Manufacturers, system integrators and users can have all common types of batteries tested and qualified in our laboratory. Flexibly programmable systems are available to apply whichever charging and load profiles are needed. We also offer long-term tests lasting several months in the laboratory and the field. Developers of charge controllers can have their equipment tested and optimised.

DC testing and development laboratory

We measure, test and evaluate complete photovoltaic systems or individual components with respect to energy consumption and efficiency, operation management performance, fault performance, protection against incorrect operation and electromagnetic compatibility. Long-term tests and stress tests are the basis for making predictions of the lifetime and reliability with practical relevance. As a further service, we offer training courses for technicians and engineers on measurement and testing.

Lighting measurement laboratory

We investigate electrical characteristics of light sources and lamps for photovoltaic systems, including efficiency, operation management performance, fault occurrence and lifetime. We also make precise measurements of lighting-technology parameters such as luminous flux and luminous efficacy, luminance and operating performance.

Facts and Figures

Visiting Scientists

Participation in Associations

Congresses, Conferences and Seminars

Lecture Courses and Seminars

Trade Fairs and Exhibitions

Patents

Doctoral Theses

Press Releases

Lectures

Publications

Abbreviations

Visiting Scientists

Benjamin Diaz
Universidad de La Laguna
Tenerife, Spain
15.7.2004-31.1.2005
Research area: porous silicon and silicon nitride, anti-reflective coatings for solar cell technology

Prof. Abdelmajid El Bouardi
Université Abdelmalek Essadi
Tétouan, Morocco
1.7.-30.8.2004
Research area: collectors and collector systems, natural building materials for thermal storage in buildings

Prof. Ashok Gopinath
Naval Postgraduate School
Monterey, CA - USA
1.7.2003-30.6.2004
Research area: TPV generator

José Roberto Flores Hernández
Instituto de Investigaciones Electricas (IEE)
Puebla, Mexico
1.10.2001-30.9.2005
Research area: electrolysis

Gorka Bueno Mendieta
Escuela de Ingenieros de Bilbao
Instituto de Tecnología Microelectrónica
Bilbao, Spain
1.7.-30.7.2004
Research area: characterisation of multi-crystalline silicon with the CDI technique

Prof. Ricardo Rüther
LABSOLAR, UFSC
Florianopolis-SC, Brazil
28.5.-3.7.2004
Research area: comparison of the yields from PV systems in Brazil and Germany

Dr Nikolay Sadchikov
A.S. Ioffe Physico-Technical Institute
St Petersburg, Russia
29.8.-23.11.2004
Research area: production and development of FLATCON modules

Prof. Hongmei Yu
Dalian Institute of Chemical Physics
Chinese Academy of Science
Dalian, China
1.7.2003-31.12.2004
Research area: Investigation of membrane-electrode assemblies for fuel cells

Participation in National and International Associations

Club zur Ländlichen Elektrifizierung C.L.E.
- Mitglied im Vorstand

Deutsche Elektrotechnische Kommission (DKE)
- Komitee 373: »Photovoltaische Solarenergiesysteme«

Deutsche Physikalische Gesellschaft
- Arbeitskreis »Energie«

Deutsches Institut für Normung DIN, Fachnormenausschuss Lichttechnik (FNL 6) »Innenraumbeleuchtung mit Tageslicht«
- Mitglied

Deutsches Institut für Normung DIN, Fachnormenausschuss Heiz- und Raumlufttechnik (NHRS AA1.56) »Solaranlagen«
- Mitglied

Deutsches Institut für Normung DIN, Normenausschuss Bau NABau 00.82.00 »Energetische Bewertung von Gebäuden«
- Mitglied

European Committee for Standardisation CEN TC33 / WG3 / TG5
- Member

European Photovoltaic Industry Association (EPIA)
- Associate Member

European Solar Thermal Industry Federation (ESTIF)
- Member

Fachinstitut Gebäude-Klima (FGK)
- Arbeitskreis »Sorptionsgestützte Klimatisierung«

Fachverband Transparente Wärmedämmung
- Fachausschuss »Produktkennwerte«

FitLicht – Fördergemeinschaft innovative Tageslichtnutzung
- Mitglied

Förderprogramm »Haus der Zukunft« des Österreichischen Bundesministeriums für Verkehr, Innovation und Technologie
- Mitglied in der Jury

Forschungsverbund Sonnenenergie (FVS)
- Mitglied, Tagungsbeirat

Fraunhofer-Gesellschaft
- Senat

Fraunhofer-Verbund Energie
- Geschäftsführung

Global Network on Energy for Sustainable Development (GNESD)
- Member

Global Research Alliance (GRA)
- Coordination of Thematic Focus on Energy

Hahn-Meitner-Institut (HMI)
- Wissenschaftlicher Beirat

Hauptkommission des Wissenschaftlich-Technischen Rates der Fraunhofer-Gesellschaft
- Mitglied

Institut für Solare Energieversorgungstechnik (ISET)
- Wissenschaftlicher Beirat

International Energy Agency IEA, Paris, Frankreich:
Solar Heating & Cooling Programme SHCP
- Task 25: »Solar Assisted Air-Conditioning of Buildings«
- Task 27: »Performance of Solar Facade Components«
- Task 28: »Sustainable Solar Housing«
- Task 33/4 »Solar Heat for Industrial Processes«
- Energy Conservation in Buildings and Community Systems ECBCS

Symposium Photovoltaische Solarenergie
- Wissenschaftlicher Beirat

Verein Deutscher Ingenieure (VDI)
VDI-Gesellschaft Energietechnik
- Fachausschuss »Regenerative Energien« (VDI-FARE)

VDI-Gesellschaft Technische Gebäudeausrüstung
- Richtlinienausschuss 6018

VMPA – Verband der Materialprüfämter e.V.
- Sektorgruppe »Türen, Fenster und Glasprodukte«

Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU)
- Mitglied

World Technology Network (WTN)
- Member

Zeitschrift »Physik Journal«, Wiley-VCH
- Sprecher des Kuratoriums

Zentrum für Solarenergie und Wasserstoff (ZSW)
- Kuratorium

Congresses, Conferences and Seminars organised by the Institute

7. Fachforum Innovative Lüftung in Gebäuden
Regensburg, 27./28.1.2004

OTTI-Energie-Kolleg
10. Symposium Innovative Lichttechnik in Gebäuden
Bad Staffelstein, Kloster Banz, 29./30.1.2004

SOLTRAIN Train-the-Trainer Workshop
Freiburg, 1.–13.2.2004

OTTI-Energie-Kolleg
19. Symposium Photovoltaische Solarenergie
Bad Staffelstein, Kloster Banz, 10.–12.3.2004

Fraunhofer-Forum Südlicher Oberrhein
Photovoltaik-Monitoring
Freiburg, 15.3.2004

Freiburger ISR und InWEnt
Netzferne PV-Energieversorgung in Entwicklungsländern
Freiburg, 5.–16.4.2004

8. Europäische Passivhaustagung
Krems, 16./17.4.2004

15. Symposium Thermische Solarenergie
Bad Staffelstein, Kloster Banz, 27.–29.4.2004

OTTI-Profiforum
Wiederaufladbare Batterien
Ulm, 5./6.5.2004

7. Deutsches Weltbankforum
Gemeinschaftsstand mit
Fraunhofer IML, IGB, IPK
München, 12.5.–10.8.2004

Hyforum 2004
Peking, China, 25.–28.5.2004

TPV 6th Conference on Thermophotovoltaic Generation of Electricitiy
Freiburg, 14.–16.6.2004

EuroSun2004 – 5th ISES Europe Solar Conference
14. Internationales Sonnenforum der DGS e.V.
Freiburg, 20.–23.6.2004

Intersolar
Kompaktseminar Photovoltaik-Technologie
Freiburg, 25.6.2004

2. Symposium Forschungsallianz Kristalline Silicium-Solarzellentechnologie (FAKT)
Freiburg, 26.6.2004

OTTI-Energie-Kolleg
Kompaktseminar Solaranlagen erfolgreich verkaufen
Freiburg, 26.6.2004

European Fuel Cell Forum
Lucerne, Switzerland, 28.6.–2.7.2004

Fraunhofer Solar Building Innovation Center SOBIC*
Qualitätssicherung bei der Finanzierung von Solarstromanlagen
Freiburg, 6.7.2004

Fraunhofer Solar Building Innovation Center SOBIC*
Qualitätssicherung bei der Finanzierung von Solarstromanlagen
Freiburg, 21.9.2004

Fraunhofer Solar Building Innovation Center SOBIC*
Wärmeversorgung von Passivhäusern
Freiburg, 19.10.2004

2. Forum Wärmepumpe
Berlin, 21./22.10.2004

14th Marie Curie Sustainable Energy Fellows Conference
Freiburg/ Stuttgart, 23.–28.10.2004

Fraunhofer Solar Building Innovation Center SOBIC*
Sommerlicher Wärmeschutz, Blendschutz und Tageslichtnutzung im Verwaltungsbau – Grundlagen
Freiburg, 2./3.11.2004

Fraunhofer Solar Building Innovation Center SOBIC* und OTTI Profiforum
Fachseminar EMV und Blitzschutz in Photovoltaik-Anlagen
Freiburg, 24./25.11.2004

Jahrestagung Forschungsverbund Sonnenenergie (FVS)
Berlin, 25./26.11.2004

Fraunhofer Solar Building Innovation Center SOBIC*
Wärmeversorgung von Passivhäusern
Osnabrück, 8.12.2004

Fraunhofer Solar Building Innovation Center SOBIC*
Nachhaltige Energieversorgung in Krankenhäusern
Freiburg, 9.12.2004

Workshop Deutsche Gesellschaft für Kristallwachstum und Kristallzüchtung e.V. (DGKK)
Freiburg, 9./10.12.2004

** Fraunhofer SOBIC is the joint demonstration centre of Fraunhofer IBP and Fraunhofer ISE.*

Lecture Courses

Dr. Dietmar Borchert
Photovoltaik
Vorlesung SS 04
Technische Fachhochschule Georg Agricola
Bochum

Dr. Bruno Burger
Leistungselektronische Systeme für regenerative Energiequellen
Vorlesung WS 04/05
Fakultät für Elektrotechnik und Informationstechnik
Universität Karlsruhe

Dr. Andreas Gombert
Mikrostrukturierte Oberflächen mit optischen Funktionen
Vorlesung SS 04 und WS 04/05
Fakultät für Angewandte Wissenschaften
Albert-Ludwigs-Universität Freiburg

Sebastian Herkel
Bauökologie und Solare Energiesysteme
Vorlesung SS 04
Staatliche Akademie der Bildenden Künste
Stuttgart

Prof. Joachim Luther
Photovoltaische Energiekonversion
Vorlesung SS 04
Thermische Solarenergiewandlung
Vorlesung WS 04/05
Solare Energiekonversion
Oberseminar SS 04 und WS 04/05
Albert-Ludwigs-Universität Freiburg

Jens Pfafferott
Klimagerechtes Bauen – Passive Kühlung
Vorlesung WS 04/05
Fachhochschule Biberach

Prof. Roland Schindler
Halbleitertechnologie II (Bauelemente)
Vorlesung SS 04
Photovoltaik II
Vorlesung SS 04
Hableitertechnologie I (Technologie),
Vorlesung WS 04/05
Photovoltaik I
Vorlesung WS 04/05
Fernuniversität Hagen

Dr. Heribert Schmidt
Photovoltaik Systemtechnik
Vorlesung SS 04
Fakultät für Elektrotechnik und Informationstechnik
Universität Karlsruhe

Dr. Jürgen O. Schumacher
Brennstoffzellen: Grundlagen und Anwendung
Vorlesung SS 04
Interdisziplinäres Seminar
Albert-Ludwigs-Universität Freiburg

Priv. Doz. Dr. Gerhard Willeke
Halbleitertechnologie und Physik der Solarzelle
Vorlesung SS 04
Universität Konstanz

Priv. Doz. Dr. Volker Wittwer
Energieversorgung für Mikrosysteme
Vorlesung SS 04 und WS 04/05
Fakultät für Angewandte Wissenschaften
Albert-Ludwigs-Universität Freiburg

Trade Fairs and Exhibitions

34. Convegno Mostra Expo Comfort, jointly with Associazione Italiana Condizionamento dell'Aria Riscaldamento e Refrigerazione (AICARR)
Milan, Italy, 2.–6.3.2004

1st ClimaMed Trade Fair and Conference, jointly with Associação Portuguesa da Indústria de Refrigeração e Ar Condicionado (APIRAC)
Lisbon, Portugal, 16.–20.4.2004

Hanover Trade Fair, HMI 2004
Hanover, 19.–24.4.2004

Weltkonferenz »renewables 2004«
»Woche der Umwelt« im Park der Villa Hammerschmidt
Bonn, 1.–5.6.2004

Optatec
Frankfurt/Main, 22.–25.6.2004

19th European Photovoltaic Solar Energy Conference and Exhibition
Paris, 7.–11.6.2004

Intersolar 2004
International Trade Fair and Congress for Solar Technology
Freiburg, 24.–26.6.2004

5th Annual Staff Exchange Program & Knowledge Sharing Conference and Expo
joint stand of Fraunhofer-Gesellschaft and Free State of Bavaria
Washington D.C., U.S.A. 28./29.6.2004

f-cell 2004
Stuttgart, 27./28.9.2004

Patent Applications

Andreas Hinsch, Udo Belledin, Ronald Sastrawan, Andreas Georg
"Configuration of and procedure to produce a photoelectrochemical solar cell"

Michael Oszcipok, Peter Schossig
"Procedure to operate a fuel cell"

Lisbeth Rochlitz, Jörg Martin
"Device and procedure to produce a tar-free reformate gas by gasification of biomass"

Felix Holz
"Procedure to reduce and avoid biofouling in membrane systems for treatment of aqueous solutions"

Eric Schneiderlöchner, Jochen Rentsch, Ralf Preu
"Procedure for structuring the surface of a semiconductor to reduce optical reflection"

Peter Nitz
"Solar collector with translucent cover"

Alexander Disch, Claas Müller, Benedikt Bläsi, Jörg Mick
"Large-area substrate with a macro-structured and micro-structured surface and procedure to produce this type of large-area substrate"

Daniel Biro, Josef Gentischer
"Transport device with special chain links to transport elements to be processed through a temperature zone"

Rüdiger Löckenhoff
"Semiconductor component able to withstand high currents and procedure to produce it"

Axel Maurer, Christian Siegel, Klaus Wanninger
"Procedure and reactor for reforming"

Frank Dimroth
"Transparent contact and procedure to produce it"

Stefan Reber
"Procedure for simultaneous recrystallisation and doping of semiconductor films and semiconductor film systems produced with this procedure"

Stefan Glunz, Ansgar Mette, Ralf Preu, Christian Schetter
"Semiconductor component with an electric contact on at least one surface"

Andreas Georg
"Gasochromic glazing element with additional coating"

Patents Granted

Andreas Georg, Anneke Hauch
"Photovoltaically self-charging storage system"

Benedikt Bläsi, Volkmar Boerner, Andreas Gombert, Michael Niggemann
"Device for anisotropic light scattering and procedure to produce the device"

Andreas Georg, Wolfgang Graf, Volker Wittwer
"Glazing element"

Harry Wirth, Volker Wittwer
"Light-redirecting element for daylighting purposes"

Ralf Lüdemann
"Thin-film solar cell configuration and procedure to produce it"

Andreas Bühring
"Compact heat pump unit with integrated primary-energy heat source for controlled ventilation and heating of low-energy buildings or passive houses"

Daniel Biro
"Transport device and procedure to transport elements to be processed through a high-temperature zone"

Jörg Jungjohann
"Sun-shading device made of a material transparent to sunlight"

Andreas Bühring, Pedro da Silva
"Ventilation configuration for buildings"

Andreas Georg
"Optical component"

Daniel Kray, Gerhard Willeke
"Procedure and device for segmentation of bodies"

Heribert Schmidt
"Radiation sensor with reduced sensitivity to interference"

Dominik Marin Huljic
"Procedure for temperature-controlled processing of substrates"

Adolf Goetzberger
"Procedure and device for large-area production of solar cells"

Bruno Burger, Robert Hahn, Christopher Hebling, Andreas Schmitz
"Fuel-cell system constructed of printed circuit boards and procedure for its production"

Konstantin Ledjeff, Roland Nolte
"Polymer fuel cell"

Doctoral Theses

Jörg Isenberg
"Neue Infrarotmesstechniken für die Photovoltaik"
(New infra-red measurement techniques for photovoltaics)
Doctoral thesis, University of Constance
Constance, 2004

Stefan Peters
"Rapid Thermal Processing of Crystalline Silicon Materials and Solar Cells"
Doctoral thesis, University of Constance
Constance, 2004

Jens Pfafferott
"Enhancing the Design and the Operation of Passive Cooling Concepts"
Doctoral thesis, University of Karlsruhe (Technical)
Karlsruhe, 2004

Thomas Rampe
"Experimentelle Untersuchung der Bioethanolreformierung - Entwicklung eines allothermen Reformers"
(Experimental investigation of bio-ethanol reforming - development of an allothermal reformer)
Doctoral thesis, University of Essen
Essen, 2004

Stefan Rein
"Lifetime Spectroscopy - a Method of Defect Characterization in Silicon for Photovoltaic Applications"
Doctoral thesis, University of Constance
Constance, 2004

Helge Schmidhuber
"Neue Materialien in der Photovoltaikmodul-Produktion und ihr Einsatz in hocheffizienten Kleinmodulen"
(New materials in photovoltaic module production and their application in highly efficient, small modules)
Doctoral thesis, University of Bremen
Bremen

Ferdinand Schmidt
"Optimizing Adsorbents for Heat Storage Applications: Estimation of Thermodynamic Limits and Monte Carol Simulations of Water Adsorption in Nanopores"
Doctoral thesis, University of Freiburg
Freiburg, 2004

Eric Schneiderlöchner
"Laserstrahlverfahren zur Fertigung kristalliner Silizium-Solarzellen"
(Laser beam procedure to process crystalline silicon solar cells)
Doctoral thesis, University of Freiburg
Freiburg, 2004

Roland Schregle
"Daylight Simulation with Photon Maps"
Doctoral thesis, University of Saarbrücken
Saarbrücken, 2004

Benoit Sicre
"Energieversorgung von Niedrigstenergie- und Passivhäusern mittels erneuerbarer Energie, Wärmepumpen und Kraft-Wärmekopplung im Kleinstleistungsbereich"
(Energy supply for lowest-energy and passive houses using renewable energy, heat pumps and combined heat and power in the lowest power range)
Doctoral thesis, University of Chemnitz (Technical)
Chemnitz, 2004

Klaus Tüber
"Experimentelle Untersuchung und numerische Simulation von Polymer-Elektrolyt-Membran-Brennstoffzellen für portable, elektrische Verbraucher im Leistungsbereich bis 50 Watt im Hinblick auf den Wasser- und Wärmehaushalt"
(Experimental investigation and numerical simulation of polymer-electrolyte membrane fuel cells for portable electric devices in the power range up to 50 W with regard to water and heat management)
Doctoral thesis, University of Duisburg
Duisburg, 2004

Matthias Vetter
"Modellbildung und Regelstrategien für Erdgas-betriebene Brennstoffzellen BHKWs auf PEM Basis"
(Modelling and control strategies for combined heat and power plants operating with PEM fuel cells fuelled with natural gas)
Doctoral thesis, University of Karlsruhe (Technical)
Karlsruhe, 2004

Jochen Wagner
"Modellierung von Farbstoffsolarzellen mit polymerem Lochleiter"
(Modelling of dye solar cells with a polymer hole conductor)
Doctoral thesis, University of Freiburg
Freiburg, 2004

Press Releases

www.ise.fraunhofer.de/english/press

09.03.2004
New Tariffs for Supplying Solar Electricity Attractive to Investors – Earn Money with Photovoltaics

03.03.2004
New Approaches to Successfully Integrate Social Aspects into Rural Electrification with Photovoltaics – Training for Project Leaders and Export Companies

30.03.2004
Environmentally Friendly Power Supply with Hydrogen – Fraunhofer ISE presents developments for the market in Hanover

26.05.2004
Tailor-Made Light Management – Small structures, large areas – British company invests in Holotools, a Fraunhofer ISE spin-off

30.06.2004
Freiburger Scientists break a Solar Cell World Record – Multicrystalline Silicon Solar Cell with an Efficiency Value of 20.3 Percent

30.07.2004
Enormous Potential for Passive and Lowest-Energy Houses – Fraunhofer ISE presents Market Survey

Lectures

Agert, C.
»Erneuerbare Energien im Vergleich«, Erneuerbare Energien für Entwicklung, Potsdam, Germany, 29.3.2004

Agert, C.
»Energiewende zur Nachhaltigkeit«, Umweltforum RWTH Aachen, Aachen, Germany, 15.7.2004

Aicher, T.; Siegel, C.; Federici, F.[1]; Parodi, L.[1]; Caprile, L.[1]
»Design and Operation of a 20 kW$_{el}$ Autothermal Diesel Reformer«, International Symposium & Workshop on Fuel Cells and Hydrogen for Aerospace & Maritime Applications, Hamburg, Germany, 16./17.9.2004
([1]: Ansaldo Fuel Cells S.p.A, Italy)

Aicher, T.
»Grundlagen der Reformierung«, Gast-Vortrag im Rahmen der Vorlesung »Brennstoffzellen und Batterien« von Prof. Ivers-Tiffee an der TU Karlsruhe, Germany, 15.12.2003

Aicher, T.; Lenz, B.; Gschnell, F., Groos, U., Federici, F.; Caprile, L.; Parodi, L.
»Fuel Processors for FC AOU Applications«, 9th Ulm Electrochemical Talks, Ulm 17./18.5.2005

Aicher, T.
»Erdgasreformer für BZ-BHKWs – Stand der Entwicklungen und Aussichten«, Gastvortrag am Engler-Bunte-Institute der Universität Karlsruhe, Germany, 21.6.2004

Aicher, T.; Kästner, P.; Mittermaier, M.; Gopinath, A.; Bett, A. W.; Schlegl, T.; Gombert, A.; Hebling, C.; Luther, J.
»Development of a Novel TPV Power System«, 6th Conference on Thermophotovoltaic Generation of Electricity TPV6, 14.6.2004, Freiburg, Germany

Aicher, T.; Specht, M.[1]; Höhlein, D.[2]
»Wasserstoffgewinnung aus Erdgas – Anlagenentwicklung und Systemtechnik kleiner Wasserstofferzeuger«, in: Tagungsband, Jahrestagung Forschungsverbund Sonnenenergie FVS, Berlin, Germany, 25./26.11.2004,
([1]: Zentrum für Sonnenenergie und Wasserstoffforschung ZSW Stuttgart, Germany)
([2]: Forschungszentrum Jülich FZ, Germany)

Bett, A.W.
»III-V Solar Cells: Their Technologies and Applications«, Seminar of Physics Department, University of Ferrara, Italy, 3.2.2004

Bopp, G.; Dohlen, K. v[1]
»Blitzschutz ohne Beeinträchtigung der PV«, OTTI-Energie-Kolleg 19. Symposium Photovoltaische Solarenergie, Bad Staffelstein, Germany, 10.–12.3.2004
([1]: Erhardt + Leimer Elektroanlangen GmbH, Augsburg, Germany)

Bopp, G.
»Electrical Safety, Lightning Protection, EMC«, SOLTRAIN Train-the-Trainer Workshop, Freiburg, Germany, 1.–13.2.2004

Bopp, G.
»Elektrische Lastbestimmung für SHS und PV Hybrid Systeme«, Seminar Netzferne PV-Energieversorgung in Entwicklungsländern, Freiburg, Germany, 5.–16.4.2004

Bopp, G.
»DC/AC Wechselrichter: Funktionsweise, Wirkungsgrad, Anforderungen«, Seminar Netzferne PV-Energieversorgung in Entwicklungsländern, Freiburg, Germany, 5.–16.4.2004

Bopp, G.
»Inwieweit tragen PV-Anlagen zum Elektrosmog bei«, Otti-Profiforum EMV und Blitzschutz für Solaranlagen, Freiburg, Germany, 24./25.11.2004

Bopp, G.
»Welche EMV Normen und Grenzwerte sind für Solaranlagen relevant?«, Otti-Profiforum EMV und Blitzschutz für Solaranlagen, Freiburg, Germany, 24./25.11.2004

Bopp, G.; Dohlen, K. v.[1]
»Beispielhaft ausgeführter Blitzschutz bei Kollektor- und PV-Anlagen«, Otti-Profiforum EMV und Blitzschutz für Solaranlagen, Freiburg, Germany, 24./25.11.2004
([1]: Erhardt + Leimer Elektroanlangen GmbH, Augsburg, Germany)

Borchert, D.[1]
»Multikristalline Silicium-Solarzellen«, Friedrich-Schiller-Universität Jena, Jena, Germany, 30.4.2004
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Abbreviations

AC alternating current
ADIRA Autonomous Desalination System Concepts for Sea Water and Brackish Water in Rural Areas with Renewable Energy
AFCo Ansaldo Fuel Cell SpA
Ag silver
Al aluminium
AlGaAs aluminium gallium arsenide
AIN aluminium nitrite
AM air mass
APCVD atmospheric pressure chemical vapour deposition
APU Auxiliary Power Unit
ASTM American Society for Testing and Materials
Bi bismuth
BFC bifacial cell
BMU Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
BSF back surface field
CalLab Calibration Laboratory
CDI carrier density imaging
CFD computational fluid dynamics
CIS copper indium diselenide
CL catalyst layer
CNRS Centre Nationale de la Recherche Scientifique
CO carbon monoxide
CO_2 carbon dioxide
CPC compound parabolic concentrator
c-Si crystalline silicon
CV capacitance/voltage
CVD chemical vapour deposition
Cz Czochralski
DAP Deutsches Akkreditierungssystem Prüfwesen (German Accreditation System for Testing)
DC direct current
DIN Deutsches Institut für Normung (German Institute for Standardization)
DLTS deep level transient spectroscopy
DMFC direct methanol fuel cell
EBIC electron beam induced current
EBR etchback regrowth
ECR electron cyclotron resonance
EFG edge-defined film-fed growth
EMC electromagnetic compatibility
EMS energy management system
EN European Norm (European Standard)
ERS electrical reflection spectroscopy
EU European Union
FASTEST facade test stand
FC fuel cell
FF fill factor
FhG Fraunhofer-Gesellschaft
FCHC fluorinated/chlorinated hydrocarbons
FLATCON Fresnel Lens All-Glass Tandem Cell Concentrator
FZ float zone
GaAs gallium arsenide
GaInP gallium indium phosphide
GaSb gallium antimonide
GDM gas diffusion medium
Ge germanium
GSM Global System for Mobile Communication
GTZ German Development Co-operation
IAM incident angle modifier
IEA International Energy Agency
IR infrared
ITO indium tin oxide
K Kelvin
kWp kilowatt peak
LBIC light beam induced current
LBSF local back surface field
LED light-emitting diode
LFC laser fired contact
LPE liquid phase epitaxy
mc multicrystalline
MCFC molten carbonate fuel cell
mc-Si multicrystalline silicon
MEA membrane electrode assembly
MFCA modulated free carrier absorption
MgF_2 magnesium fluoride
MIM monolithically integrated modules
MOCVD metal organic chemical vapour deposition
MOVPE metal organic vapour phase epitaxy
MPP maximum power point
MSCM miniature solar cell mapping
MW-PCD microwave-detected photo-conductance decay
N_2 nitrogen
NOCT nominal operating cell temperature
PCM phase-change material
PCS phase-change slurries
PCU PoMS Central Unit
PCVD photocurrent and voltage decay
Pd palladium
PDA personal digital assistant
PECVD plasma enhanced chemical vapour deposition
PEM proton exchange membrane
PEMFC proton exchange membrane fuel cell
PERC passivated emitter and rear cell
PIB PoMS Interface Box
POA power optimised aircraft
PoMS Power and Power Quality Management System
Pt platinum
PV photovoltaic
PV-TEC Photovoltaic Technology Evaluation Centre
PZTS Prüfzentrum für Thermische Solaranlagen (Testing Centre for Thermal Solar Systems)
RCC rear contacted cell
RCWA rigorous coupled wave analysis
RIE reactive ion etching
RPHP remote plasma hydrogen passivation
RP-PERC random pyramid, passivated emitter and rear cell
RRC realistic reporting conditions
RTCVD rapid thermal chemical vapour deposition
RTP rapid thermal processing
S/C steam/carbon ratio
SDCS solar desiccant cooling system
SEM scanning electron microscope
SFG Solare Fassaden und Gebrauchs-daueranalyse (Solar Facades and Durability Analysis)
Si silicon
SIMOX separation by implanted oxygen
SiN_x silicon nitride
SiO_2 silicon dioxide
SIR simultaneous infiltration and recrystallisation
SMD Surface Mounted Device
SME small and medium-sized enterprises
Sn tin
SOFC solid oxide fuel cell
SPS speicherprogrammierbare Steuerung
SPV surface photovoltage
SSP silicon sheets from powder
SR spectral response
SR-LBIC spatially resolved light beam induced current
TCO transparent conducting oxide
TDI thermal defect imaging
TDLS temperature-dependent lifetime spectroscopy
TI transparent insulation
Ti titanium
TiO_2 titanium dioxide
TOPLAB Thermisch-Optisches Prüflabor (Thermal-Optical Testing Laboratory)
TPV thermophotovoltaics
UESP Universal Energy Supply Protocol
UIB UESP Interface Box
UV ultraviolet radiation
VOC open circuit voltage
WO_3 tungsten trioxide
WPVS world photovoltaic scale
ZMR zone melting recrystallisation
Zn zinc
ZSW Zentrum für Sonnenenergie- und Wasserstoff-Forschung
η efficiency value

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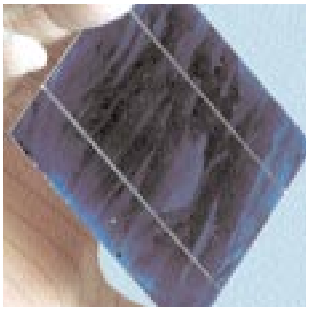

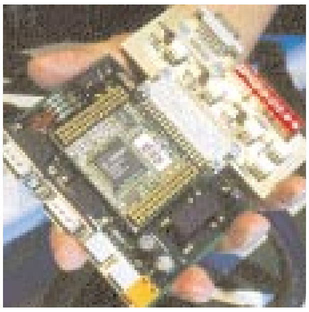

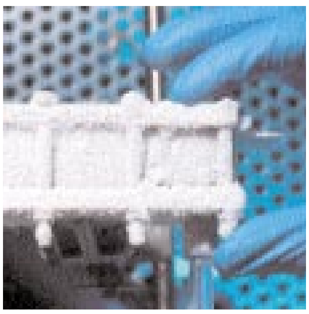

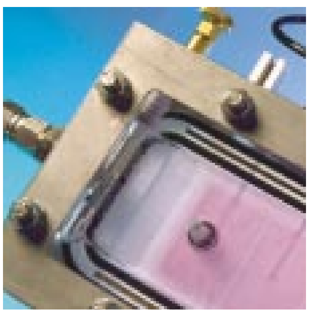

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