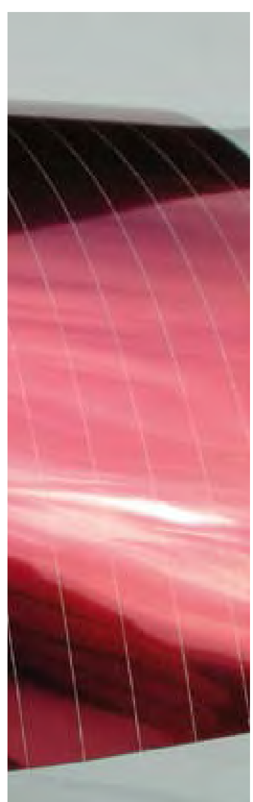
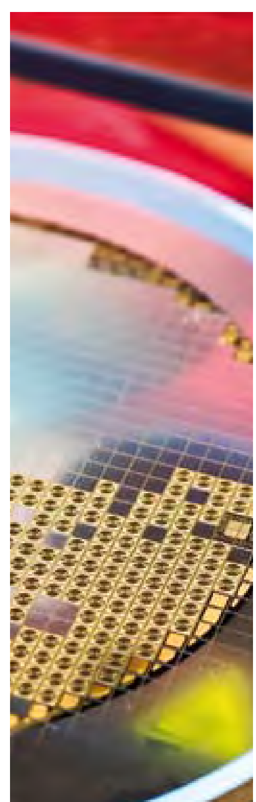
Fraunhofer Institut Solare Energiesysteme

ISE

Annual Report 2007

Achievements and Results





left
Novel giant fins of transparent polycarbonate with metallic inserts. The new product offers protection against both glare and overheating. The major target applications are external systems mounted in front of large glazed façades.

centre
Organic solar cell module. Investigation and development of coating procedures for roll-to-roll production of organic solar cells.

right
Tiny solar cells with several pn junctions made of III-V semiconductors. Because of their high efficiency values, these solar cells are used today in PV concentrator systems at light intensities of up to 1 megawatt per square metre.

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 materials, components, systems and processes for the following business areas: buildings and technical building components, optical components and systems, 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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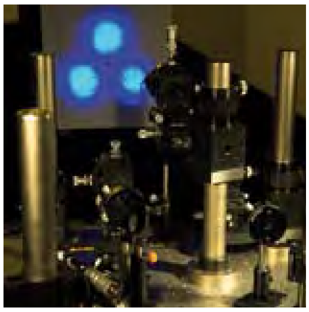

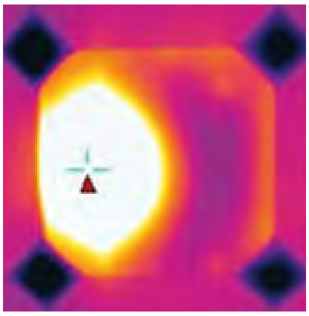

Facts and Figures

Foreword

2007 was my first complete year as the Director of Fraunhofer ISE, and I am very grateful to all staff members for what has been achieved this year. The ISE research topics in energy efficiency and renewable energy are becoming increasingly relevant, especially in light of the threat of catastrophic climate changes. In addition, the German Renewable Energy Law (Erneuerbare Energiengesetz - EEG), with its attractive tariffs for feeding renewably generated electricity into the grid, has resulted in the creation of financially strong companies, particularly in the photovoltaic sector. Many of these companies are partners of ISE in developing new technologies.

Specific highlights of the work at ISE during 2007 are presented on page 12. I would especially like to mention the world record efficiency of 98.5 % for an inverter with SiC transistors, the development of a catalytic diesel evaporator with an integrated reformer to use diesel fuel for fuel cells, a record efficiency value of 19.3 % for a silicon solar cell with screen-printed contacts on the front and laser-fired back-surface contacts, a 14.9 % efficient silicon thin-film solar cell on highly doped, multicrystalline silicon, and successful continuous operation of a compact solar system for desalination of seawater. In Almería, Spain, we participated in constructing a pilot solar-thermal power plant which includes absorber pipes developed by ISE and is distinguished by a novel, flat, Fresnel configuration of reflectors, which replace the large parabolic reflectors generally used in solar thermal plants.

The greatest objective measure of the successful work by ISE staff can be derived from developments in the budget and the number of employees. In 2007, ISE experienced further, very significant growth of more than 10 % in its budget – from 29.2 million euros in 2006 to app. 32.3 million euros in 2007 (more than 40 million euros when all investments are included) – just as the number of ISE employees increased by more than 20 % from almost 500 to more than 600 at the end of the year.

Our greatest problem at present is to find additional, qualified staff for the projects already acquired and to provide the necessary space for the associated laboratories and offices. For this reason, we have already rented further premises outside ISE this year. At the end of 2008, we plan to occupy additional, newly acquired laboratories close to the main building. Simultaneously, we will begin new construction on this site.

Beyond Freiburg, we are also working on extending our laboratories and establishing new outposts. The Laboratory and Service Centre LSC in Gelsenkirchen officially opened new laboratory and office facilities on 9th February, 2007 in the presence of Prof. Andreas Pinkwart, the Minister for Research in North Rhine-Westphalia. Also, work in the Technology Centre for Semiconductor Materials THM in Freiberg, which is operated jointly with Fraunhofer IISB Erlangen, and in our associated laboratory at the University of Constance, has made important progress this year. The completely new Centre for Silicon Photovoltaics CSP in Halle/Saale, which we operate jointly with Fraunhofer IWM in Halle/Saale, was founded on 1st June, 2007. IWM in Halle was already able to provide new rooms for CSP in new premises. In these laboratories, the first multicrystalline silicon ingot was already grown successfully before the end of the year.

In the second half of 2007, we took the first steps towards establishing a laboratory in the USA within the framework of the already existing organisation, Fraunhofer USA. The laboratories of Fraunhofer USA are each closely connected to a university. We plan to found a

Center for Sustainable Energy Systems CSE at MIT in Boston during 2008. There is also great interest in ISE's work at various places in Asia, so that 2008 is certain to bring further interesting developments in this direction.

Among the many new projects which began this year, special mention should be made of two which are supported by appreciable funding from the Fraunhofer foundation. The first project, led by Dr Stefan Reber, deals with the use of purified metallurgical silicon ("dirty silicon") for high-performance solar cells. The second one, led by Dr Christopher Hebling in co-operation with Fraunhofer IKTS, aims to develop fuel cell systems as power supplies for low-power applications. The second Fraunhofer Symposium on Micro-Energy Technology took place in Freiburg, parallel to the international Power MEMS Conference, with Dr Hebling chairing both events.

The Intersolar trade fair was held in Freiburg for the last time in 2007. This trade fair has been so extraordinarily successful over the past few years that it has outgrown the capacity of Freiburg's exhibition grounds, even though new exhibition halls had been built. For this reason, Intersolar 2008 will be held at the significantly larger exhibition grounds in Munich. Partly to compensate for this loss to the City of Freiburg, "Solar Summits" will be held annually in autumn in Freiburg. Fraunhofer ISE will be closely involved in these events, which will be devoted to a different topic each year. The first Solar Summit, entitled "Alternative Silicon Materials for Photovoltaics", will take place from 22nd to 24th October, 2008.

Furthermore, we were involved in taking Intersolar abroad for the first time: From 15th to 17th July, 2008, the first Intersolar North America will take place in San Francisco, together with Semicon West. One goal of Intersolar North America is to contribute toward the goal of significant growth rates in renewable energy in USA, particularly photovoltaics.

Among the personnel changes this year, I would like to start with the appointment of our Deputy Institute Director, Dr Volker Wittwer, to a professorship in the Faculty for Applied Science at the University of Freiburg. With our former Institute Directors, Prof. em. Adolf Goetzberger and Prof. em. Joachim Luther, who both still work at the Institute, and Prof. Roland Schindler and Prof. Gerhard Willeke, we thus currently have four further professors at ISE, as well as Dr Andreas Gombert, who also has the "Habilitation" qualification.

The success of ISE is also reflected by the career openings for our staff. Dr Carsten Agert, a group leader in the Energy Technology Department, was offered a professorship at the Carl von Ossietzky University in Oldenburg. This professorship is associated with the establishment and leadership of a new energy research centre, which is significantly funded by the energy utility, EWE AG.

Since February 2007, Prof. Luther has been a member of the newly founded expert commission of the German Federal Government devoted to research and innovation, which advises the Government on the direction of its research policies.

A further person who has particularly distinguished himself this year by his service to the Institute is our technical manager, Thomas Faasch. With his far-sighted planning, Mr Faasch has made the considerable expansion to the Institute this year feasible, and his negotiation skills were essential to finalising the contract to buy the land for our new premises adjacent to the present site before the end of the year.

Finally, I would like to thank sincerely our Board of Trustees, the representatives of the German Federal Ministries for the Environment, Research and Economics, whose continuing support of our work is so important, the staff of the relevant project management organisations, and the State Ministries in Stuttgart, which have strongly supported our expansion, for the trust they have shown us by their co-operation and support.

Andreas Bett Gerhard Willeke Karin Schneider Thomas Faasch Ralf Preu Stefan Glunz Volker Wittwer

The organisational structure of Fraunhofer ISE has 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 six business areas the Institute addresses.

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

Eicke R. Weber　Andreas Gombert　Christopher Hebling　Günther Ebert　Hans-Martin Henning　WolfgangWissler

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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 materials, components, systems and processes for the following business areas: buildings and technical building components, optical components and systems, solar cells, off-grid power supplies, grid-connected renewable power generation and hydrogen technology. Further expertise – in non-solar technology – includes display technology, lighting technology and water purification.

The Institute's work ranges from fundamental scientific and technical 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.

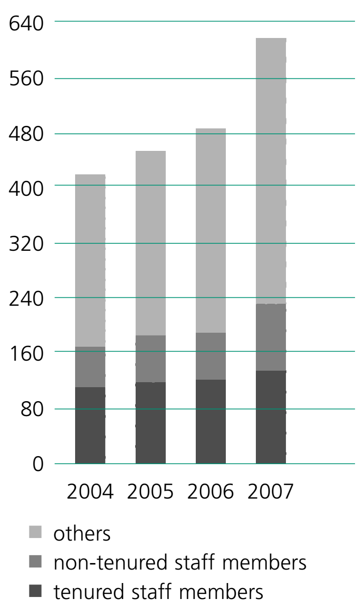
Research and Services Spectrum

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. The Institute is integrated into a network of national and international co-operation. Among others, it is a member of the ForschungsVerbund Sonnenenergie (FVS - 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. When required, the Institute can draw on expertise particularly from other Fraunhofer Institutes, so that complete interdisciplinary solutions can be offered.

Networking within the Fraunhofer-Gesellschaft

- member of the Thematic Association on "Energy"
- 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 "Nanotechnology"
- member of the Thematic Assocation on "Optically Functional Surfaces"
- co-ordination of the Fraunhofer Innovation Topic of "Microenergy Technology", in the context of "Signposts to Tomorrow's Markets"

Personnel



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 2007, 68 doctoral candidates, 102 undergraduate students, 3 apprentices and 213 scientific assistants were employed at the Institute. In this way, Fraunhofer ISE makes an important contribution to the education system.

International Clients and Co-operation Partners

The Fraunhofer Institute for Solar Energy Systems has co-operated successfully for years with international partners and clients from a wide range of business sectors. A list of our partners can be found under www.ise.fraunhofer.de/german/profile/index.html

Fraunhofer ISE external branches

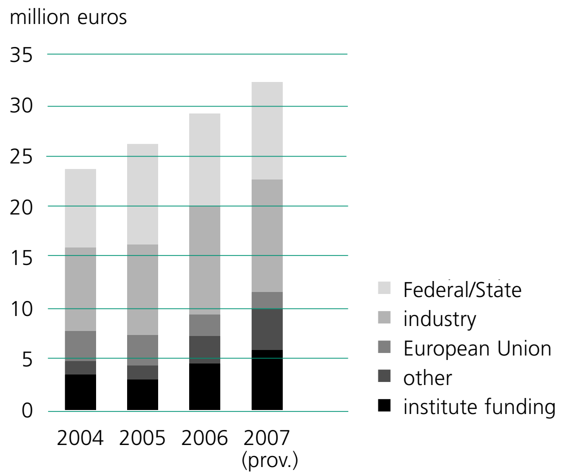
The Fraunhofer ISE Laboratory and Service Centre LSC in Gelsenkirchen, in the State of North Rhine-Westphalia (NRW), has existed since 2000 and is a partner for the photovoltaic industry also beyond the borders of NRW. Solar cell manufacturers draw on the services of LSC for quality control of their production and for rapid solutions to problems in their processing lines. The laboratory offers the simulation and optimisation of in-line processes, the development of new processes and structures for solar cells and research of large-area heterojunction solar cells of amorphous and crystalline silicon. LSC Gelsenkirchen also offers training sessions on characterisation procedures and solar cell technology.

The Technology Centre for Semiconductor Materials THM in Freiberg, Saxony, has existed since 2005 and represents a co-operation between Fraunhofer ISE and the Fraunhofer Institute for Integrated Systems and Device Technology IISB in Erlangen. Based on expertise in both Institutes, THM supports companies in research and development on material preparation and processing of 300 mm silicon, solar silicon and III-V semiconductors. Beyond this, THM offers analytical, characterisation and testing services for production by industrial partners.

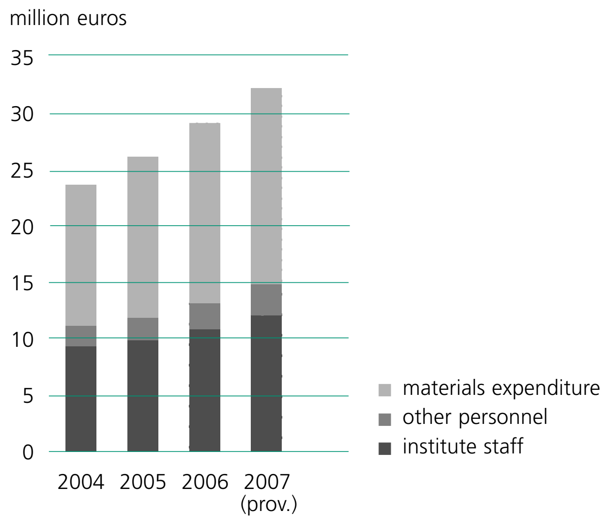
In co-operation with the Department of Physics at the University of Constance, the Photovoltaic Project Group has been run jointly by Fraunhofer ISE and the University of Constance since 2006.

The most recent external branch, the Centre for Silicon Photovoltaics CSP in Halle/Saale, is operated jointly by the Fraunhofer Institute for Mechanics of Materials IWM in Freiburg and Halle and Fraunhofer ISE. In this centre, which was founded in 2007, an internationally unique facility for crystallisation and material analysis is becoming established, in which targeted research and development on silicon material is carried out. This work is done in co-operation with industrial partners. Concepts for silicon thin-film cells and module integration are further major topics being addressed there.

Income



Expenditure



In addition to the expenditure documented in the graph, the Institute made investments of 10.4 million euros in 2007 (not including the BMU investment project, PV-TEC, which ran from 2005 to 2007).

The financial structure of the Fraunhofer-Gesellschaft distinguishes between the operational and investment budgets. The operational budget includes all expenses for personnel and materials, as well as their financing with external income and institutional funding. The integrated financial plan of the Fraunhofer-Gesellschaft allows funds to be transferred between the two budgets.

Research and Development

- successful continuous operation of decentralised compact systems for solar-thermal desalination of seawater
- test facility for measuring collector efficiency curves at temperatures up to 200 °C successfully developed and taken into operation
- innovative solar-control system developed with giant fins of glass-clear material
- novel thermal insulation system with vacuum insulation panels developed together with industrial partners
- outdoor test stand for PV modules and other solar components taken into operation on the Zugspitze, Germany's highest mountain
- new thermo-analytical laboratory commissioned for the development and characterisation of materials for heat storage and heat conversion
- paraffin emulsions operated stably as heat transfer fluids over several weeks for the first time (co-operation with Fraunhofer UMSICHT)
- demonstration Fresnel collector set up in co-operation with MAN Ferrostaal, Solar Power Group, DLR and PSE in Almería
- selectively coated absorber pipes and secondary reflectors for operating temperatures of 450 °C produced with a length of 100 m
- organic solar cells contacted through perforations and monolithically connected modules produced for the first time
- innovative connection technique developed for solar module of MWT (metal wrap-through) cells
- interference lithography with three waves implemented for the first time for hexagonal texturing of solar cells
- wave-optical modelling of microstructures and nanostructures for light trapping in solar cells
- commissioning of optimised control-room operation with distributed generators by the utility badenova AG
- commissioning of a web-based smart metering system
- efficiency improvement of 2.4 % achieved for a triple-phase inverter
- record efficiency value of 98.5 % achieved for a single-phase 5 kW inverter incorporating SiC MOSFET's
- international scope of expert reports on yields and quality assurance services for photovoltaic systems appreciably extended
- ZENITH software for predicting yields of photovoltaic systems completed, with a significantly broadened application area
- ISE module calibration laboratory achieved the highest accuracy in an international measurement round robin
- improvement in the earning situation due to the introduction of photovoltaic systems in rural areas of developing countries analysed
- new communication standards developed for photovoltaic hybrid systems
- battery management system successfully tested under real operating conditions
- PV fuel-cell hybrid system to supply power to stand-alone measurement station tested successfully under extreme ambient conditions
- purely mechanical cleaning procedure developed for membranes in water purification systems
- scalable monitoring system for operation control of power supply systems developed on the basis of embedded systems
- silicon solar cell with screen-printed front contacts and a dielectrically passivated back surface with laser-fired contacts (LFC) achieves an efficiency value of 19.3 %
- photoluminescence and electroluminescence techniques successfully established for spatially resolved characterisation of materials and solar cells

- high-efficiency solar cells produced with an efficiency value of 21.7 %, applying amorphous silicon for passivation and locally laser-alloyed back surface contacts
- cost-effective pilot screen-printing process developed for back surface contacted solar cells of multi-crystalline silicon with an efficiency value of 16.4 % (14.9 % module efficiency value)
- wafer-equivalent solar cell with an epitaxial emitter achieves an efficiency value of 14.9 %
- industrial units for in-line, light-induced plating constructed for reinforcement of solar cell contacts with silver or copper
- development of a back surface contacted, high-efficiency solar cell for mass production (in co-operation with ISFH) is the basis for the investment decision by Q-Cells AG to build a pilot production line
- industrially relevant crystallisation and wafering technical centre established
- first multicrystalline silicon ingots weighing app. 250 kg produced successfully
- heterojunction solar cell process developed as an investigation method for the interaction between the solar cell process and material
- masked printing of 10 µm narrow openings achieved with inkjet technology
- highly efficient III-V laser power converters developed with efficiency values exceeding 50 % for monochromatic illumination by a laser at 810 nm
- GaAs solar cell produced with an efficiency value of 25.4 % (AM 1.5g) as measured by ISE CalLab
- catalytic diesel evaporator with an integrated reformer (CPOX) presented
- fuel-cell system (300 W) developed for an autonomous service robot and optimised thermally
- hydrogen generator based on pyrolysis of hydrocarbons proves itself with more than 500 cycles
- injection-moulded, planar direct-methanol fuel-cell module presented

Professorships, Awards and Prizes

- Prof. Joachim Luther, former Director of Fraunhofer ISE, is a member of the Expert Commission on Research and Innovation, which was established in February 2007 to advise the German Federal Government on the direction of its research policies.

- Prof. Gerhard Willeke was appointed to a professorship at the University of Constance in March 2007.

- Prof. Volker Wittwer was appointed to a professorship at the University of Freiburg in October 2007.

- Dr Carsten Agert was offered a professorship in "Energy Technology" at the Carl von Ossietzky University in Oldenburg. This professorship is associated with the establishment and leadership of a new energy research centre, which is significantly funded by a large German energy utility, EWE AG. The "EWE Research Centre for Energy Technology" is to focus on renewable energy, energy efficiency and energy storage.

- Georg Mülhofer was awarded a prize by VDI Rheinland-Pfalz for his Master's thesis on "Investigation and optimisation of a solar-driven membrane distillation system for desalination of seawater".

- Marcel Wieghaus was honoured at the World Congress of IDA (International Desalination Association), 22.-26.10.2007 in Gran Canaria, for the "Best presentation" in the field of "Other desalination technology".

- Dr Oliver Schultz was invited to joint the "Think Tank 30 Deutschland" in 2007. The think tank is an interdisciplinary and intercultural forum of young people aged about 30, which was founded under the auspices of the "Club of Rome" in 2004 and concerns itself with questions of the future. As an independent group, the think tank contributes to debate in society and formulates recommendations for sustainable politics.

- Gerhard Peharz received an award from the Department for Environmental System Science of the University of Graz for his Master's thesis on "Development and characterisation of a highly efficient system for photovoltaic hydrogen generation".

- The poster on "Alternatives to Screen Printing for the Front Side Metallization of Silicon Solar Cells" by Mónica Alemán, Norbert Bay, Stefan Glunz, Andreas Grohe and Annerose Knorz received a Poster Award at the PVSEC in Japan.

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 work programme of Fraunhofer ISE.
Status: 24th November, 2007

Buildings and Technical Building Components

Optical Components and Systems

Solar Cells

Off-Grid Power Supplies

Grid-Connected Renewable Power Generation

Hydrogen Technology

Service Units

Buildings and Technical Building Components

Sustainable buildings not only protect the atmosphere, but are also easier to market. In particular, the marketing aspect will become more important now that the "building energy passport" has been introduced, as in future, the user will be able to evaluate the energy efficiency of a building. Buyers and tenants can be found more readily for buildings which use regenerative energy and feature high energy efficiency. This applies equally for new buildings and for the existing building stock, for commercial buildings and family homes. At the same time, sustainable buildings offer more user comfort: an abundance of natural lighting without glare, pleasant temperatures throughout the entire year and fresh air without draughts.

In Germany, around 40 % of the end energy continues to be consumed to keep building occupants comfortable. Although the energy demand per floor area has been reduced, this reduction has been outweighed by a larger living area per capita and other effects. Rational use of energy reduces the amount of energy consumed for heating, cooling, ventilation and illumination and often improves the user comfort at the same time. One principle applies in general: 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 new solutions are sought or if particularly high demands are to be met. We develop new equipment and concepts, turn them into practicable products or processes and test them in demonstration buildings. We also support the design of sophisticated buildings with simulation tools which we can develop further if required. The topics are treated at all levels, ranging from fundamental development to market introduction of materials, components and systems.

These tasks rely on co-operation between many disciplines - from materials research and coating design up to development of components and systems, including the necessary testing. For their application in building projects, we offer advice, planning and concept development on questions of energy and user comfort, as well as the implementation of new approaches to energy-efficient operation management and controls. Furthermore, we accompany completed projects with high-quality scientific monitoring. We support national demonstration programmes with comprehensive analyses.

Important aspects of our work on the building envelope include daylighting and solar control. In lightweight constructions, the heat capacity of the building is playing an increasingly important role, particularly when energy-saving cooling concepts are to be realised. We are developing new processes and systems for this application based on phase-change materials.

In heating, ventilation and air-conditioning (HVAC) technology, heat pumps are playing an increasingly important role in buildings with low energy consumption. Combined heat and power systems - or their extension as combined heat, power and cooling systems – are also gaining significance. In addition to solar-heated domestic hot water and solar-assisted space heating, promising solar energy applications for the future are offered by building integration of photovoltaics and solar-driven air-conditioning in summer.

Operation management is essential for optimal functioning of the complete system - building envelope, HVAC technology and users. New, model-based concepts for operation management are used to constantly monitor and evaluate, and if necessary correct, the performance of individual building components.

Working in a team together with architects, professional planners and industrial representatives, we develop the buildings of tomorrow. In doing so, we follow an integrated planning approach, optimising concepts with respect to economic viability, energy efficiency and user comfort. We help to define the international boundary conditions for this work by participating in programmes of the International Energy Agency IEA.

The long-term durability of new materials and components is becoming increasingly important. Thus, we are continuously extending our work on this topic and offer services which include not only characterisation by measurements but also model-based prediction of the aging process.

Buildings and Technical Building Components

In co-operation with TÜV Rheinland, an outdoor weathering facility for PV modules was installed on the "Schneefernerhaus" near the Zugspitze. Extreme temperature differences, high snow and wind loads and a high proportion of UV radiation serve to test products which must withstand extreme weathering conditions and provide a reference for the development of testing procedures for accelerated aging.

Contacts

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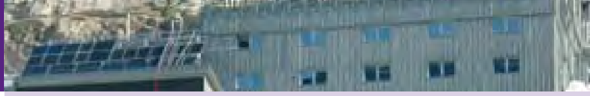


Synthesis and Analysis of Heat Storage Materials for Heating, Cooling and Heat Transformation

We have considerably extended the expertise in materials analysis, component development and system optimisation which had already existed on thermally active materials at Fraunhofer ISE. As a result, we now have comprehensive equipment available to synthesise and analyse materials for storing heat at high and low temperatures and for heat transformation based on sorption materials and phase-change fluids.

Stefan Gschwander, Stefan Henninger, Ferdinand Schmidt, York Tiedtke*, **Peter Schossig**, Hans-Martin Henning

* PSE GmbH Forschung Entwicklung Marketing, Freiburg

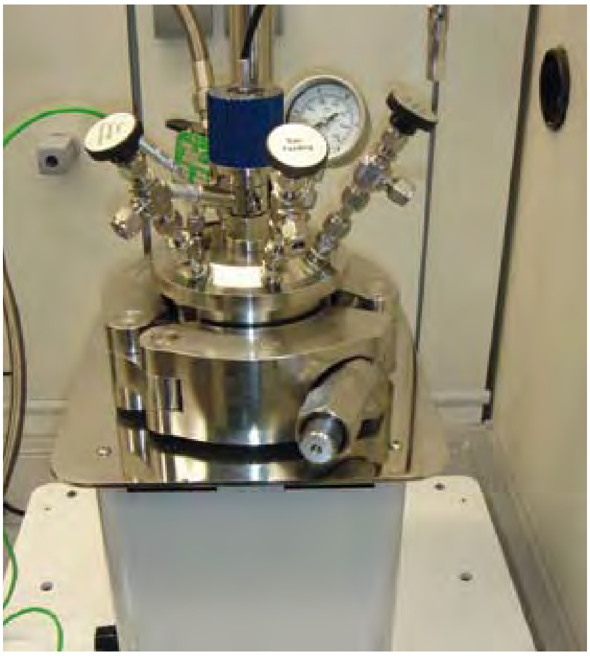


Fig. 1: Autoclave with stirring accessory for synthesis of highly porous sorption materials in the new synthesis laboratory.

Fig. 2: New system for simultaneous thermogravimetry and dynamic differential calorimetry, for the thermal analysis of sorption materials. The samples to be investigated can be heated to a temperature of up to 1200 °C with a graphite heating mantle.

In the newly equipped materials laboratory at Fraunhofer ISE, novel storage materials can be synthesised and developed specifically for planned applications in heat storage and transformation.

The laboratory is designed for research on sorption and phase change materials, two classes of materials which are particularly interesting for heat storage and transformation. This laboratory will allow us to advance materials development in the production of phase-change fluids more specifically in future. With our ontinuously operating reactor to synthesise sorption materials, we aim to accelerate the transition from laboratory synthesis to industrial implementation. Furthermore, we now have equipment to coat sorption materials on heat-exchanger substrates, which shortens the iteration cycle between materials and component development.

In addition, we have extended the existing capacity for materials and structural analysis. For thermal analysis, we have two further systems besides the one for thermogravimetry. The system for simultaneous thermogravimetry and dynamic differential calorimetry allows changes in mass and heat development to be recorded simultaneously, while the other system is for BET surface area analysis.

We also completed our spectrum of analytical facilities for phase change materials. We now have all fundamental systems available for analysing disperse systems, ranging from rheology to stability analysis.

The extension of our laboratory capacity was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Development of Process-Heat Collectors

There is increasing interest in the development of process-heat collectors which are suitable for applications with operating temperatures between 80 °C and 250 °C. Process-heat collectors are needed to access new application areas such as providing heat for industrial processes and solar-thermal air-conditioning and cooling. We support industrial developments in this direction both with our test stand and with simulation programs.

Stefan Heß, Korbinian Kramer, Stefan Mehnert, **Matthias Rommel**, Thorsten Siems, Wolfgang Striewe, Christoph Thoma, Hans-Martin Henning

Three technological approaches are distinguished in the current activities on developing process-heat collectors in the temperature range from 80 °C to 250 °C: 1) optimised flat-plate and evacuated tube collectors, 2) collectors with ow concentration factors, which are designed such that they do not have to track the sun (CPC collectors), 3) concentrating collectors, which can convert only direct solar radiation and thus have to track the sun. The third group includes parabolic trough concentrators, Fresnel collectors with fixed receivers and collectors with fixed reflectors and tracking receivers.

A total of 14 different process-heat collector developments were investigated within a Task of the IEA (International Energy Agency). Figure 1 shows the Fresnel collector from the Freiburg company, PSE GmbH. Together with PSE, we have analysed measurement data from trial operation of the collector, in order to determine the parameters for calculating the thermal performance. One set of measurement results is shown in Fig. 2.

In order to support the industry in developing process-heat collectors, we have developed a test stand in which we can measure the collector efficiency curve up to 200 °C in our testing centre. Specifically for the development of concentrating collectors, we have developed simulation programs to optimise the geometrical configuration of reflectors for process-heat collectors.

Fig. 1: Fresnel collector from the Freiburg company, PSE GmbH. The collector is used in Bergamo, Italy for a cooling application (NH_3/H_2O absorption chiller). The construction with the primary reflectors lying parallel to the roof means that the collector offers little wind resistance, so that it can easily be integrated into the building structure.

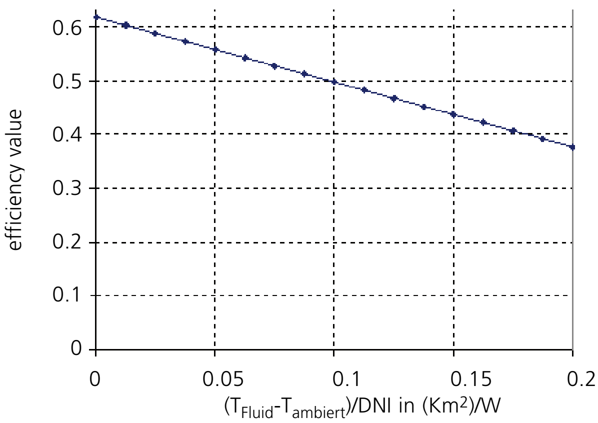
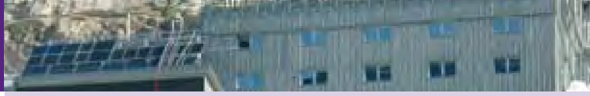


Fig. 2: Collector efficiency curve for a test collector of the same type, which is operated in Freiburg. In analogy to the determination of collector efficiency curves for flat-plate and evacuated tube collectors specified by EN 12975, operating phases with quasi-stationary conditions were analysed. The efficiency value is determined with reference to the direct normal irradiance (DNI). The aperture area for this collector is the area of the primary reflectors. The incidence angle modifier (IAM), which is also required for the analysis, was determined by PSE by ray-tracing simulation.

The work was carried out under our leadership as part of Working Group C (Collectors and Components) within the international IEA project on "Solar Heat for Industrial Processes" and was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).



Adsorber Development for Sorption-Based Heat Pumps and Chillers: New Characterisation Capabilities

One aim of our work on thermally driven heat pumps and chillers is to develop very compact systems. Zeolite coatings on porous metallic substrates and optimised evaporator structures offer great potential to raise the power density in adsorption technology. A new test stand allows small adsorbers to be characterised thermodynamically under conditions typical for applications. In another new testing facility, composite adsorbant samples can be rapidly thermally cycled to gain information on their cycling stability.

Anna Jahnke, Gunther Munz, **Ferdinand Schmidt**, Lena Schnabel, Daniel Sonnekalb, Marc Sosnowski, **Ursula Wittstadt**, Hans-Martin Henning

Fig. 1: Test stand for thermodynamic measurement of small adsorbers with a volume of up to 20 litres. The system is designed for an average cooling power of 400 W. The evaporator/condenser unit is deliberately over-dimensioned. This allows evaporation and condensation effects to be separated from processes occurring during adsorption.

A new test stand (Fig. 1) to measure small adsorbers has closed the gap at Fraunhofer ISE between the synthesis and characterisation of sorption materials, and the evaluation of thermally driven heat pumps and chillers. At present, the main adsorbers we are measuring are highly porous metallic structures coated with zeolite on different heat-exchanger structures. The power density which can be achieved is determined essentially by the good thermal coupling of thin zeolite layers (d < 150 µm) to substrate structures with a large specific surface area and good thermal conductivity, e.g. aluminium foams. Efficiency and power density are not the only relevant aspects, when adsorber elements are to be developed to commercial maturity. It is also important to demonstrate that continuously operating systems will function stably over their whole lifetime.

For this reason, a second experimental facility is used for thermal cycling of composite samples to investigate their lifetime. Inert gases formed during aging processes are analysed in a mass spectrometer. The underlying degradation processes can be deduced from this information. Pool evaporators are commonly chosen for the simplicity of the chemical engineering processes involved. In experimental investigations of different geometric configurations for heat exchangers, we can demonstrate the potential for improving the evaporation performance (Fig. 2).

The work is being carried out within an internal research project on “Thermally driven, high-performance cooling processes THOKA”, which is financed by the Fraunhofer-Gesellschaft, and the SORCOOL project on “Development of an adsorption chiller with high power density”, which is funded by the German Federal Ministry for Economics, and Technology.

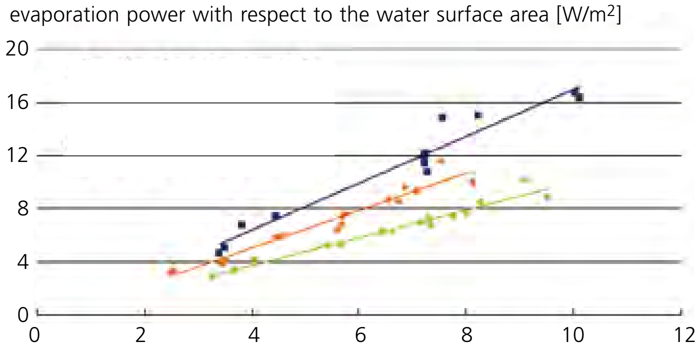


Fig. 2: The linear plots for the heat flux for fin and bundled pipe heat exchangers indicate that bubbling has not yet started and that evaporation is occurring from the water surface. As the structures were not completely immersed in water, the separation distance (d) between fins or the structured pipe surface could increase the water surface area by capillary effects and result in higher evaporative power due to thin-film evaporation.

Renovation with a Factor of Four

Within the IEA Task on "Advanced Housing Renovation with Solar & Conservation", new energy supply concepts for existing buildings are being developed on the basis of completed building renovation projects. The goal is to achieve a balanced energy budget averaged over the year.

Sebastian Herkel, Florian Kagerer, Hans-Martin Henning

The Fraunhofer Institutes for Solar Energy Systems ISE in Freiburg and for Building Physics IBP in Stuttgart, together with the "Passivhaus-Institut" in Darmstadt, have formed a national team of experts in the Working Group on "Advanced Housing Renovation with Solar & Conservation" within Task 37 of the "Solar Heating and Cooling Programme" of the International Energy Agency IEA. The aim of the joint work is to develop procedures and measures which result in an end-user energy demand in renovated residential buildings for heating (space heating, domestic hot water, auxiliary energy, ventilation) that is about a factor of four lower than the applicable national typical end-user energy demand.

In close co-operation with the industry, we are concentrating at the national level on the following points:

- the development of new or modified energy supply concepts for buildings
- work on comparative evaluation of existing and new demonstration buildings
- the assessment of new construction and building technology systems
- the development of appropriate design tools.

Fraunhofer ISE is leading the Working Group on "Design and Concepts". By monitoring two buildings in Heidelberg and Freiburg, we were able to prove the feasibility of implementing these concepts at a commercially acceptable cost. The detailed analysis revealed that the energy demand can be reduced above all for building technology systems and household appliances.

The work is supported by the German Federal Ministry for Economics and Technology (BMWi).

Fig. 1: Buildings renovated by the "Freiburger Stadtbau GmbH" under the project names of KfW 40 and KfW 60. We gained results from the renovation which allow us to compare different ventilation systems – with and without heat recovery – in detail.

Fig. 2: The GGH company in Heidelberg has implemented a zero-emission concept prepared by the planner, "solares bauen GmbH", in renovating its "Blaue Heimat" building. The combined heat and power (CHP) plant, together with a buffer storage tank, meets 95 % of the building's demand for heating energy.

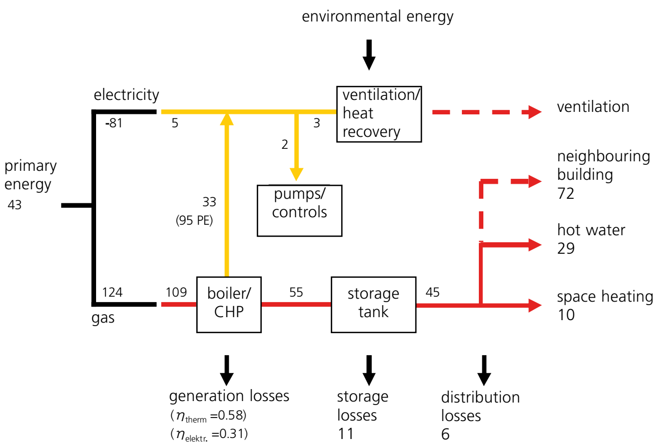
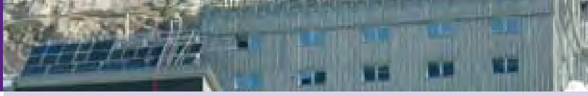


Fig. 3: Energy flow chart for the "Blaue Heimat" building in Heidelberg for the period from 10/2006 to 9/2007. It clearly shows that the energy consumption for domestic hot water is higher than that for space heating, which amounts to 10 kWh $m^{-2}a^{-1}$.



Energy-Efficient and Solar Cooling

We prepare concepts for energy-efficient building air-conditioning, which includes the use of both low-temperature heat sinks such as the ground and (solar) thermally driven cooling processes. A main aspect is always a balanced energy budget for the total heating and cooling demand, which is checked by participation in monitoring programmes. Beyond this, we work on new air-conditioning processes.

Martin Fischer, Daniel Gessner, Sebastian Herkel, Doreen Kalz, Alexander Morgenstern, Björn Nienborg, Tomas Nuñez, York Tiedtke*, Peter Schossig, **Jens Pfafferott, Edo Wiemken**, Hans-Martin Henning

* PSE GmbH Forschung Entwicklung Marketing, Freiburg

Fig. 1: Installation of three underground pipes, each reaching a depth of 80 m, in front of the Fraunhofer ISE premises. In summer, the underground loop is used for heat rejection for a solar-thermally driven adsorption chiller with about 15 kW of thermal power for re-cooling (Fig. 2). In winter, the underground pipes supply low-temperature heat for heat-pump operation of the same machine.

Solar-thermally driven cooling and air-conditioning can make an important contribution toward reducing the primary energy consumption in buildings and significantly lightening the load on the public electricity grid. However, it is only meaningful to install this technology in connection with building planning or renovation which aims for energy efficiency and minimisation of the cooling demand. This is the only way to limit the dimensions and thus the cost of the system components.

Fraunhofer ISE offers its expertise on systems technology as a service to support system planning. Advantage is currently being taken in the following projects of experience from a number of pilot and demonstration projects:

- "Solar Air-Conditioning and Refrigeration", Task 38 of the International Energy Agency IEA. Under the leadership of Fraunhofer ISE, package solutions are being developed for small, solar cooling systems with a rated cooling power of up to 20 kW. For larger systems, we are developing system concepts and standards.
- Fraunhofer ISE is co-ordinating the research on solar cooling systems, which is accompanying the "Solarthermie 2000plus" funding programme. The main tasks of this research are to assess the submitted project sketches, support the programme management in selecting suitable projects for funding, and subsequently subjecting the measurement data to comparative analysis. In the second half of 2007, the largest system for solar-thermally assisted air-conditioning in Germany was commissioned at the FESTO company in Berkheim: evacuated tubular collectors (1200 m^2), together with exhaust process-heat and gas-fuelled peak-load boilers, supply the energy for the three existing adsorption chillers. The rated cooling power of the system is 1 MW and serves to air-condition the offices.

Two further projects to test new systems technology will be presented in the following paragraphs:

- A small adsorption heat pump for solar-thermally assisted preparation of cold water (cooling power of 5.5 kW) from the SorTech company has provided the canteen at Fraunhofer ISE with cool air in summer and heat in winter since 2007. Recent developments in this power range open up an interesting market for year-round usage of solar heat in the residential sector, particularly in Mediterranean countries. The work was supported by the European Union.
- The rooms of the Engelhardt & Bauer printing company in Karlsruhe are cooled with ground-source heat pumps. The heat is removed from the offices by PCM cooling ceilings (SmartBoard™ phase change material) supplied by the ILKAZELL company. A prerequisite for this cooling concept with its small temperature differences is an optimised energy and building concept. Initial measurements in the EnSan project have shown that the indoor climate within the building is almost always acceptable, but that the cooling concept can be optimised further. Thermo-hydraulic optimisation is intended to double the cooling power and halve the pumping power. The goal for 2008 is an annual coefficient of performance of 10 kWh cooling energy per kilowatt-hour of input electricity.

The work is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the Solarthermie 2000plus Programme, and in the EnSan project by the German Federal Ministry for Economics and Technology (BMWi).

Fig. 2: Adsorption chiller with a heat-pump function. The rated cooling power amounts to 5.5 kW. The input air for the kitchen of the Institute canteen is cooled with this plant. The driving heat is supplied by flat-plate collectors with an area of 22 m² and by the heating circuit of the Institute. The plant was developed by the SorTech company, a spin-off from Fraunhofer ISE, with the support of the Institute.

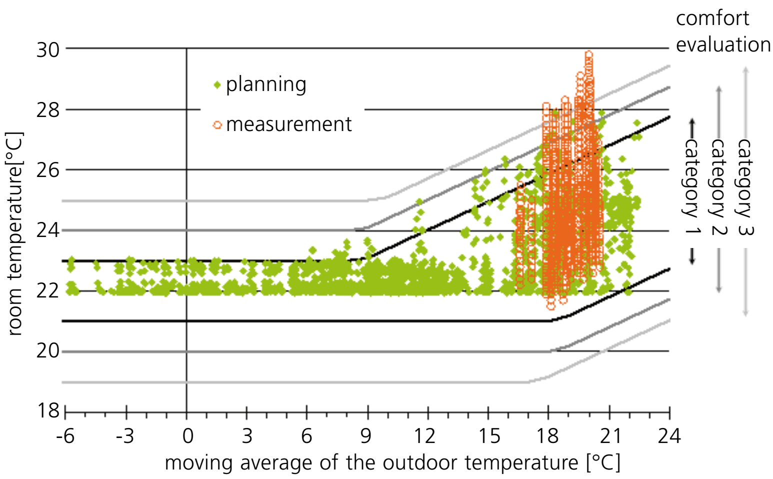
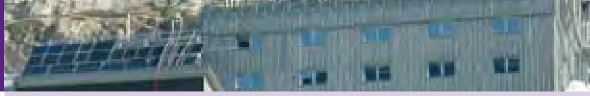


Fig. 3: Room temperatures in the Engelhardt and Bauer printing company, plotted in a comfort diagram according to EN 15251 (category 1 = very high, 2 = normal and 3 = modest demands on the indoor climate). Category 2 should be achieved in new construction and renovation projects. In the summer of 2007, the building was about 2 K warmer than predicted on hot days because the cooling ceilings were not yet optimally operated.



Optimisation of Solar Control for Complex Façade Systems

The transmittance of direct solar radiation by innovative façades has a strong angular dependence. This is important to guarantee a clear view outwards and simultaneously achieve effective solar control in summer. The application of a new calculation procedure for the angular dependence of the total solar energy transmittance (g value) was demonstrated using the new headquarters of Thyssen Krupp Ag as an example.

Sebastian Herkel, Tilmann Kuhn, **Jan Wienold**, Hans-Martin Henning

Fig. 1: Simulation model of the vertically rotatable sun-shading elements for the headquarters of Thyssen Krupp AG. The sun-shading elements can track the sun so that they both provide effective solar control and allow a good view of the surroundings.

Fraunhofer ISE has advised Thyssen Krupp AG on optimising the building façade and its solar control, on thermal and visual comfort, and on the energy demand of its new headquarters.

Sun-shading devices which can be rotated around a vertical axis were designed for the main building. This construction takes account of the office orientation to the east and west. Each sun-shading element consists of fixed horizontal slats which are mounted on a rotatable axis. We optimised the spacing between the slats and the slat angle such that not only solar control but also sufficient visibility outwards and extensive glare protection are achieved. Another special feature is that the slats of adjacent axes are offset so that they can interlock. This prevents vertical gaps from forming.

The angle-dependent total solar energy transmittance (g value) was calculated with a newly designed calculation tool based on the RADIANCE program for lighting simulation. The angle-dependent g value was used in turn as an input parameter for thermal calculations with the ESP-r simulation environment. This made it feasible to take the strongly angle-dependent behaviour of the sun-shading elements adequately into account in the thermal building energy simulation.

Fig. 2: Photo of a functional sample of the sun-shading elements illustrated in Fig. 1. The slats are made of stainless steel.

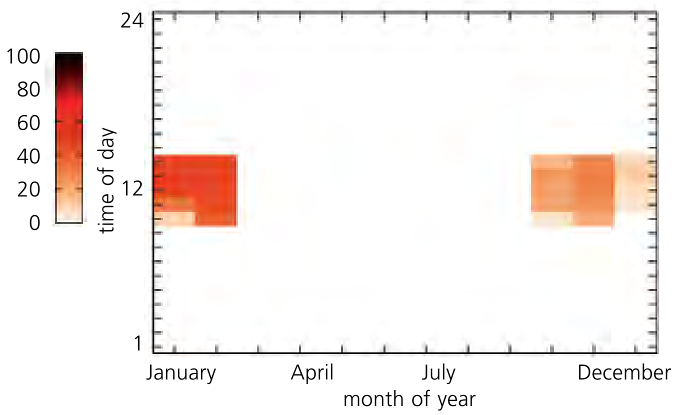


Fig. 3: Calculation of the transmittance of direct illumination for the optimised sun-shading elements. The diagram shows the temporal distribution (over the hour of day and month of the year) of direct glare at the occupant's work place. The colour indicates the relative frequency of glare. Direct illumination enters between the slats only in the winter months. During these months, the solar-control function is deactivated so that passive solar gains can be used. Complementary glare protection is provided by an additional roller blind.

Giant Slat of Glass-Clear Material for an Innovative Solar-Control System

Our newly developed giant slats provide solar control and glare protection for large façades. The 70 cm wide and up to 17 cm high elliptical slats consist of a glass-clear polycarbonate envelope and highly reflective metal inserts. They can provide very good solar control (effective g values ≤ 0.15) and glare protection. In addition, the transparent envelope allows daylight to be redirected via the metal reflectors into the room without causing glare.

Tilmann Kuhn, Peter Nitz, Thomas Schmidt, Hans-Martin Henning

The development of solar-control systems has been a focus of work on efficient buildings at Fraunhofer ISE for many years. Comprehensive procedures that we have developed to assess the solar-control and glare-protection effects go beyond the state of the art, because they take realistic user behaviour, realistic irradiation conditions and the angular dependence of façade properties into account. Our accredited laboratory for thermal and optical testing helps us in characterising prototypes during the development and experimental validation phases (see also Service Units, p. 104).

The essential goals in developing the new giant slats were:

- very good solar control with effective total solar energy transmittance values (g values) ≤ 0.15
- high degree of glare protection
- glare-free daylighting
- "light" appearance, distinguishing them clearly from the competing slats made of painted aluminium sheets
- conformity with the remaining building-science requirements

We designed the basic structure for the giant slat to be an extruded form of glass-clear polycarbonate. All development goals were achieved with this prototype. A patent application has been lodged for the new system. It will be introduced to the market by the company which commissioned this research project, Prokuwa Kunststoff GmbH in Dortmund.

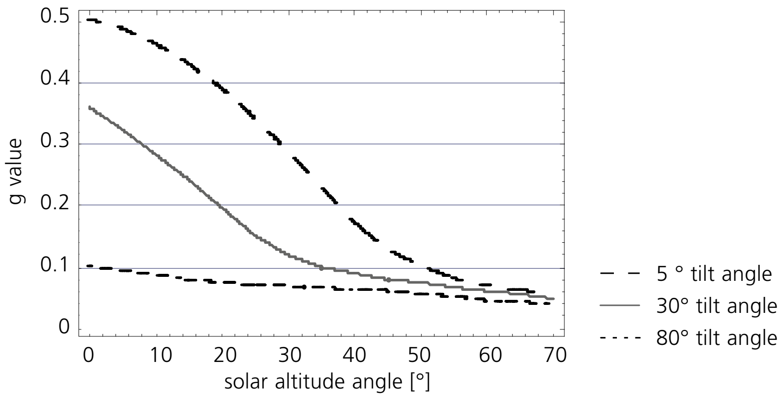


Fig. 1: Angle-dependent g value for the new giant slat from Prokuwa. It is evident that a very low g value below 0.10 is obtained already for a slat tilt angle of 30 ° and a solar altitude angle of more than 35 °.

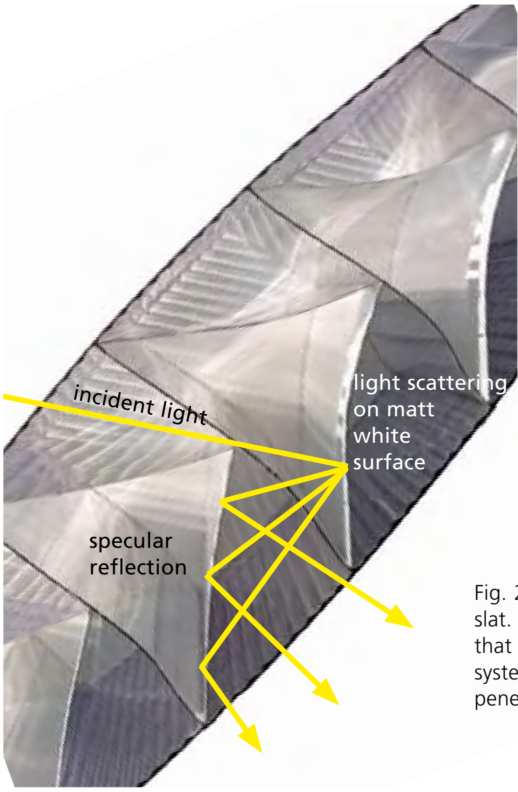
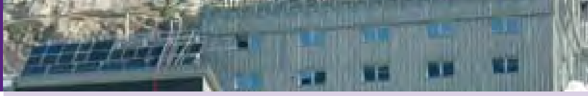


Fig. 2: Cross-section through a giant slat. The ray-tracing demonstrates that direct radiation is blocked by the system but that diffuse daylight can penetrate for indoor illumination.



Heat Pumps for High Energy Efficiency in Residential Buildings

Heat pumps are becoming increasingly important for supplying heat to residential and commercial buildings. According to estimates by the "Bundesverband für Wärmepumpen" (BWP – German National Association for Heat Pumps), the installation of heat pumps will increase by more than a factor of ten up to 2020. The ecological balance for compression heat pumps can be improved further by using natural cooling agents. We are supporting plant manufacturers in this sector in the development of new equipment or components, with system and component simulation, prototype development, test stand characterisation, evaluation of preliminary series and broadly based field measurement campaigns.

Till Gottschalk, Thomas Kramer, **Marek Miara, Thore Oltersdorf, Christel Russ**,
Robert Salignat, Benoît Sicre,
Jeannette Wapler*, Hans-Martin Henning

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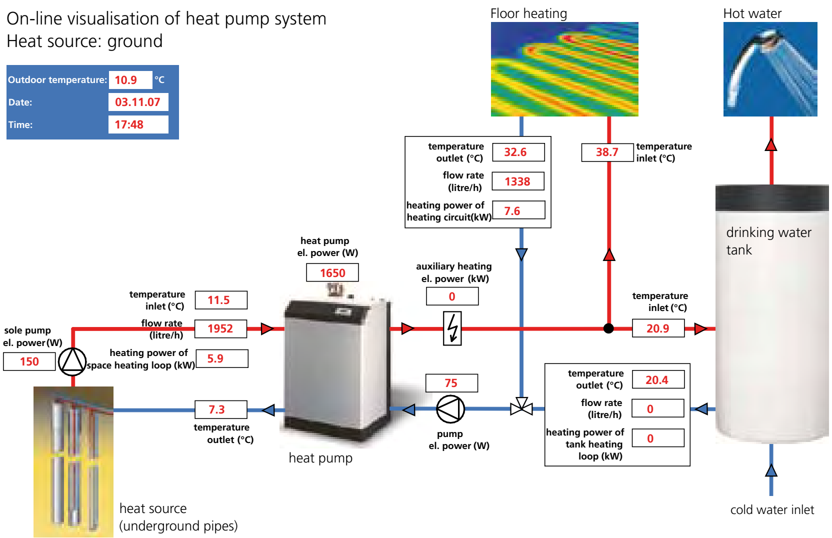


Fig. 1: At present we are carrying out intensive measurements of around 150 heat pumps operating in residential buildings. In addition to the electricity consumption of the heat pump and all auxiliary equipment, we also record the flow rates and temperatures of the heat source and the heating circuit every minute. In this way, we can analyse the operating behaviour in detail and derive recommendations for optimisation.

Heat pumps allow energy from the surroundings or low-temperature solar heat to be used to a large extent for space heating and domestic hot water. In general, electricity is used to operate compression heat pumps. Therefore, not only low production and operating costs but also high efficiency and robust operation are essential.

Fraunhofer ISE supports industrial partners in implementing innovative ideas and carries out its own developments of equipment and patents. By combining different sources of heat (exhaust air, outdoor air, ground, solar heat), we increase the efficiency and broaden the range of possible applications for heat pumps. In addition, we support the transition from fluoro-hydrocarbons to natural cooling agents such as propane or CO_2.

During our component and system development, we use the Modelica simulation environment, e.g. to investigate the cooling circuit during dynamic operation and to check control strategies under varying operating conditions. In extensive monitoring projects, we are conducting field measurements on 240 systems both in existing buildings and in newly constructed low-energy housing projects. The energy-relevant, economic and ecological efficiency of heat pumps from a wide variety of manufacturers is being investigated. To this purpose, we will record all the important system parameters on the heat source and heat sink sides of 150 heat pumps every minute during the 2007/08 heating period. The data will be radio-transmitted daily for acquisition at the Institute. Some systems will be visualised as examples on the Internet. We check supply reliability by analysing system behaviour under different boundary conditions. From this, we prepare recommendations for developing the equipment further and optimising the systems.

The projects are supported by the German Federal Ministry for Economics and Technology (BMWi), industrial partners and energy utilities.

Polymer Materials for Solar-Thermal Applications

Solar collectors made completely of polymer materials display clear cost advantages compared to collectors produced out of metal and glass. The objective is to find a material which meets the optical and mechanical specifications for a high-performance solar collector. In addition, the geometrical configuration must be optimised to compensate for the unfavourable thermal conductivity of polymers. We have developed suitable simulation tools for this purpose.

Hannes Franke, **Michael Köhl**, Eva Stricker, Karl-Anders Weiß, Hans-Martin Henning

In order to achieve optimal system performance, we are co-operating with other research laboratories and companies from the polymer and solar technological branches to develop a completely new system design for thermal solar collectors within Task 39 of the "Solar Heating and Cooling Programme" of the IEA (International Energy Agency). Central topics are the absorption of solar radiation, the thermal conductivity and the heat capacity of the new materials. To optimise the absorber design, a simulation tool was developed on the basis of the COMSOL Multiphysics finite-element program package. We use this program to carry out parameter sensitivity and optimisation studies by calculating the flow profiles (Fig. 2) and the temperature distribution (Fig. 1) for different geometrical configurations of the flow channels. Another important aspect for developing the system design is the feasibility of extrusion. It is a decisive criterion for mass production and thus cost reduction. In the course of a study, commercially available polymer materials were identified to be suitable on the basis of their properties, their utility and their processing options. In addition, the problems which can be anticipated for solar-thermal applications due to UV radiation, high temperatures and mechanical loads on the materials were documented.

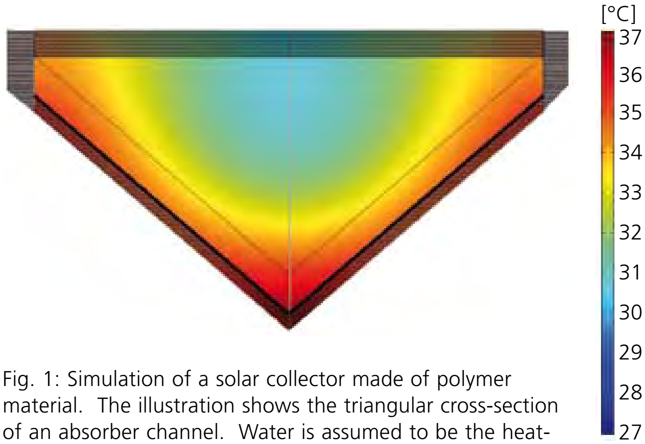


Fig. 1: Simulation of a solar collector made of polymer material. The illustration shows the triangular cross-section of an absorber channel. Water is assumed to be the heat-transfer medium. Insulating materials, glazing, etc. have not been included here. The temperature distribution in the various materials is shown. The solar radiation is absorbed on the internal surface of the lower walls of the triangle.

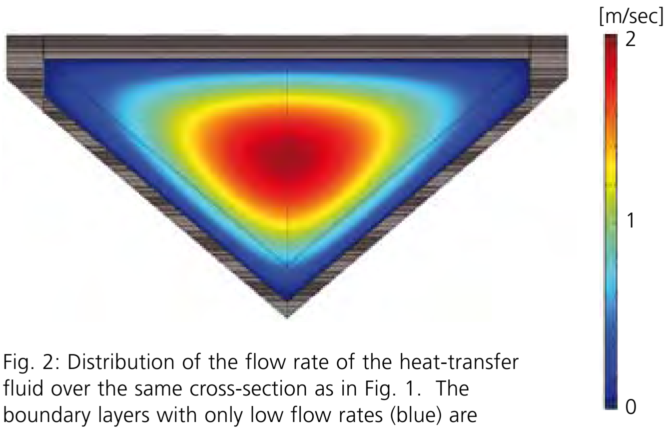
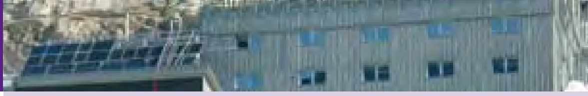


Fig. 2: Distribution of the flow rate of the heat-transfer fluid over the same cross-section as in Fig. 1. The boundary layers with only low flow rates (blue) are clearly evident. These layers correspond to the warmest regions (red) in Fig. 1.



Development of Production Technology for Evacuated Insulating Glazing

Evacuated insulating glazing allows windows to be produced with low heat transfer coefficients and very slim frames. The production processes which have been applied up to now do not yet completely meet the demands of the market. In a joint project, we are developing new production techniques which allow also large-area evacuated insulating glazing units (IGU's) to be manufactured. The feasibility of implementing a novel concept for a vacuum-tight edge seal plays a key role in this development.

Wolfgang Graf, Josef Steinhart, Walter Schnetzler, Armin Zastrow, Andreas Gombert

Fig. 1: Display sample of evacuated insulating glazing with a glass/metal edge seal (before edge polishing and framing) and glass spacers.

Fig. 2: Damage to an experimental sample caused by impact from a steel ball. The glass breaks at the position of these spacers, which were thus classified as unsuitable.

Evacuated insulating glazing has lower heat transfer coefficients (U values) than conventional thermally insulating glazing, combined with appreciably lower mass and IGU thicknesses < 10 mm. The gap between the panes, which is defined by spacers, can be of the order of one millimetre. The existing production technology for evacuated insulating glazing is complicated and cannot be scaled up to large glazing areas.

In co-operation with industrial and other research partners, we are developing new production techniques which feature a vacuum-tight, metal edge seal (Fig. 1). Fundamental work on this edge seal and important aspects of production technology was already completed during the first project phase up to the end of 2006. Solutions were found for cleaning and drying the glass, for suitable getter materials and for producing joins in the edge seal. Resistance to the mechanical loads on the edge seal during the evacuation process and point loads such as those caused by hail were also tested (Fig. 2).

Now our work is concentrating on testing the feasibility of producing large-area evacuated IGU's with a test facility. Our industrial partners are integrating special cleaning and positioning/joining equipment into an existing vacuum system at Fraunhofer ISE, so that prototype evacuated IGU's can be produced.

Practicable Exterior Thermal Insulating System with Vacuum Insulation Panels

A high potential for insulating buildings with vacuum insulation panels has been predicted for many years. However, a practicable thermal insulating system was lacking, which combined a slim design, minimal thermal bridges, protection against damage and adaptability to building tolerances. Together with industrial partners, Fraunhofer ISE developed the LockPlate® system. We investigated optimisation of the construction, heat and moisture transport and permeation through barrier films.

Michael Köhl, Daniel Philipp, **Werner Platzer**, Christel Russ, Thomas Schmidt, Helen Rose Wilson, Andreas Gombert

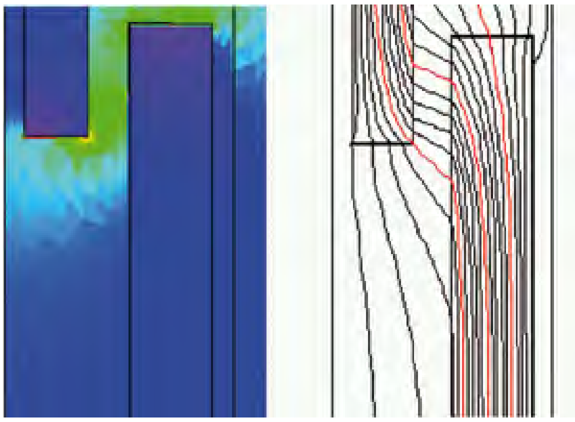


Fig. 1: Calculated distribution of the heat flux density (left, colour-coded) and isotherms (right) in the investigated composite external insulation system based on vacuum insulation technology. Edge region of a construction with VIP (d = 30 mm, long rectangle) in the main layer and VIP (d = 20 mm, short rectangle) in the cover layer.

In order to achieve the thermal insulation values demanded today ($U_W < 0.3$ $Wm^{-2}K^{-1}$), often double-layer walls with external insulation are built. A cost-effective solution is presented by composite systems of exterior insulation and finish. An insulating layer thickness of 200 – 300 mm occupies a large volume and can be architecturally undesirable. Compared with styrofoam or mineral wool, vacuum insulation panels (VIP) offer much slimmer solutions due to the 8 – 10 times lower thermal conductivity in the panel core. Together with our industrial partners, Porextherm and Maxit Deutschland, we have developed an exterior insulation and finish system (LockPlate® system), which offers a number of advantages compared to previous prototypes:

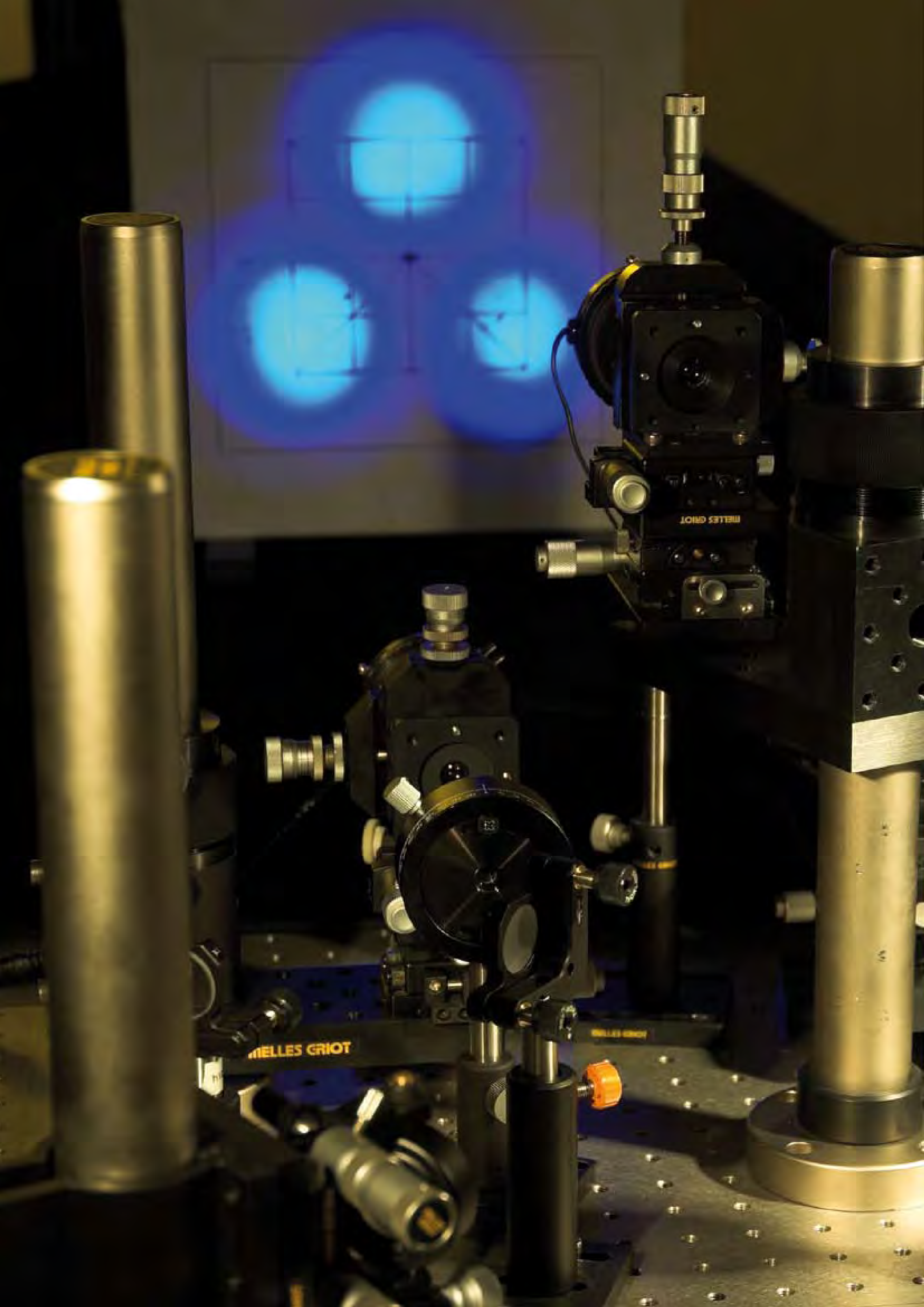
- better protection of the panels against damage
- production of only a few standard sizes necessary, as flexible adaptation to different dimensions is possible
- penetration points can be easily planned
- minimised thermal bridges

The practicable optimum was found to be a system of vacuum insulation panels surrounded by expanded polystyrol (EPS). Theoretical simulations and experimental measurements of the heat transport of different construction variants supported the development. The minimised permeation characteristic of the barrier films and the good sorption properties of the core material determine the lifetime of the VIP's.

Fig. 2: Demonstration building (free-standing house near Giengen/Brenz) clad with the new VIP composite external insulation system (thickness 90 mm). Heat transfer coefficient (U value) of the wall, $U_W = 0.13$ $Wm^{-2}K^{-1}$.

As a demonstration, a free-standing house was clad with the insulating system with a total thickness of 90 mm (passive house variant is 110 mm) and equipped with measurement technology for monitoring.

The project was supported by the German Federal Ministry for Economics and Technology (BMWi) within the VIBau programme (www.enob.info).


MELLES GRIOT

Optical Components and Systems

Solar energy systems convert solar energy, which is incident on the earth as electromagnetic radiation, into thermal, electric or chemical energy. We develop optical components and systems to better transmit, reflect, absorb, filter, redirect or concentrate solar radiation, depending on the requirements.

The broad bandwidth of the solar spectrum, covering wavelengths from 0.3 to 2.5 µm, and the need to produce optical components and systems inexpensively over large areas, present major challenges. To meet these, we follow novel approaches, which combine materials research, optical design and production technology. In addition to optical know-how and close co-operation with our clients, comprehensive knowledge of solar energy systems is necessary to transfer the approaches successfully to new products for solar technology. Fraunhofer ISE provides excellent opportunities for the synergetic interaction needed for this.

The interdisciplinary topic, "Optical Components and Systems", is the basis for several market sectors of solar technology: windows and façades, solar thermal collectors, photovoltaics and solar power stations. Our expertise is also appreciated by clients who do not come from the solar sector. For example, we provide support for lighting and display technology.

Switchable coatings on window panes allow the window transmittance to be reduced when the building is in danger of overheating. Gasochromic glazing, in which the absorption can be varied over a wide range, has already been tested successfully in demonstration façades. Laboratory samples of photochromic and photoelectrochromic systems have shown very good optical results and are extremely promising for glazing units. Microstructured surfaces form the basis for sun-shading systems which reflect undesired direct solar radiation but still transmit diffuse daylight.

The combination of micro-optical know-how and interference lithography over large areas has allowed Fraunhofer ISE to expand its activities in an area outside solar technology, namely display technology. Here, we are working on micro-structured polymer films which improve the brightness and contrast of displays. Light redirection is a central topic in lighting technology. Drawing on our work for daylighting technology, we also offer our expertise in optical materials and surface properties for optical design in artificial lighting technology.

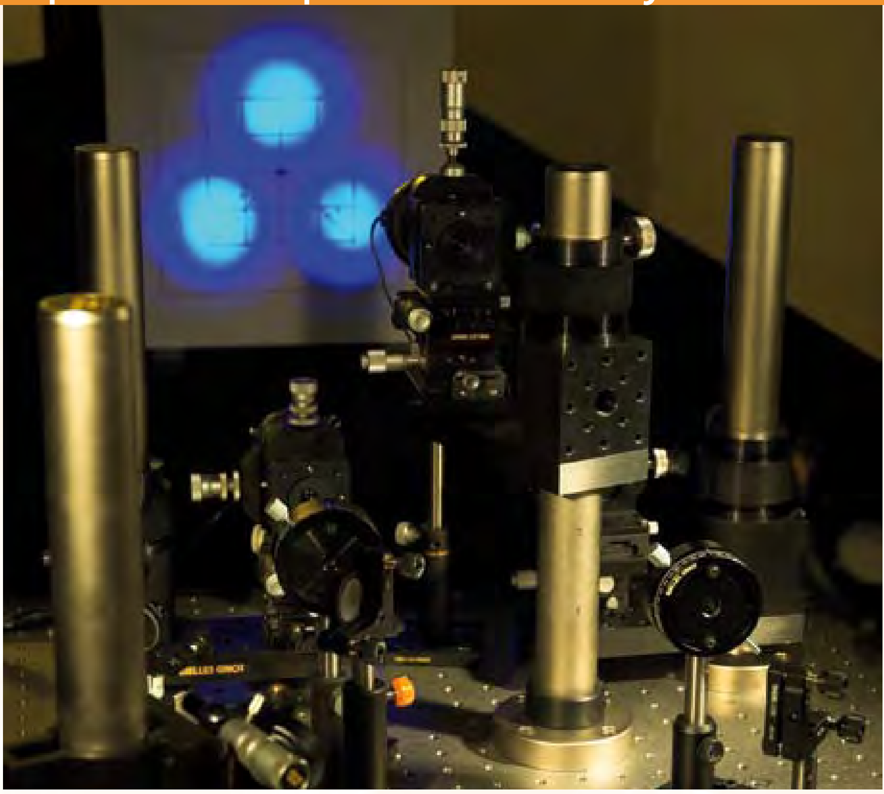
We have developed selective absorber coatings for solar thermal collectors (temperatures of up to 230 °C) and transferred them to industrial production for many years now. However, coatings for absorber pipes in solar-thermal power plants must permanently withstand much higher temperatures of around 400 °C. This is achieved by integrating additional layers into the coating stack to act as diffusion barriers, selected according to the type of absorber pipe.

In photovoltaic concentrator modules, solar radiation is concentrated onto tiny, high-performance solar cells. We optimise the required concentrator optics with respect to efficiency and costs.

Over the past years, we have continually extended our modelling capacity. It encompasses fundamental physical models such as effective-medium theory, rigorous and scalar diffraction theory, scattering theory, thin-film methods, geometric and non-imaging optics, as well as planning tools, e.g. for lamp design. This means that we can respond quickly and efficiently to clients' enquiries in determining the feasibility of a desired optical component. Vacuum coating and micro-structuring processes are available to us as production methods. Our characterisation methods not only include standard procedures but also use special equipment, e.g. to determine bi-directional optical properties. Whenever needed, we extend the palette of services by close co-operation with recognised research institutions within and outside the Fraunhofer-Gesellschaft.

Special facilities:

- vacuum deposition system for quasi-industrial production of complex coating systems over large areas (140 cm x 180 cm)
- interference-lithography equipment for homogeneous production of microstructures and nanostructures over areas of up to 120 cm x 120 cm
- optical measurement technology: spectrometry with integrating spheres, goniometry, light-scattering measurements



Facility for interference lithography, in which three coherent waves are superimposed to create a hexagonal structure (see also p. 38). In the foreground are the optical components, with which the three laser beams are redirected and broadened. In the background is a screen for demonstration purposes, onto which the three broad beams are projected. For an exposure process, the screen is removed, so that the partial waves can be superimposed in a plane behind the screen position.

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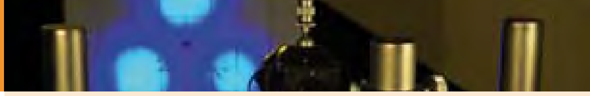


Transparent Electrodes for Solar Cells based on Thin Silver Films

In some thin-film solar cells, but also in organic light-emitting diodes, tin-doped indium oxide (ITO) coatings are used as transparent layers for conducting the electricity. The rapidly rising price for the raw materials has stimulated the search for alternatives. Thin silver films have high transmittance values and conductivity, and can be produced inexpensively. We have successfully tested the first samples with organic solar cells.

Andreas Georg, Wolfgang Graf,
Michael Niggemann, Tobias Schosser,
Andreas Gombert

Five Institutes of the Fraunhofer-Gesellschaft are currently working on the development of transparent, electrically conductive thin-film systems, which are needed for many opto-electronic applications and above all for thin-film photovoltaics. The tasks for Fraunhofer ISE include the development of thin-film stacks based on thin silver films. We have obtained the first important results for application in organic solar cells.

Transparent, electrically conductive electrodes are produced by sputtering. An approximately 10 nm thin silver film is sandwiched between two dielectric layers. The film below the silver must promote good coverage by the silver itself, so that high conductivity can be achieved with the thinnest possible film, resulting in high transmittance. ZnO or SnO_2 are suitable materials for this purpose. The dielectric cover layer should stabilise the thin silver coating and establish good electric contact to the following systems, in this case an organic solar cell. In principle, this electrode can also be used for other systems such as organic light-emitting diodes or other thin-film solar cells. In all cases, not only electronic but also optical adaptation is possible by depositing a multi-layer stack with appropriately selected film thicknesses and additional dielectric layers. The interferences within the multi-layer

Fig. 1: Schematic stack structure of an organic solar cell with a transparent silver electrode

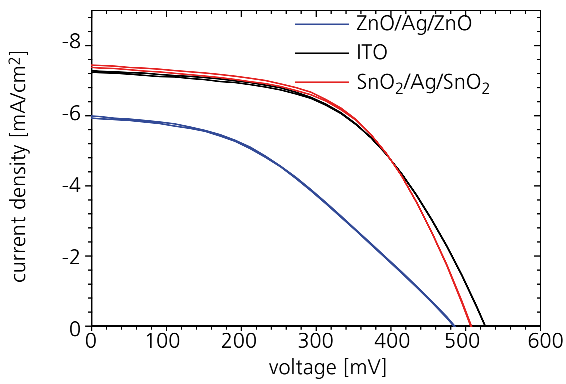


Fig. 2: Characteristic curves under illumination (AM1.5) of three organic solar cells with a PEDOT:PSS layer and ITO, ZnO/Ag/ZnO or SnO_2/Ag/SnO_2 as the electrodes.

stack are tailored to optimise the optical properties, e.g. the absorption of solar radiation in the photoactive layer of solar cells.

In an organic solar cell, the next layer to be deposited can be of electrically conductive polymer (polyethylene dioxy-thiophene doped with polystyrene sulphonic acid – PEDOT:PSS). However, the aim is to dispense with this layer. Then comes the actual photoactive layer, a mixture of P3HT (poly [3-hexyl thiophene 2,3 diyl]) and PCBM (phenyl C61 butylic acid methyl ester). The counter-electrode is created by an aluminium coating (Fig. 1).

In earlier experiments, ITO films were compared to Ag electrodes, in which the silver layer was embedded in SnO_2 or ZnO. A PEDOT:PSS layer was then deposited on these electrodes. Whereas the Ag/ZnO combination compared unfavourably with the cell with ITO, particularly concerning its short circuit current and internal series resistance, the combination of Ag and SnO_2 is comparable with the ITO system (Fig. 2).

In more recent experiments, a combination of ZnO/Ag/WO_3 was compared with ITO. In one case, the solar cell was constructed with the PEDOT:PSS layer (Fig. 3), in the other case without it (Fig. 4). With PEDOT:PSS, the internal series resistance with ITO is significantly lower than with ZnO/Ag/WO_3. This is not due to a higher conductivity of the ITO layer itself. The conductivity values for ITO and ZnO/Ag/WO_3 were comparable. Rather, it is the interface in the WO_3/PEDOT system which is unfavourable.

Without PEDOT, the system with ITO is significantly worse than with ZnO/Ag/WO_3. From the dark characteristic curve, which is not illustrated here, it can be deduced that the internal series resistance of the system with ITO is higher than with ZnO/Ag/WO_3. Furthermore, the illuminated characteristic curve in Fig. 4 shows a lower open circuit voltage with ITO than with ZnO/Ag/WO_3. This agrees with measurements made in parallel, which demonstrated that the ZnO/Ag/WO_3 has a higher work function.

The work is supported by the Fraunhofer-Gesellschaft in the MAVO METCO project.

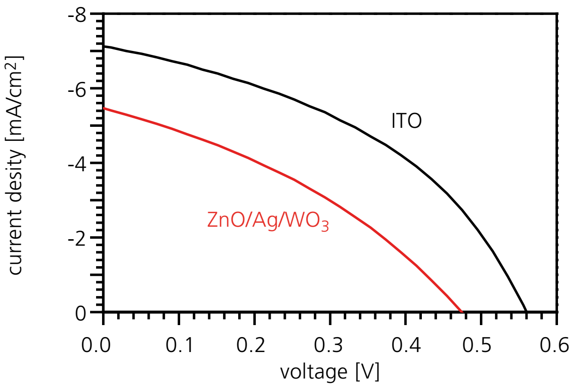


Fig. 3: Characteristic curves under illumination (AM1.5) of two organic solar cells with a PEDOT:PSS layer and ITO or ZnO/Ag/WO_3 as the electrodes.

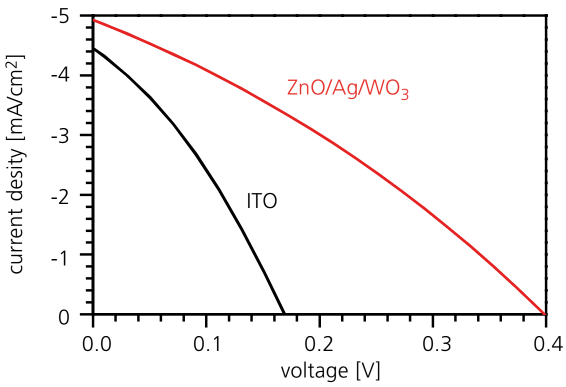
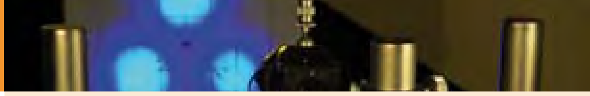


Fig. 4: Characteristic curves under illumination (AM1.5) of two organic solar cells without a PEDOT:PSS layer and with ITO or ZnO/Ag/WO_3 as the electrodes.



Innovative Concepts for Texturing Multicrystalline Silicon Solar Cells

The efficiency of solar cells can be increased by texturing the surface. However, tailored texturing of multicrystalline silicon substrates could previously be achieved only with very complex processes. We have developed novel texturing procedures at Fraunhofer ISE and have identified suitable profile forms by optical modelling.

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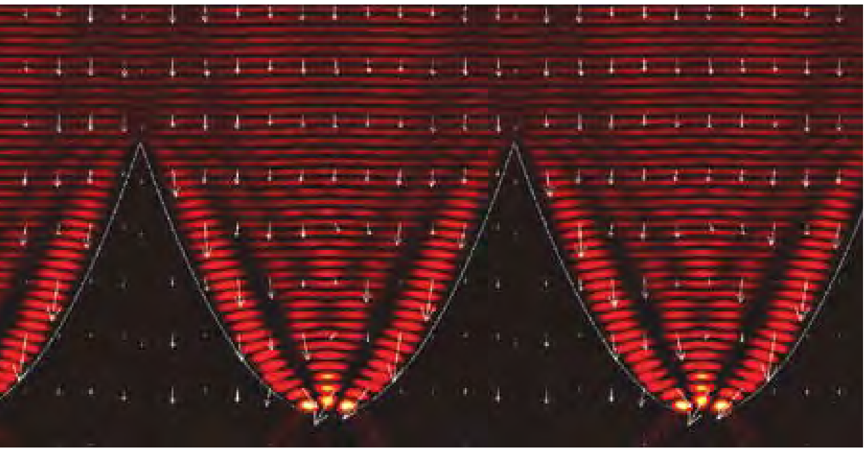


Fig. 1: Wave-optical modelling of a parabolic-linearly structured silicon surface with a structure period of 8 µm (wavelength: 680 nm). The illustration shows the intensity distribution in the near-field region of the structure. The energy flux is visualised by the Poynting vectors (white arrows).

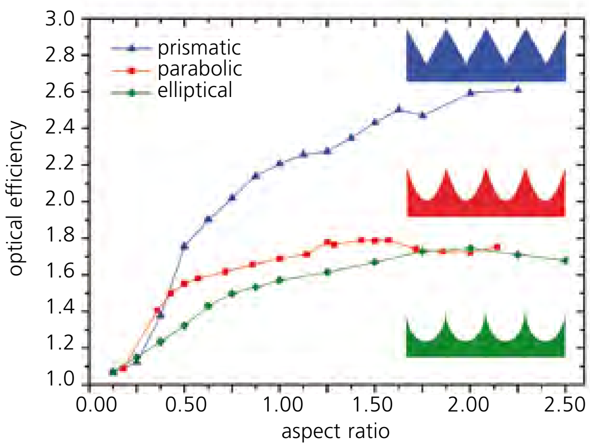


Fig. 2: Optical efficiency (OE) of a linearly structured silicon surface for different profile forms as a function of the aspect ratio (ratio of structure depth to structure width). The OE serves as a measure both for the lengthened light path within the cell (light-trapping efficiency) and for the increased transmittance compared to an unstructured surface (OE = 1).

The efficiency of solar cells can be increased by texturing the upper surface. The increase in efficiency caused by texturing is due to a reduction of reflection from the upper surface and light-trapping effects. The term, "light trapping", describes the resulting lengthening of the light path within the cell. Processes which are already well established for texturing solar cells made of monocrystalline silicon cannot be applied for multicrystalline silicon because of the varying crystal orientations.

With the goal of texturing multicrystalline silicon, we at Fraunhofer ISE have worked both on modelling the optical behaviour of these surfaces and on the necessary processing technology.

The optical properties of micro-structured surfaces were modelled in this context both with geometrical optical (ray-tracing) and wave-optical approaches. The effects of the structure period, profile forms and depth on the reflection and transmission were investigated in the calculations. Figures 1 and 2 show results of such calculations as examples. The modelling demonstrated that the optical efficiency can already be more than doubled with an aspect ratio of 1.

Deliberate texturing of multicrystalline silicon substrates requires the use of a structured etching mask. We have developed a process chain which is suitable for structuring such a mask. Conventionally, an etching mask is structured by photolithography. In order to implement this on multicrystalline silicon, the substrates must be previously polished in a complex chemical-mechanical process. The alternative process chain which we developed aims for inexpensive structuring of etching masks on uneven surfaces.

The individual steps of the process chain concept are: Interference lithography (generation of the master form of a surface structure), replication of the structure in silicone (production of a tool), nano-imprint lithography (structuring a photoresist layer on the substrate) and finally plasma-etching processes (texturing the substrate). After a master form has been generated (Fig. 3) and replicated in a flexible material, which then serves as an embossing tool, there follows a UV nano-imprint lithographic step, which is suitable for mass production. In this process, a UV-curable photoresist is applied to the substrate to be structured and is hardened by exposure during the embossing. By using a flexible material for the embossing tool, unevenness in the silicon surface can be compensated and well-defined resist masks can be applied onto rough surfaces (Fig. 4). We were able to demonstrate that these structured resist layers can be used as etching masks for the subsequent plasma-etching processes.

In further projects, we intend to further develop this novel process chain for texturing multicrystalline silicon, in order to achieve optimal structure forms and adapt the process to the requirements of industrial production.

The work was funded by Fraunhofer ISE within the "Microsol" project.

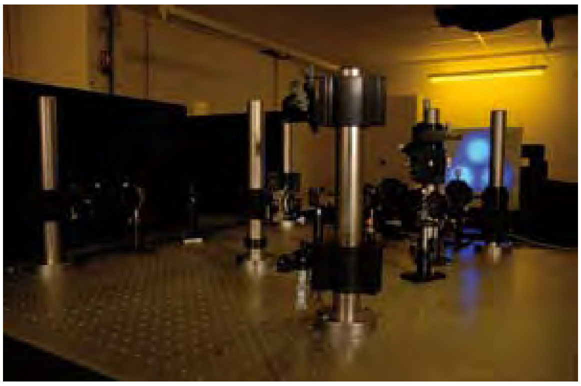


Fig. 3: Optical set-up for three-beam interference lithography. A laser beam is split into three equally intense beams, which are expanded and then superimposed on a photoresist-coated sample. The resulting interference pattern has hexagonal symmetry.

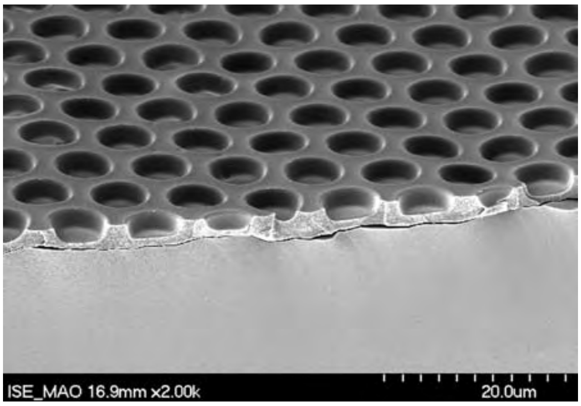
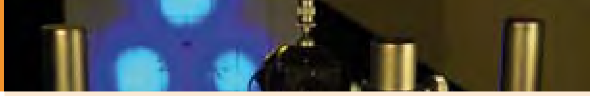


Fig. 4: Etching mask on a multicrystalline silicon substrate, which has been structured by nano-imprint lithography. The surface roughness caused by sawing damage was reduced by wet-chemical etching before masking. By using flexible embossing tools, the photoresist layer can be homogeneously structured, despite the roughness of the unpolished surface.



Optical Characterisation of Key Components of Linear Fresnel Collectors

To optimise the technology of linear Fresnel collectors, we have developed a series of procedures to characterise key components. We have investigated the function of the secondary concentrator and the imaging properties of the concentrating reflectors in the horizontal reflector array. With the presented methods, we are supporting the development of new components and establishing quality-control procedures both for the laboratory and on site during the construction of solar power stations.

Anna Heimsath, Nicolaus Lemmertz, **Werner Platzer**, Markus Tscheche, Andreas Gombert

Solar-thermal power stations generate electricity with concentrating solar collectors and a conventional thermal power-generation process. In solar-thermal power stations with linear Fresnel collectors, the solar radiation is concentrated onto a receiver by slightly curved reflectors with single-axis tracking. The receiver consists of a stationary absorber pipe with a secondary concentrator, which allows a wide reflector field to be used. We are developing and optimising the Fresnel technology further in a demonstration project at the "Plataforma Solar de Almería", together with our industrial partners, MAN-Ferrostaal, Solar Power Group and PSE, and our research partner, the German Aerospace Centre DLR (see article on p. 83). As the performance of the collectors is strongly influenced by the optical accuracy of the components and their positioning, a main focus is on developing various procedures to optically characterise the individual components and their interaction.

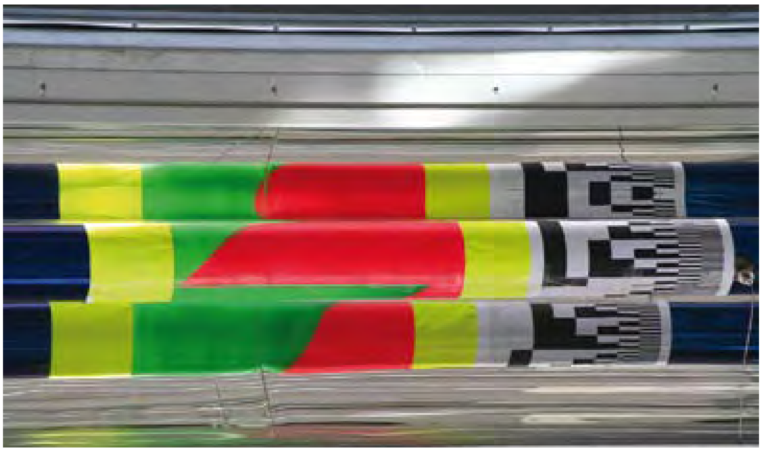


Fig. 1: Receiver acceptance measurement: A colour-coded target and its reflection in the secondary receiver of a Fresnel collector, photographed with a camera from a pre-defined angle. The proportion of solar radiation incident on the absorber pipe is determined and compared with that for the ideal geometric configuration.

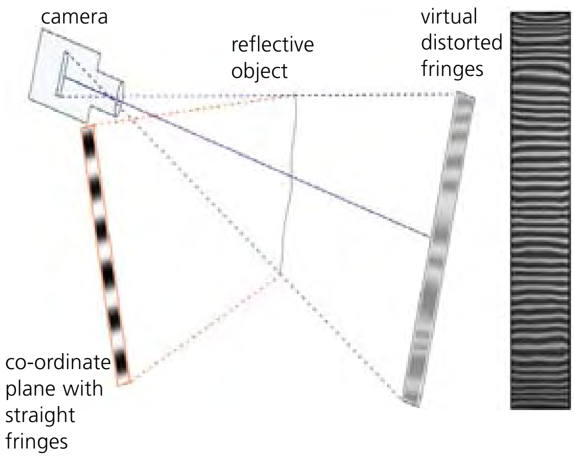


Fig. 2: Left: Operating principle of fringe reflectometry: The reflection of a fringe pattern is photographed with a camera. The surface gradient, curvature and form are determined from the image deformation. Right: Example of a fringe pattern as reflected by a primary reflector.

The goal in developing concentrating solar collectors is to reflect the direct solar radiation with as little loss as possible via the reflectors onto the absorber pipe. In order to measure the optical quality of the secondary concentrator, images of colour-coded target points are evaluated numerically. This is used to determine how accurately the concentrated solar radiation hits the target (Fig. 1).

We apply luminance measurements to characterise the intensity distribution along the focal line of the primary reflectors. Comparison with the ideal intensity distribution reveals reflection faults due to reflector and installation errors.

The fringe reflectometry technique is used to gain information on the three-dimensional curvature and form compliance of a reflector (Fig. 3). The deformation in a fringe pattern reflected by a reflector is photographed with a camera. The deformation is analysed and used to determine the local surface angles of the reflector.

The high sensitivity of the method means that slightest deviations in the surface angle, on the order of tenths of a degree, can be detected and used to characterise the surface quality. Manufacturing faults and defects are identified.

To characterise the narrow reflecting elements of Fresnel collectors, we have developed a compact measuring instrument to test the reflectors both parallel to production and outdoors in the reflector field.

With the measurement methods presented, we support the development of new key components by providing reliable quality control. Targeted design optimisation of collectors is checked experimentally. This makes an increase in the collector performance and reduction in the electricity generation costs feasible.

The work described here was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

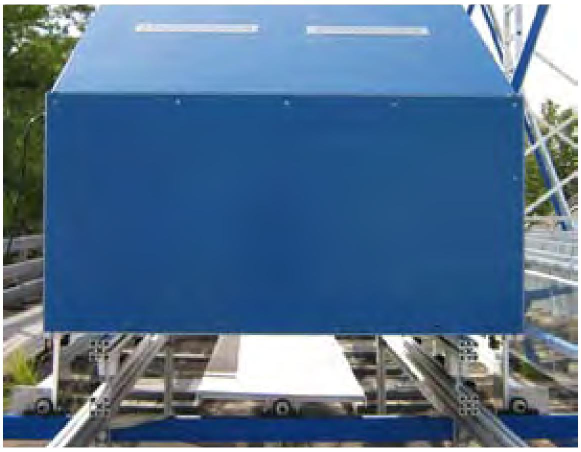


Fig. 3: Equipment to measure the form compliance of narrow reflectors. Here it is being used to measure a reflector for the demonstration collector of PSE GmbH in Freiburg. The compliance of the reflecting component form with specifications is tested.

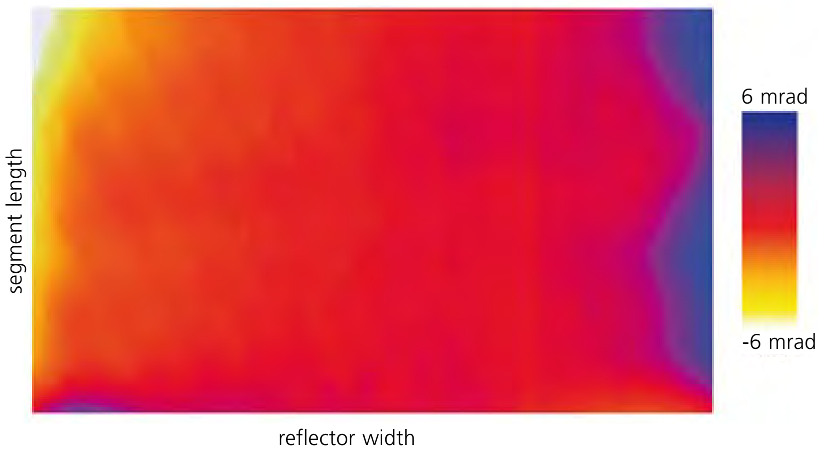
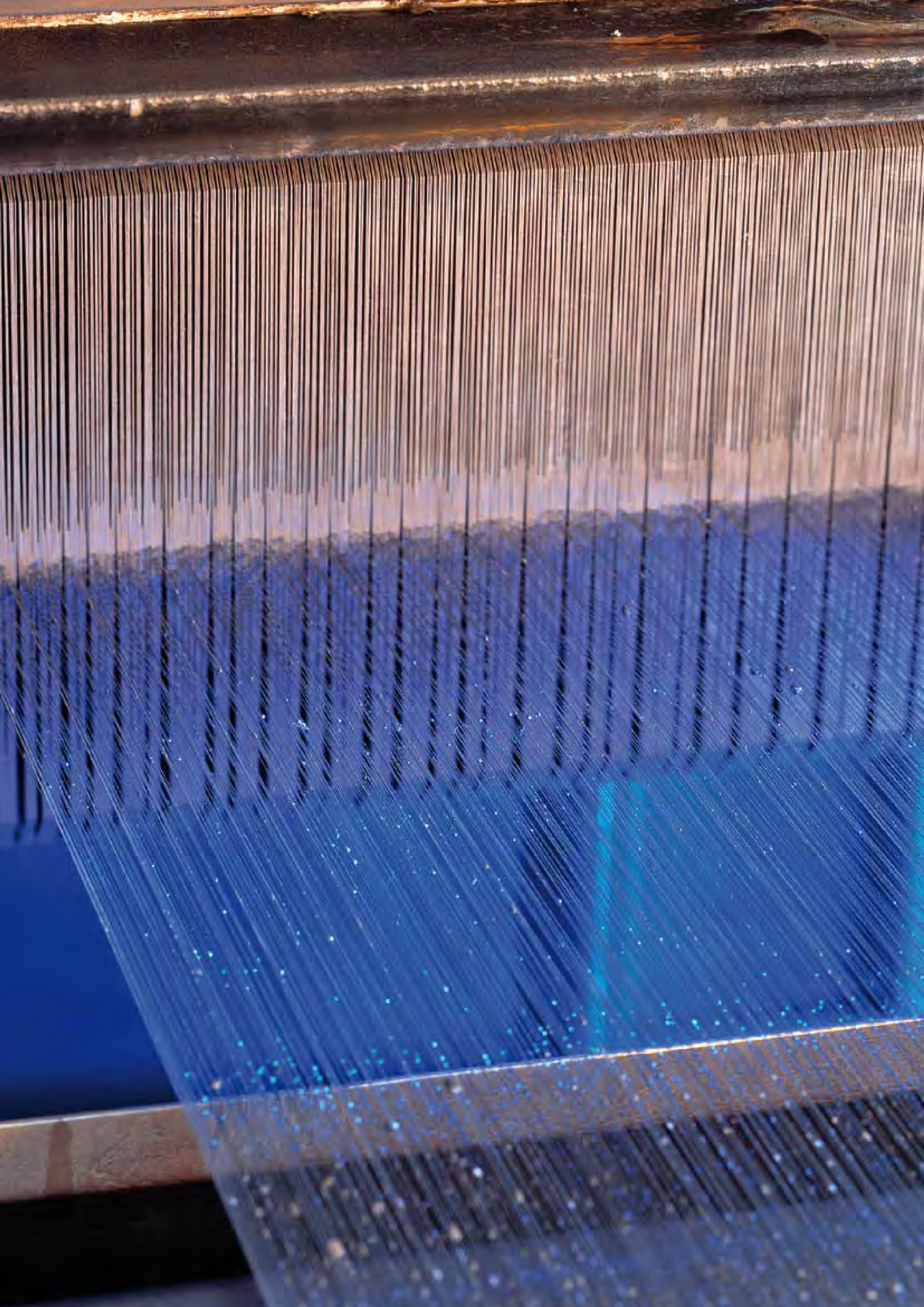


Fig. 4: Reflector segment: Distribution of the local angular deviation from the ideal surface angles in mrad. Systematic deviations at the reflector edge are clearly evident, which were caused by the manufacturing process. The form compliance is also analysed statistically. This segment has a standard deviation of 1.6 mrad.



Solar Cells

Photovoltaics has experienced a boom for more than ten years, which was encouraged particularly by the targeted market introduction programmes in Japan and Germany: The globally installed peak power capacity increased during this period from a few hundred MW to around 6 GW.

More than 90 % of the solar cells manufactured today are 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.

In order to reproduce the value chain for crystalline silicon photovoltaics more completely, we significantly expanded our activities on materials development, particularly crystallisation, in 2007. We commissioned a crystallisation facility in new laboratories in Freiburg with which multicrystalline blocks weighing up to 250 kg can be produced. Our scientific work here focuses on investigating the crystallisation process of solar silicon. At the Centre for Silicon Photovoltaics (CSP) in Halle/Saale, we will establish further capacity in this field. The CSP should start operation as planned in 2008. A new focus in our work is on the development of solar cell processes based on the use of purified metallurgical silicon ("dirty silicon").

In our Photovoltaic Technology Evaluation Center PV-TEC, we have appreciably extended the basic processing line for producing solar cells with screen-printed contacts, as is common in industry, and can now also reproduce solar cell processes with high-quality surface passivation on a pilot scale. An essential pre-requisite for this was further development of in-line single-surface etching technology, so that it is now possible to etch one surface of wafer substrates with different surface properties. Furthermore, we have set up an in-line galvanisation system for silver, with which contact nucleation layers can be thickened to result in excellent electrical conductivity. Overall, in-line, contact-free processing technology is considered to be of central importance for future production of solar cells. We have also set up equipment for in-line diffusion, a system for ink-jet coating for mask production and a further laser-treatment facility.

In our clean-room laboratory, we are advancing the development of high-efficiency solar cell concepts and processes. Together with our characterisation and simulation pool, we are thus in a position to offer all stages from development to industrial implementation.

One highlight of the past year was the development of a back-contact solar cell in co-operation with the Institut für Solarenergieforschung ISFH in Hameln for the Q-Cells company, which has since established a technological plant for pilot production of this highly efficient cell structure.

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. As very small amounts of high-purity silicon are needed, the wafer equivalent concept is largely independent of the supply situation for solar silicon, allowing very dynamic market growth. The experimental results are very promising.

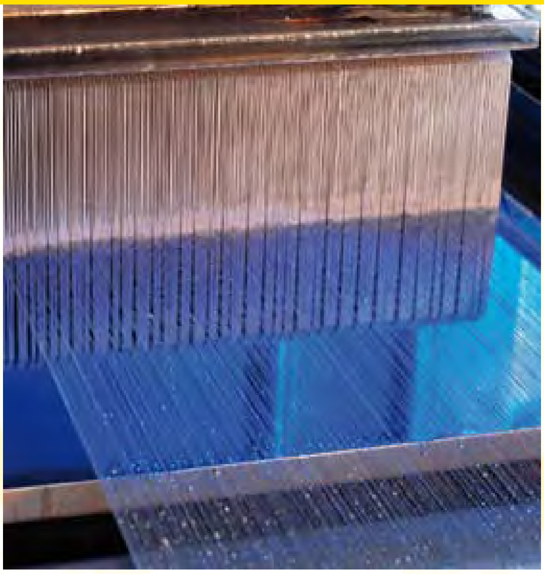
Finally, the ISE prototype module production laboratory allows new cells and materials to be processed in industrially relevant quantities and formats. Processing steps and systems technology for module production are developed up to the preliminary stage of mass production. The core equipment includes a flexible tabber-stringer and a laminator, accompanied by a selection of measurement and testing systems.

Solar cells must be durably encapsulated to protect them against weathering. There is still considerable potential for increasing quality and reducing costs in this field. We are working on new module concepts and materials combinations, also for thinner, large-area solar cells and those with contacts only on the back surface. Deeper understanding of aging mechanisms and procedures to characterise them play a key role in our contribution toward increasing the long-term quality of photovoltaic modules.

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 concentration, laser power transfer and other special applications. We are working on radiation-resistant, triple to sextuple cells for extra-terrestrial applications. For terrestrial use, we are developing concentrator cells for the highest optical concentration factors and appropriate characterisation technology.

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. We were able to demonstrate that modules of dye solar cells can be produced with industrially relevant technology such as screen-printing and new sealing technology. The possibility for applying design aspects was demonstrated in prototypes. The module durability is being tested in the laboratory and outdoors. Organic solar cells are opening up new application areas because of their mechanical flexibility and are attractive due to their fundamentally low production costs. We work on optical and electrical modelling of organic solar cells, test the suitability of new materials and processing variations with an automated characterisation line and develop new cell configurations to optimise efficiency and cost-effective production. The first modules with up to 22 single cells were produced successfully.

Our solar cell activities in Freiburg are complemented by work at other centres throughout Germany. The Fraunhofer ISE Laboratory and Service Centre in Gelsenkirchen, North Rhine-Westphalia moved into new, larger premises in 2007. The Technology Centre for Semiconductor Materials THM in Freiberg, Saxony, is operated jointly with Fraunhofer IISB. As mentioned above, the Centre for Silicon Photovoltaics CSP in Halle/Saale, Saxony-Anhalt is currently being planned together with Fraunhofer IWM.



Silicon wafers after completion of a sawing process with an industrial, multi-wire saw. The wafers are still suspended from the transport rail, the wire array has been lowered. Multi-wire technology is the key technology today for producing thin silicon wafers for solar cell production. Fraunhofer ISE is working on decreasing the sawing gap (about 180 µm today) and the wafer thickness (about 160 µm today). Another goal is to reduce surface damage, so that the losses of high-value silicon can be kept as low as possible and the yield from a silicon block is increased. To achieve this, the wires, the slurry (silicon carbide particles in a liquid medium) and the machine parameters must be appropriately adapted. Sawing gaps of 120 µm and wafer thicknesses of 80 µm have already been obtained.

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Crystallisation and Wafer Production with Contaminated Silicon

The crystallisation of silicon ingots is a central processing step in the long sequence from silicon feedstock to completed solar modules. Despite decades of research, there are still many unanswered questions here. Over the last few months, we have built up the required infrastructure for an industrially relevant technological facility for crystallisation and wafer production, with the aim of answering some of these questions.

Yannis Bdioui, **Achim Eyer**, Fridolin Haas, Stefan Reber, Matthias Singh, Andreas Bett

Fig. 1: Our system (height = 3.5 m) for the crystallisation of multicrystalline silicon ingots, which is close to the current standard in the photovoltaic industry. It features great flexibility: We can produce ingots in variable sizes with a base area of app. 20 x 20 cm^2 up to 68 x 68 cm^2. Several sets of heating elements allow us also to crystallise and characterise silicon of very different quality grades.

Fig. 2: Crystallised silicon ingot of highly doped "tops and tails", waste material from the microelectronics industry. The ingot has a base area of app. 68 x 68 cm^2, and with a height of app. 25 cm, weighs about 270 kg.

The raw material for the silicon wafer solar cell that currently dominates the market must first be crystallised in ingots of several hundred kilograms, before it is cut into wafers. This crystallisation step is exceedingly important, as it effectively determines the efficiency of the solar cell. Over the last 20 years, knowledge of the crystallisation process has increased greatly, but there is still considerable potential for optimisation and thus cost reduction. To assist the industry in exploiting this potential, we began last year to set up a complete technological facility for crystallisation and wafer production. It includes all the systems and processes belonging to the current state of the art, starting with an anti-adherent coating for the melting crucible, and continuing through ingot crystallisation up to separation of the ingots into columns, wafer production and wafer cleaning. In this way, we can not only carry out research on individual process steps on a small scale (ingots weighing app. 20 kg) but also replicate industrial processes up to the maximum capacity of the system (app. 300 kg). The first successful crystallisation experiments have demonstrated that we are capable of mastering this demanding task. Accordingly, one of our projects addresses probably the most difficult aspect of crystallisation – the production of good crystals from only slightly purified and thus inexpensive silicon. Its concentration of remaining impurities sets us the task of finding innovative solutions for the crucible coating and management of the crystallisation process. In combination with our high-throughput PV-TEC laboratory for solar cell production and our module production facility, we now have the unique opportunity of conducting research at every stage of the value-creation chain.

The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) supported us in the purchase of the crystallisation system. The work is funded by the Fraunhofer-Gesellschaft within the "Silicon Beacon" project.

Reduction of Sawing Losses from Multi-Wire Sawing of Silicon

Sawing losses and the wafer thickness must be decreased to reduce the wafer costs and save resources in solar cell production. We investigated multi-wire sawing processes with wires of only 100 µm thickness and have achieved similarly good wafer quality and yields as with the wires of 140 µm thickness that are commonly used today.

Markus Bergmann, **Achim Eyer**, Roland Schindler, Mark Schumann, Andreas Bett

Work by Fraunhofer ISE on multi-wire sawing of silicon is carried out on an industrial machine together with the Technology Centre for Semiconductor Materials (THM) in Freiberg, a joint department of the two Fraunhofer Institutes, IISB in Erlangen and ISE in Freiburg.

Multi-wire sawing technology is the main technology used today to produce thin silicon wafers for manufacturing solar cells. To increase the material yield and thus reduce the wafer costs, it is important both to reduce the silicon losses from the sawing gap (currently app. 160 µm) and to produce thinner wafers than is usual today (180 – 200 µm). To reduce the sawing losses, the wire diameter (typically 140 µm at present) must be decreased considerably to 100 µm or less, without noticeably affecting the wafer quality and yield. The slurry (silicon carbide particles in a liquid, usually polyethylene glycol) and the machine parameters must be adapted accordingly. We subjected wires with diameters between 160 and 100 µm to tensile strength tests and determined that their tensile strength was similar. The wires were used to saw monocrystalline silicon columns (cross-section 125 x 125 mm^2), using slurries with different viscosity values and particle dimensions.

The surface properties of the sawn wafers were analysed (roughness, thickness variation (TTV), damage depth). We found out that both the sawing performance and the surface properties of the silicon wafers remain the same for thin wires with diameters down to 100 µm. A minimum sawing loss of 125 µm was achieved, which corresponds to a reduction of 25 % in comparison to the present standard sawing loss.

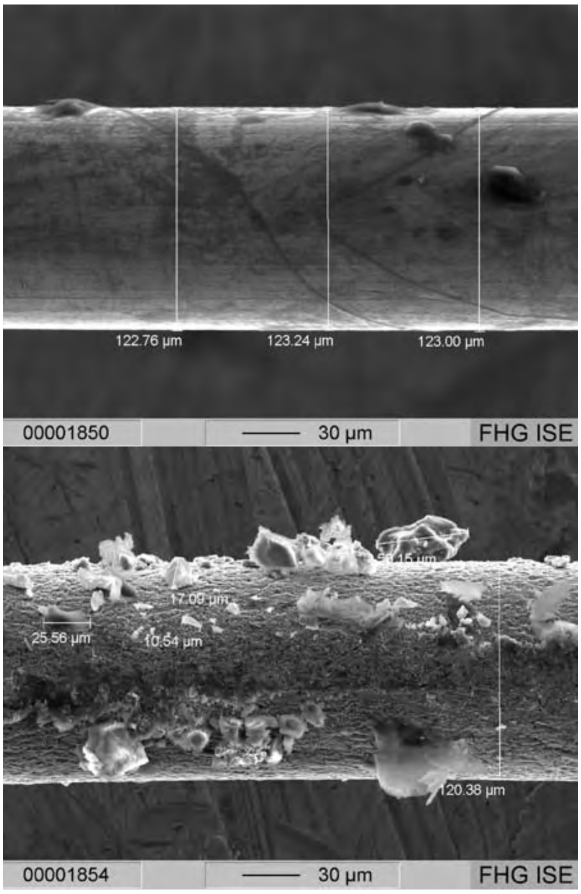


Fig. 1: Wire with a diameter of 120 µm before (top) and after (bottom) sawing. The rough surface caused by wear on the wire is visible; in addition, SiC particles from the slurry adhere to the wire.

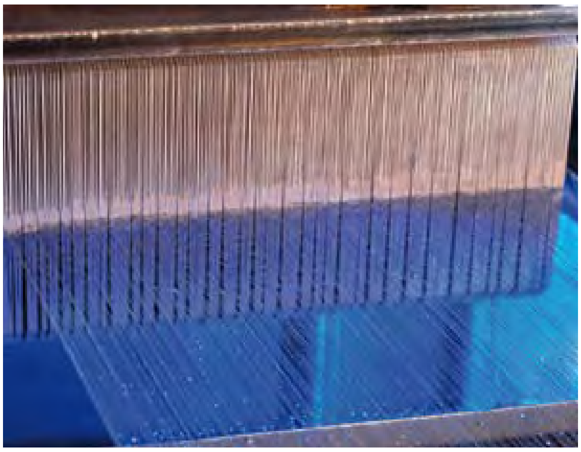
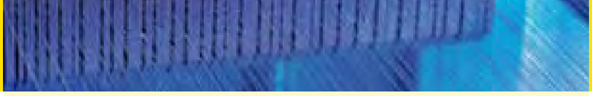


Fig. 2: Wire array of the multi-wire saw (foreground) and already sawn wafers (background).



High-Efficiency Solar Cells with Screen-Printed Front Surface Contacts

In comparison to standard industrial solar cells, where the back surface is completely covered with aluminium, the efficiency of crystalline silicon solar cells can be significantly increased by electrical passivation and optical reflection from the back surface of the cell. We have now succeeded in combining this technology with screen-printed front-surface metallisation, applying several innovative processes which are suitable for mass production. This led to solar cells with screen-printed front-surface metallisation being produced for the first time with an efficiency value exceeding 19 %.

Denis Erath, Anke Herbolzheimer, Antonio Leimenstoll, Ansgar Mette, Ralf Preu, Phillip Richter, Elisabeth Schäffer, **Oliver Schultz**, Sonja Seitz, Stefan Glunz

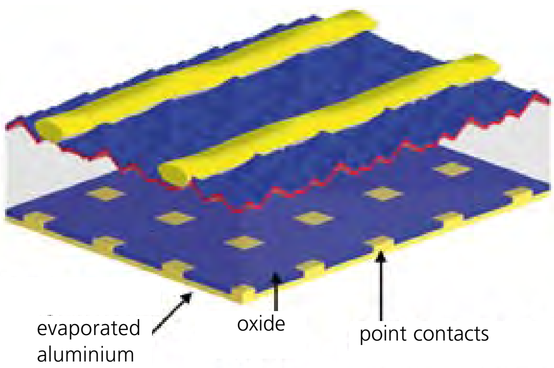
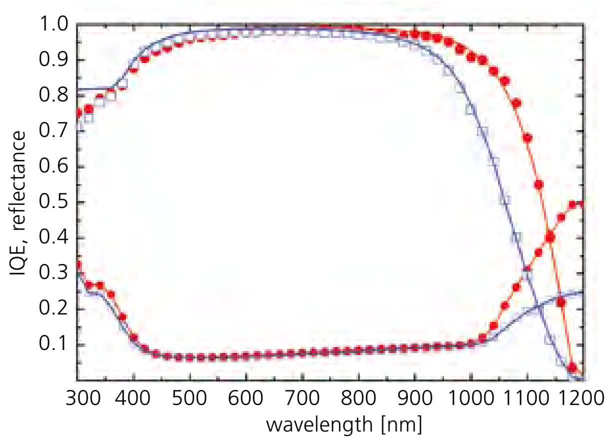


Fig. 1: Highly efficient industrial solar cell structure. The metal contacts on the front surface were made by screen-printing with a silver-containing thermoplastic paste, firing and then galvanic reinforcement. The back surface is passivated by an oxide which grew thermally under wet processing conditions. Point contacts were made by the laser-fired contact (LFC) process.



High-efficiency silicon solar cells require excellent surface passivation and very good internal reflection. Both for monocrystalline and multicrystalline silicon cells holding world records, thermal oxidation is the decisive technology. Whereas Fraunhofer ISE has already successfully demonstrated the LFC process (laser fired contacts) to be an industrially applicable approach for treating the back surface of the cell, the focus of the development presented here is on the combination of a dielectrically passivated back surface with screen-printed metallisation of the front surface.

In comparison to a standard silicon solar cell, the newly developed cell structure (Fig. 1) is distinguished by localised contacts on the back surface (occupying only 1 – 2 % of the area), while the remaining area features excellent passivation due to the oxidation. In addition, very good internal optical reflectance for the cell is obtained with evaporated aluminium, so that the long-wavelength portion of the spectrum is used optimally (Fig. 2). This measure in particular has allowed us to achieve an efficiency value of 19.3 % (V_{oc} = 655 mV, J_{sc} = 38.2 mA/cm^2).

After successfully implementing the concept over small areas on a laboratory scale, the results are currently being transferred to the pilot-production scale.

This work is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), as well as five German solar cell manufacturers, within the "LFC Cluster" project.

Fig. 2: Internal quantum efficiency (IQE) and reflectance of the newly developed solar cell structure (red) compared with a standard industrial concept with an aluminium contact covering the entire back surface (blue). The oxide-passivated solar cell is superior particularly in the long-wavelength spectral range, where it converts more of the available energy. With this concept, we have achieved peak efficiency values of 19.3 %.

In-Line Plating for Solar Cell Contacts

The new metallisation methods developed at Fraunhofer ISE are based on a two-stage procedure, in which a seed layer is deposited, which is then reinforced by plating. We apply light-induced plating for the reinforcement of solar cell contacts. A semi-automatic batch facility became available for this elegant process some time ago. In co-operation with an industrial partner, we have constructed two industrial systems suitable for in-line integration, which allow both silver and copper to be used for the reinforcement.

Mónica Alemán, Jonas Bartsch, Norbert Bay, René Bergander, Aleksander Filipović, Stefanie Greil, Matthias Hörteis, Anke Herbolzheimer, Michael Menkö, Ansgar Mette, Valentin Radtke, Jochen Rentsch, Philipp Richter, Christian Schetter, Daniel Schmidt, Oliver Schultz, **Stefan Glunz**

Fig. 1: In-line galvanisation unit at Fraunhofer ISE. The light sources in the bath are clearly visible.

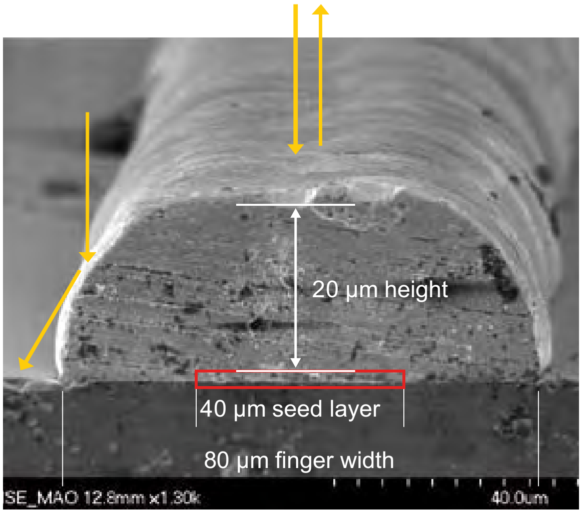


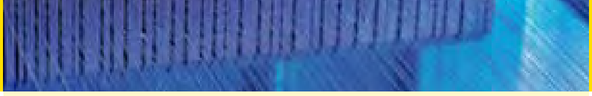
Fig. 2: Contact finger of a silicon solar cell which has been reinforced by light-induced plating. The seed line prepared by aerosol printing is only 1 µm high and 40 µm wide. The remaining cross-sectional area is filled with highly conductive plated silver. The rounded form means that light which is incident on the sides of the finger can be reflected onto the cell and absorbed. Thus, the "optical width" of the finger is narrower than the "geometric width".

The standard process to manufacture front-surface contacts on crystalline silicon solar cells is screen-printing with silver-containing pastes. In this single-stage method, the manufacturing process must be optimised with regard to both the conductivity and the contact properties. This is possible only to a limited degree. Thus, the potential of this technology for improved efficiency is also restricted. In order to achieve better results, we are developing processes based on a two-stage concept, in which first a seed layer is deposited (see Annual Report 2006) and then is reinforced by plating.

We have been applying light-induced plating for the second step for a number of years. Here, only the back surface of the solar cell must be contacted in order to apply a protective potential with respect to a silver anode. When the cell is illuminated, an additional negative potential is generated in the front-surface contact grid, which initiates the plating process. As deposition occurs selectively only on the seed layers, extremely efficient use is made of the material.

Light-induced plating is much simpler to implement industrially than direct contacting of the fine front-surface contact grid. Therefore, we have co-operated with two companies, Gebr. Schmid and Rohm and Haas, to develop industrial prototypes suitable for in-line integration. Two systems (for silver and copper plating) were constructed at Fraunhofer ISE (Fig. 1) and successfully taken into operation. Plating is particularly advantageous when the seed line is as narrow as possible, as can be achieved with our aerosol printing process (Fig. 2) or nickel-plating.

This work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Gebr. Schmid company within the "Gasol" project.



Laser Chemical Processing of Solar Cells

Innovative local micro-structuring processes can be implemented for silicon solar cells by coupling a laser beam into a reactive liquid jet. With our LCP technology (laser chemical processing), we demonstrated the creation of a selective emitter (locally highly doped with phosphorus) in a single processing step.

Andreas Fell, Christoph Fleischmann, Sybille Hopman, **Daniel Kray**, Kuno Mayer, Matthias Mesec, Ralf Müller, Arpad Mihai Rostas, Stefan Glunz

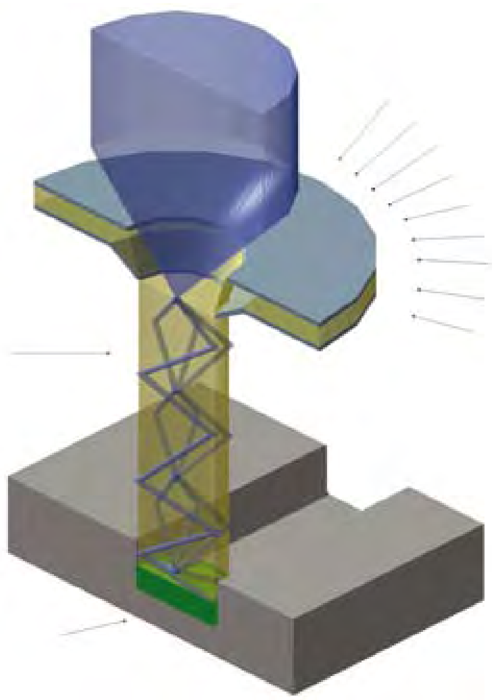


Fig. 1: The proprietary Laser Chemical Processing (LCP) is based on a water-jet guided laser from Synova®. Choosing a reactive liquid makes a large number of highly flexible, local, laser chemical processes feasible.

The efficiency of solar cells can be increased if the doping underneath the front-surface contacts is higher than over the non-metallised zones. This so-called selective emitter is produced in a complex process by photolithography or conventional laser processing with a subsequent damage etch. Furthermore, the entire wafer must usually be subjected to a high-temperature step for a second diffusion process. By contrast, if the selective emitter is prepared by LCP (laser chemical processing, Fig. 1), the anti-reflective coating can be opened in a single step and local laser diffusion can occur which does not require any subsequent etching. In this way, we avoid a number of processing steps and the need to heat the entire wafer, which is particularly disadvantageous for multicrystalline silicon. By applying LCP with phosphoric acid as the medium and a Nd:YVO_4 laser (wavelength 532 nm), we successfully introduced selective emitters into industrial solar cells. Figure 2 shows the illuminated IV curve for a planar solar cell with a selective emitter produced by LCP. It clearly demonstrates that the selective emitter can be created locally with very little damage, without disturbing the already existing emitter diffusion. Measurements of the pseudo fill factor by the Suns-V_{OC} method confirm this result. With this approach, the effort needed to produce solar cells with a selective emitter can be reduced considerably.

The work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), as well as the companies, Deutsche Solar AG, Manz Automation AG, Renewable Energy Corporation Group and Synova S.A..

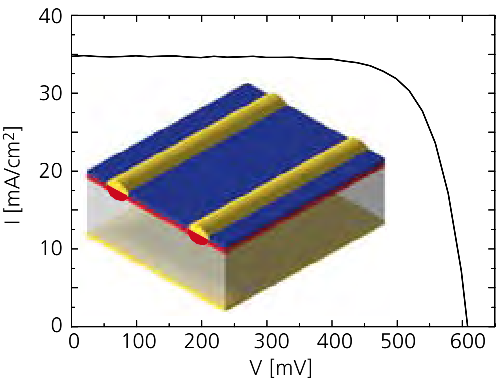


Fig. 2: Illuminated IV curve for a planar solar cell with an aluminium BSF (back surface field) covering the entire surface and a selective LCP emitter. Analysis of the characteristic curve demonstrated that the LCP treatment had been successful. The existing emitter over the whole area was structured without creating shunts or recombination centres in the volume charge zone. An efficiency value of 15.9 % was achieved with float-zone material.

Amorphous Silicon for Surface Passivation of Crystalline Silicon Solar Cells

Amorphous silicon is one of the most effective materials to passivate silicon interfaces. At Fraunhofer ISE, we were able to produce highly passivating amorphous silicon coatings by the industrially applied Plasma-Enhanced Chemical Vapour Deposition (PECVD) process. With a stack of amorphous silicon and silicon dioxide layers, we have created passivation coatings with good long-term stability which can withstand high temperatures.

Dirk Bareis, Marc Hofmann, Norbert Kohn, Rainer Neubauer, **Jochen Rentsch**, Christian Schmidt, Stefan Glunz, Ralf Preu

Electrical passivation of the back surface of solar cells becomes increasingly important when the wafer thickness is decreased. The PECVD process is considered to be one of the most efficient methods to passivate the surfaces of p-doped silicon wafers. However, the thermal stability and the deposition reproducibility of amorphous silicon coatings present one of the greatest challenges in the industrial application of this technology to back-surface passivated and locally contacted high-efficiency silicon solar cells.

Thin-film stacks of amorphous silicon and SiO_x, which are deposited directly by an industrial PECVD in-line system, display excellent passivation quality. This is indicated by effective charge carrier lifetimes from 900 to 1600 µs and resulting surface recombination velocities between 9 and 3 cm s^{-1} on FZ silicon material. Even after longer exposure to a temperature of 400 °C, these layers still display an excellent lifetime value of around 900 µs. Even pure amorphous silicon layers without SiO_x masking have lifetimes after the same treatment of about 200 µs. The demonstrated temperature stability opens up new application opportunities also for amorphous silicon films in the industrial production of highly efficient solar cell structures.

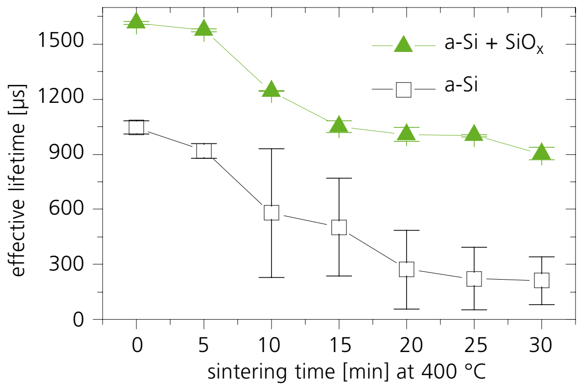


Fig. 1: Effective minority charge carrier lifetime for different sintering times (at 400 °C) for a coating stack of a-Si and SiO_x, as well as a pure a-Si coating. Although degradation of the lifetime is evident, a long lifetime can be maintained even after long durations at the high temperature.

Fig. 2: Automated, industrial PECVD unit for in-line deposition of amorphous silicon, silicon nitride and silicon dioxide.

In-Line Measurement Technology – Development and Testing for Application in Industrial Solar Cell Production

With regard to rising efficiency values and lower tolerances on processing parameters, process control is becoming increasingly important in solar cell production and demands rapid, in-line measurement technology to match the high throughput. An inductive sheet-resistance measurement procedure was investigated for in-line characterisation of emitter layers and was tested according to the specifications required for photovoltaics.

Gernot Emanuel, Alexander Krieg, **Stefan Rein**, Isolde Reis, Meinrad Spitz, Albrecht Weil, Ralf Preu

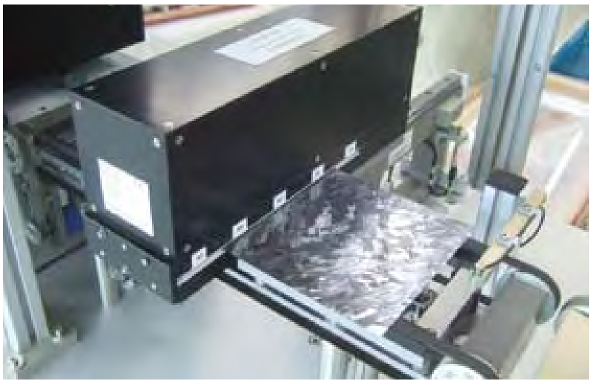


Fig. 1: Inductive in-line sheet-resistance measurement instrument by Kitec, integrated into an automated production line of the PV-TEC pilot line. As the measurement is made on the moving sample, a spatially resolved sheet resistance profile is measured in the transport direction. By positioning several sensors perpendicular to the transport direction, this profile can be recorded along several traces, making it feasible to control the homogeneity of the diffusion process (Fig. 2).

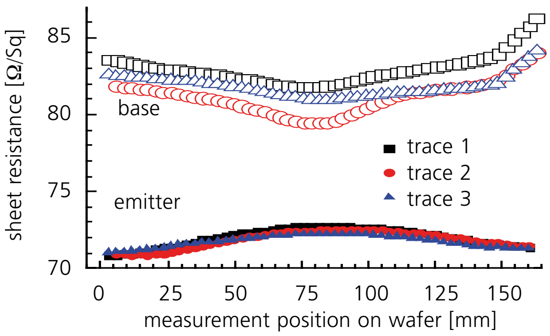


Fig. 2: Characteristic sheet resistance profiles for the base (open symbols) and the emitter (solid symbols) of a wafer, measured with the inductive measurement system along three measurement traces. The emitter sheet resistance is determined by calculation based on measurements made before and after diffusion.

The Photovoltaic Technology Evaluation Center (PV-TEC) presents an ideal platform to develop and test new in-line measurement methods, as measurement instruments can be integrated into existing automated production lines and their in-line operation tested. In addition, the complete range of relevant samples can be provided for the tests, and comprehensive characterisation methods are available for comparative measurements. This allows not only the absolute accuracy of the methods but also their reproducibility and robustness to be tested efficiently.

At Fraunhofer ISE, we have investigated an inductive sheet-resistance measurement instrument from Kitec for in-line emitter characterisation (Fig. 1). Although the eddy current technique is well known, it has not yet been used in the PV industry for emitter characterisation. We were able to prove that the emitter sheet resistance of monocrystalline silicon wafers can be determined precisely over the entire resistance range, independent of the surface structure. By contrast, surface-dependent systematic errors of up to 34 % occur with the four-point probe technique, which is widely regarded as the reference method (Fig. 3). As the inductive method offers the further advantages of not requiring any contacts, allowing transfer rates of up to 2000 wafers per hour, and has a reproducibility of better than 2.5 %, it is very well suited for in-line characterisation of emitters.

The work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) as part of the "PV-TEC" and "PV-QC" projects.

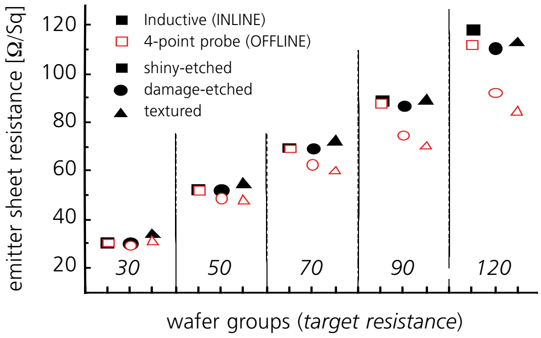


Fig. 3: Emitter sheet resistance measured with the inductive (solid symbols) and four-point probe methods (open symbols) on Cz-Si wafers with 5 target emitters and 3 surface treatments. Whereas the inductive method allows precise determination, independent of the surface structure, systematic measurement errors occur with the four-point probe method, which increase rapidly with increasing surface roughness and increasing emitter sheet resistance.

Ink-Jet Technology for Industrial Manufacturing of High-Resolution Mask Structures for High-Efficiency Solar Cells

High-resolution structuring processes for the industrial production of solar cells are a pre-requisite for implementing solar cell structures with the highest efficiency potential. We apply rapid ink-jet processes to print masks, for example, which allow selective application of the subsequent wet-chemical treatments.

Mónica Alemán, Udo Belledin, **Daniel Biro**, Raphal Efinger, Denis Erath, Anke Lemke, Nicola Mingirulli, Jochen Rentsch, Jan Specht, David Stüwe, Ralf Preu

Ink-jet technology allows large-area substrates to be coated with finely structured films. The system used at Fraunhofer ISE can print pastes in a hot state (app. 70 – 90 °C) and even allows so-called hot-melt pastes to be processed. The viscosity of hot-melt pastes is greatly reduced when the temperature is raised. This enables excellent printing with the paste. It solidifies immediately on the substrate and thus allows very high resolution of the printed structures. This procedure has been used at Fraunhofer ISE since the middle of 2007 to carry out various masking processes. For example, the formation of very fine, long finger structures is particularly interesting for solar cell production. Beyond that, localised opening of points in the dielectric layers is very important for solar cells with back-surface passivation. Already at this very early stage of the technology, we could consistently create structural dimensions of app. 50 µm, both for galvanically deposited nickel films and also for layers which were deposited with PVD (physical vapour deposition) methods in combination with lift-off processes. Finer structures with a resolution of about 10 µm have already been achieved on film substrates. The applied process is very rapid and can be easily up-scaled, so that app. 1000 wafers per hour can be processed by a machine with several printing heads.

This work is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

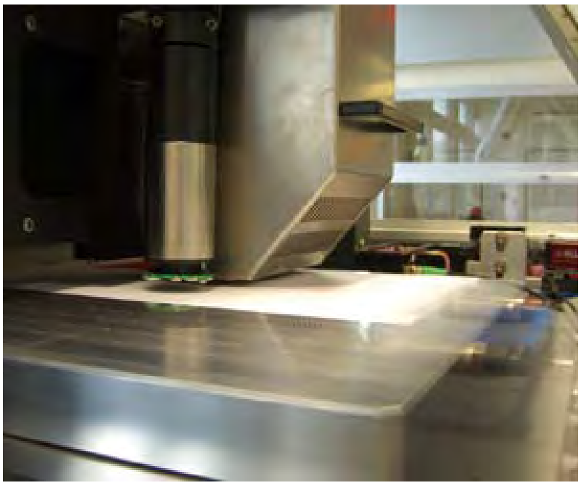


Fig. 1: Precise ink-jet unit at Fraunhofer ISE for printing silicon wafers with hot-melt pastes. The system is able to operate with different pastes and printing head modules. In addition, a simpler printing system is available, with which new pastes and printing heads can be tested, before they are transferred to the main unit.

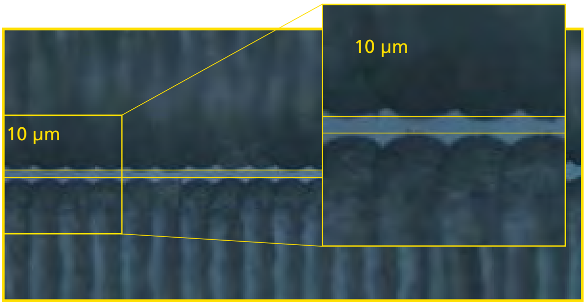


Fig. 2: Structural dimensions on the order of 10 µm can already be achieved consistently on film substrates. The illustration shows a fine line which has been left unprinted, so that selective treatment of this position can occur in subsequent processing steps.

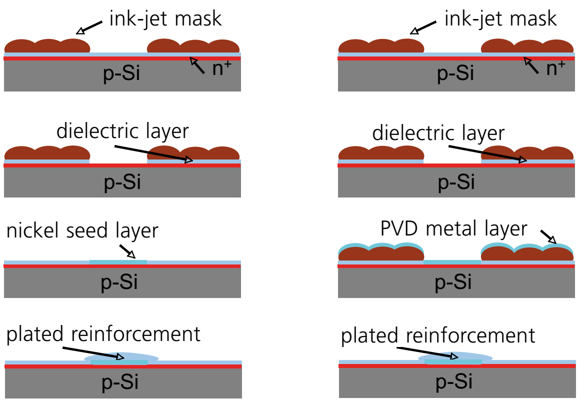
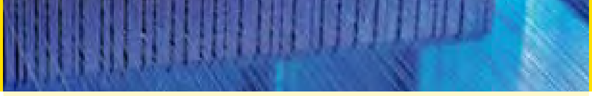


Fig. 3: Examples of processing options to produce fine contact structures for front-surface contacts on solar cells. The ink-jet mask is used to allow selective processing of a dielectric anti-reflective coating. Left: For nickel seed layers. Right: For lift-off processes in combination with PVD deposition over the whole surface.



Metal Wrap-Through Solar Cells

The metal wrap-through (MWT) solar cell is a cost-effective option to implement a solar cell with back-surface contacts, which is strongly oriented toward the current industrial production process. At Fraunhofer ISE, a manufacturing process for MWT solar cells was developed and implemented in the Photovoltaic Technology Evaluation Center (PV-TEC) with industrially relevant processes. We have achieved efficiency values of up to 16 % to date with multicrystalline silicon. The first modules with MWT cells have also been produced at Fraunhofer ISE.

Udo Belledin, **Daniel Biro**, Florian Clement, Rene Hönig, Denis Erath, Heike Furtwängler, Andreas Grohe, Christian Harmel, Tim Kubera, Michael Menkö, Nicola Mingirulli, Ralf Preu

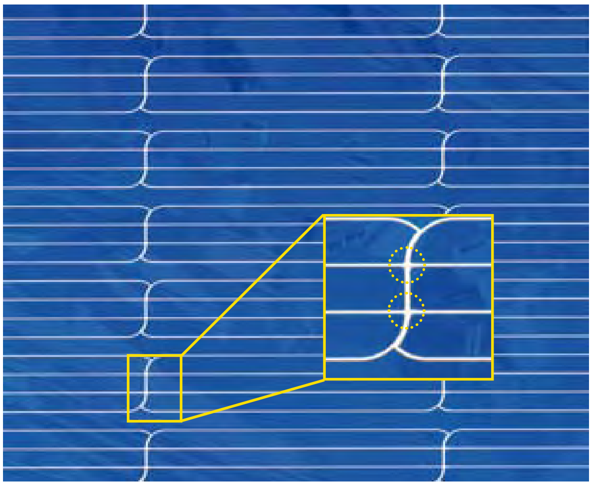
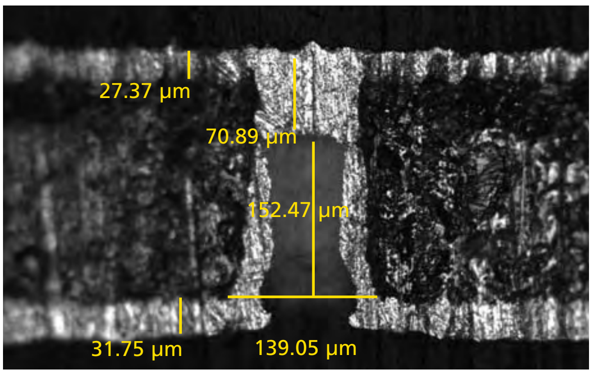


Fig. 1: MWT solar cell of multicrystalline silicon (125 x 125 mm²). The enlargement shows the newly developed contact structure, with vias (each under the centre of the circles) creating the contact to the back surface of the cell.



To facilitate the market introduction of the MWT cell, we have deliberately imitated the standard manufacturing process for solar cells in developing the manufacturing process for MWT cells.

In contrast to the standard solar cell, the MWT cell does not have a bus bar on the front surface. All the areas needed for contacting are located on the back surface of the cell. Shading can be reduced in this way by about 3 % and gains in the short circuit current of the solar cell can be achieved.

We have developed rapid laser drilling processes to produce the holes for the contact paths. With high-precision, industrial screen printers, we can align the metallisation and the vias (contact paths) precisely with each other. A special front-surface grid structure was developed which reduces the demands on alignment and thus allows a robust industrial process. The special metallisation technology enables very reliable electrical contact through the vias. The back surface of the solar cells was designed such that an optimised cell connection structure with larger conductive cross-sections could be used for the module circuit.

Modules with efficiency values of up to 15 % were produced from the multicrystalline solar cells which had been manufactured in the PV-TEC laboratory with efficiency values of up to 16 % (see article on p. 55).

The fundamental development of the MWT solar cell was made within the PV-TEC project, which is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Fig. 2: Cross-section through a MWT via. The light-coloured regions of the contacts, which connect the front and back surfaces of the solar cell with each other through the hole, can be clearly recognised.

Prototype of a Solar Module with 16 MWT Solar Cells (MWT: Metal Wrap-Through)

Higher efficiency values and rational processes for module production are required to reduce the peak-watt costs of solar modules. At the technological centre for PV modules at Fraunhofer ISE, we have produced a MWT solar module with a module efficiency value of 15 % in co-operation with the Photovoltaic Technology Evaluation Center (PV-TEC). The ohmic losses can be minimised and the manufacturing process accelerated with innovative wiring technology.

Tim Kubera, Marco Tranitz, **Harry Wirth**, Andreas Gombert

In contrast to standard solar cells, all the areas needed for contacting of MWT cells are located on the back surface (see article on p. 54). This means that a larger proportion of the front surface can be used to generate electricity. Furthermore, wiring elements – so-called cell connectors – with larger conducting cross-sections can be used, as these do not cause any shading losses. The ohmic losses, which are inevitably caused by the series connections within a module, can be kept very low by a special contact configuration on the back surface of the cells and a corresponding structure for the cell connectors. With this novel wiring technology, a module fill factor of 76.6 % was achieved. The fill factors of the MWT cell had an average value of 77.5 %, so that the reduction in fill factor (from the cell to the module) was less than one percentage point.

This approach offers promising advantages, particularly with regard to the connection of larger solar cells which supply higher currents. In addition, contacting exclusively on the back surface opens up new possibilities for connection technology, resulting in significant potential for rationalising string production. A special contact soldering process was developed to produce the MWT module. Other processes such as laser soldering and induction soldering are currently being investigated at the technological centre for PV modules at Fraunhofer ISE.

The SiRKo project (simultaneous back-surface contacting) is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

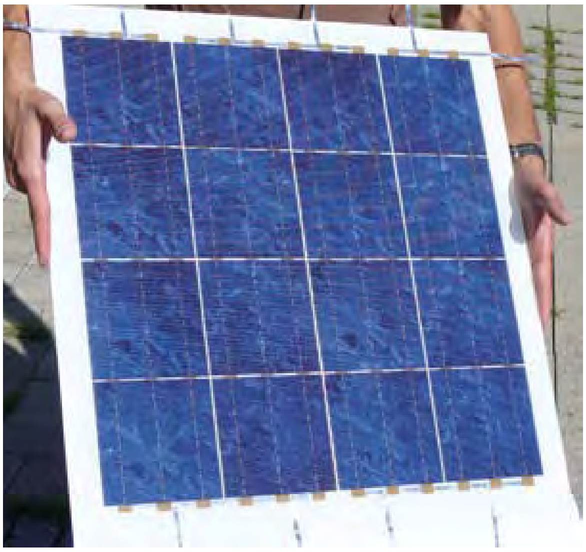
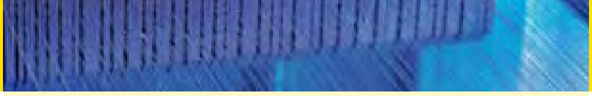


Fig 1: The MWT module consists of 16 multicrystalline silicon solar cells with an edge length of 125 mm. The MWT cells were designed in co-operation with PV-TEC. This allowed new connection technology, with very low ohmic losses, to be implemented.

		module	average cell
V_{oc}	[V]	9.84	0.64
I_{SC}	[A]	5.19	5.22
P_{MPP}	[W]	39.1	2.47
FF	[%]	76.6	77.5
η	[%]	14.9*	15.8

* reference area: 51.4 x 51.2 cm^2

Fig. 2: Comparison of the electrical parameters (open circuit voltage V_{OC}, short circuit current I_{SC}, maximum power P_{MPP}, fill factor FF and efficiency value η) for the MWT module and the MWT solar cells used for its production. Comparison of the fill factors confirms the low ohmic losses caused by the new connection technology.



Heterojunction Solar Cell Processes for Materials Analysis

A central aspect in optimising solar cell processes for multicrystalline silicon is understanding the interaction between solar cell processing and the materials involved. In order to investigate this interaction, we have developed a new method which combines heterojunction solar cell processing and high-resolution short-circuit current topography. In this way, the raw material and also partly processed cells can be effectively included in the investigations.

Dietmar Borchert, Daniel Dopmeier, Stefan Müller, Maik Pirker, **Markus Rinio**, Katrin Schmidt, Mark Scholz, Ralf Preu

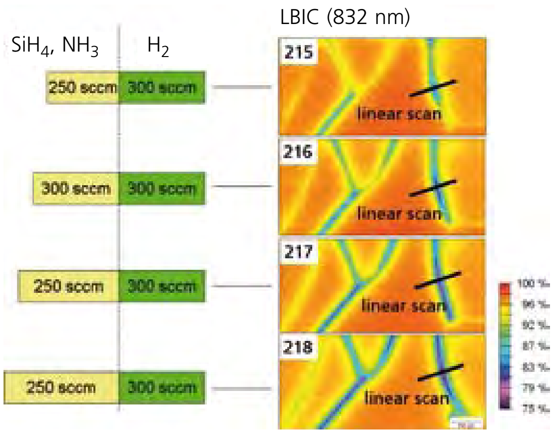
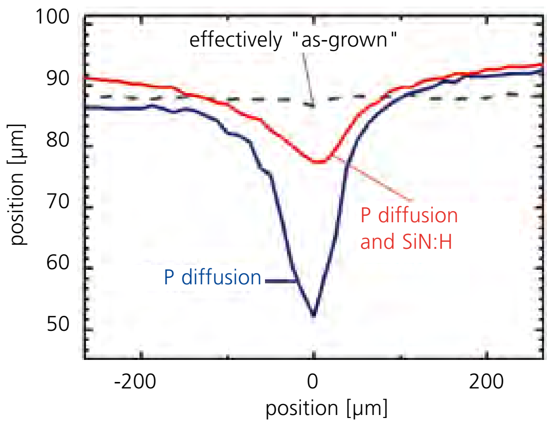


Fig. 1: The influence of the gas mixture during deposition of the SiN layer on the quality of the grain boundaries in the wafer was visualised by short-circuit current topography. Left: Gas flow rates in sccm. Right: Topograms of the measured internal quantum efficiency on differently processed neighbouring wafers. A relatively higher proportion of H_2 improves the grain boundaries, which then appear lighter in the image.



In optimising the material and process, it is decisive that we understand the interaction between multicrystalline solar cell material and the manufacturing process.

High-resolution short-circuit current topography is a measurement method to investigate the behaviour of defects in solar cell material but it always requires a solar cell structure. However, (conventional) production of such a structure always modifies the material itself. In order to avoid this, we have developed an investigation method which allows also the raw material and even partly processed wafers to be included in the investigations. This new approach consists of a combination of high-resolution short-circuit current topography and a heterojunction solar cell process. The heterojunction solar cell process is a low-temperature process which allows cells to be produced at temperatures lower than 250 °C. It does not cause any modifications to the solar cell material. In order to accommodate substrates with the dimensions that are currently used in industrial production, we have transferred the heterojunction process to larger areas of 15.6 cm x 15.6 cm. The developed method is interesting for manufacturers of both solar cells and raw material.

Materials manufacturers can test the performance of new material in our standard process and thus assess its viability for solar cell production. The procedure allows solar cell manufacturers to monitor the reaction of various defects to each processing step in turn.

Fig. 2: Linear scan perpendicular to a grain boundary on three neighbouring wafers. The first wafer was processed to become a heterojunction solar cell and shows the state of the initial material ("quasi as-grown"). The second wafer was subjected to conventional diffusion but does not have a SiN layer. On the third wafer, an additional SiN layer was deposited and fired. The grain boundary initially became worse during the conventional solar cell process and was then improved by the SiN treatment.

Imaging Luminescence Method to Characterise Silicon

Imaging the luminescent radiation of silicon wafers and cells has quickly proved to be an extremely interesting characterisation technique because it is rapid and cost-effective. Nevertheless, it is more difficult to extract quantitative information from luminescence images than from other procedures. We have developed different approaches to solve this problem. One simple and promising method is calibration with a quantitative lifetime measurement in combination with a suitable model for the photoluminescence.

Martin Kasemann, Martin Schubert, Manuel The, **Wilhelm Warta**, Stefan Glunz

In operation, the power generated by a solar cell is essentially determined by the achieved density of optically generated charge carriers. Images of the charge carrier density allow inhomogeneous distributions and thus different loss mechanisms to be identified. For silicon, the band-band recombination radiation (photoluminescence PL) can be recorded with a CCD camera (PL imaging), allowing the charge carrier density to be imaged. We are working on making this rapid method useful for completely and partly processed solar cells, and for material during production.

Compared to the established techniques of CDI (carrier density imaging) and ILM (infrared lifetime mapping), in which the charge carrier density is determined via absorption and emission of the free charge carriers in the medium infrared, PL imaging can be faster and less expensive. However, CDI and ILM provide an image which is proportional to the lifetime of the charge carriers, whereas this does not apply for PL imaging. For this reason, PL images "as recorded" only reveal qualitative differences.

We are working on different ways to allocate a quantitative scale to qualitative PL images and thus provide information on the actual conditions that underlie the observed differences. With the help of a model for the emission of luminescent radiation from the silicon, we have succeeded in deriving a calibration for the PLI measurement from comparison of CDI and PLI measurements of a reference wafer (see figures). This can be applied generally for a specific measurement configuration and under defined conditions.

The work has been supported by the German Federal Ministries for Education and Research (BMBF) and for the Environment, Nature Conservation and Nuclear Safety (BMU) within the "Netzwerk Diagnostik" and "SiCPass" projects.

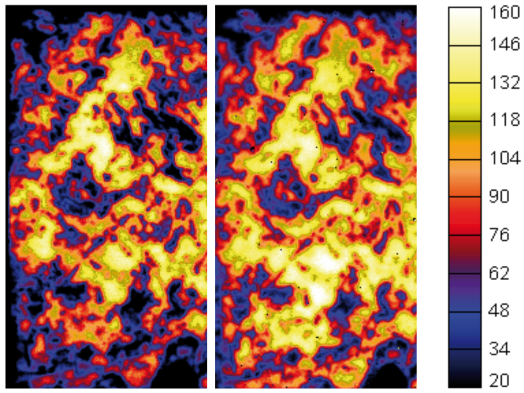


Fig. 1: Photoluminescence (PL) lifetime image (in µs) of a multicrystalline wafer with a passivated surface (left) and a reference measurement of the same sample with CDI (right). The PL image has been calibrated with our new method. The agreement between the two measurement results is very good. A wafer area of 100 x 50 mm² is shown.

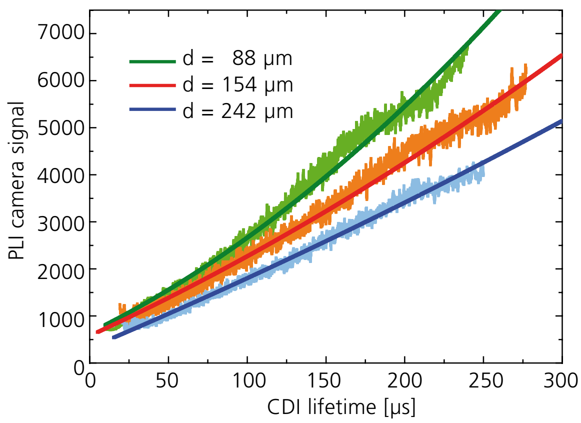
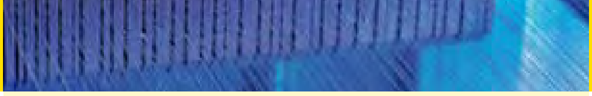


Fig. 2: The measured PL signal is plotted against the CDI signal for three parallel wafers of different thickness d. The CDI data represent the actual charge carrier lifetime. It is clearly evident that the PL results are not linearly dependent on the lifetime. The solid lines show the expected theoretical dependence according to our model. They agree very well with the measured data. This approach allows quantitative data to be extracted from PL images.



Characterisation of III-V Multi-Junction Solar Cells under Varying Spectral and Thermal Conditions

Monolithic triple-junction solar cells made of the semiconductor materials GaInP/GaInAs/Ge are the preferred choice for supplying energy to non-terrestrial systems and terrestrial concentrator systems. These cells are distinguished by very high efficiency values of up to 40 %. We are working to improve these cells still further, e.g. by characterising the solar cell structure exactly and adapting it to specific thermal and spectral conditions.

Frank Dimroth, Martin Hermle,
Raymond Hoheisel, Simon Philipps,
Daniel Stetter, **Gerald Siefer**, Andreas Bett

Multi-junction solar cells are exposed to widely varying environmental conditions in their different applications. In terrestrial concentrator systems, the cells are subjected to high intensities of up to 100 W cm^{-2} and temperatures exceeding 80 °C. The solar cells in space experience completely different conditions. On space missions to distant planets such as Jupiter or Mars, the cells operate at extremely cold temperatures down to -150 °C and solar irradiation of only 4 W cm^{-2}. In addition, the spectral distribution of the radiation is quite different to that on earth. With our extremely flexible solar simulators, we are able to imitate the environmental conditions for almost every application exactly and determine the properties of the solar cells. In this way, our clients obtain reliable information about the performance of their products. In addition, important insights about possible modifications and improvements to the solar cell structure can be gained from the measurements.

Measurements at low temperatures are made in the laboratory with the aid of a cryostat (Fig. 1), which uses liquid nitrogen to achieve temperatures down to -190 °C. Figure 2 shows an example for the quantum efficiency of a GaInP/GaInAs/Ge triple-junction solar cell at different temperatures. The measurement demonstrates how the absorption edge of the partial cells shifts to shorter wavelengths as the temperature decreases. This solar cell was shown to reach an efficiency value of 30.3 % under the operating conditions that prevail on Jupiter.

We co-operate closely with AZUR SPACE Solar Power GmbH, the European Space Agency (ESA-ESTEC) and the German Aerospace Centre (DLR) in further development of the solar cell structures and improvement of the measurement technology.

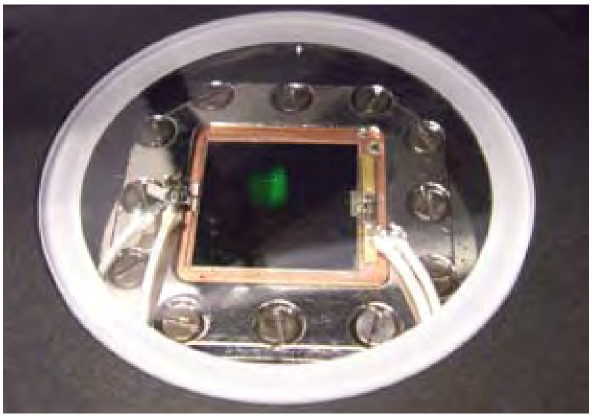


Fig. 1: Triple-junction solar cell in a cryostat to measure the solar cell parameters at very low temperatures down to -190 °C.

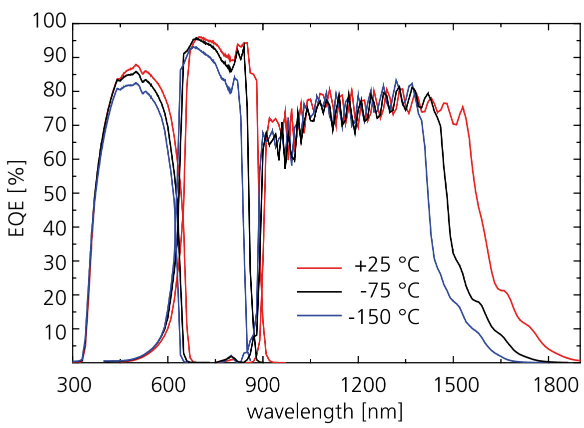


Fig. 2: External quantum efficiency (EQE) of a GaInP/GaInAs/Ge triple-junction solar cell for different temperatures. During space missions to the planets of Jupiter and Mars, the temperature of the solar cell can decrease to -150 °C. This has an effect on the band gap of the different sub-cells and affects the current-matching properties of the multi-junction solar cell.

Highly Efficient Laser Power Converters

We have developed numerous different, highly efficient photovoltaic cells for monochromatic illumination. The development responded to clients' requests for adapted semiconductor materials and higher output voltages for optical energy transfer. We achieved efficiency values exceeding 50 % for monochromatic illumination with laser radiation at 810 nm.

Frank Dimroth, Wolfgang Guter, Rüdiger Löckenhoff, Eduard Oliva, Manuela Scheer, Johannes Schubert, Gerald Siefer, Alexander Wekkeli, Andreas Bett

As is well-known, energy conversion of solar radiation by solar cells makes use of the photovoltaic effect. Efficiency values for standard silicon solar cells are around 20 % and are around 40 %for multi-junction solar cells of III-V semiconductors under concentrated solar radiation. We achieve efficiency values exceeding 50 % when we use monochromatic radiation sources instead of the solar spectrum to illuminate the PV cell. We call such a cell a "laser power converter". There are many application fields for these highly efficient laser power converters. For example, an optical energy supply is of great interest in environments where there is a high risk of explosion or strong electromagnetic interference, as electric cables should not be installed there. Video cameras, sensors or switches are then supplied with energy via laser transmission.

In response to the demand from clients, we have developed diverse and novel laser power converters this year. One focus of our work was the application of different semiconductor materials such as GaSb, GaAs and GaInP, in order to achieve the highest possible efficiency values for specific laser wavelengths. Another requirement is a high output voltage. We have connected individual cells on one chip to achieve this (Fig. 2). In this way, we are now able to cover the voltage range from 1 to 6 V. Further, we have developed tandem cells in GaAs for monochromatic illumination, which supply a voltage of approximately 2 V. Thus, a wide spectrum of laser power converters is now available to our clients. The cells can also be mounted in transistor housings if required.

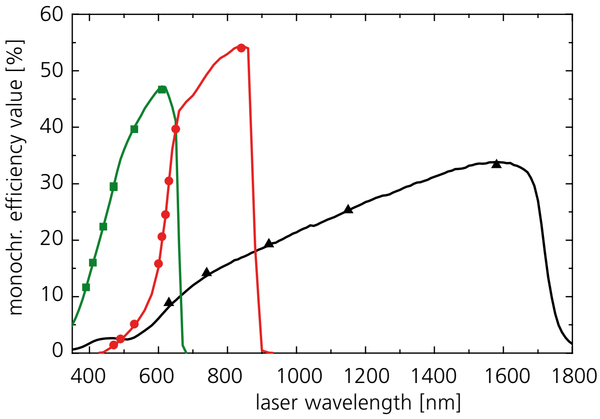


Fig. 1: The figure shows the experimentally derived monochromatic efficiency value as a function of the laser wavelength for cells made of the materials GaInP (green), GaAs (red) and GaSb (black). The input radiative power of the laser is always 20 W/cm^2.

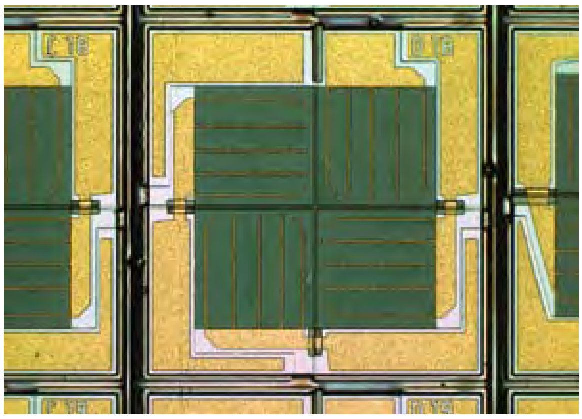
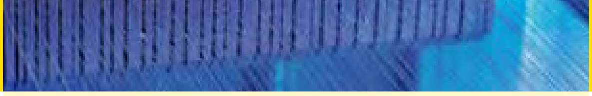


Fig. 2: Illustration of a 1.6 x 1.6 mm^2 laser power converter, in which we have connected four segments on one chip. With this circuit, we have achieved operating voltages of app. 4 V. The monochromatic efficiency for a laser wavelength of 810 nm and an incident radiation intensity of 40 W cm^{-2} is 50 %.



Dye Solar Cells

Dye solar cells are produced at Fraunhofer ISE with a screen-printing process. The durable sealing is achieved by glass soldering. Unlike conventional solar cells, a metal-organic dye is used here to convert light into electricity.

Henning Brandt, Simon Hemming*, **Andreas Hinsch**, Mathias Nittel, Piotr Putyra**, Sandra Simeaner, Welmoed Veurman, Uli Würfel**, Andreas Gombert

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Fig. 1: Demonstration unit for trade fairs – constructed of several dye solar cell modules (30 cm x 30 cm), which are laminated between panes of architectural glass. Different options for integration into the building envelope are shown: lamination of semi-transparent modules in a glazed façade (left) and integration into a ventilated façade (right).

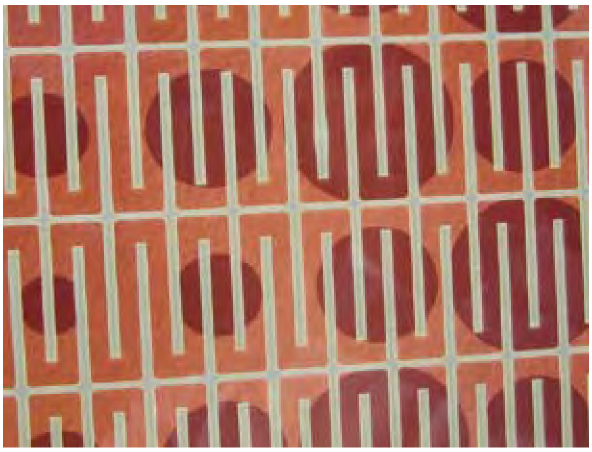

Fig. 2: Detail of a glass-soldered, semi-transparent dye solar cell module according to the meander concept, mounted in front of a white façade. The visual appearance (pattern with circles) was achieved by applying a light-scattering layer behind the photoactive layer. In this way, a decorative design can be achieved without affecting the surface which is relevant for the cell efficiency.

With the possibility of including different colours and partly transparent areas, the dye solar cell opens up new design options for building-integrated photovoltaics, as well as in the combination of classic façade functions (protection against weathering, solar control, etc.) with design and electricity generation. At Fraunhofer ISE, we have produced module prototypes for integration into glazed façades and demonstrated them at trade fairs and a leading-user workshop with architects (Fig. 1). We have developed a special module design (meander design, Fig. 2), which can be simply up-scaled and has screen-printed point contacts for integrated electric series connection. Under outdoor conditions, we have achieved a solar efficiency value of 3.5 % with a prototype of this module having a total area of 30 cm x 30 cm. With the long-term goal of producing more cost-effective dye cells, we at Fraunhofer ISE developed dye cells with glass-soldered sealing in accordance with the so-called monolithic cell concept. With this concept, we succeeded in replacing the expensive counter-electrode by a screen-printed graphite layer which does not require platinum as a catalyst. Impedance investigations of the monolithic dye solar cells that were prepared in this way demonstrated good electrical conductivity of the counter-electrode (sheet resistance < 10 ohm/square) and high catalytic activity (junction resistance 1.2 ohm*cm^2 with standard electrolyte).

The work is carried out within the project entitled "ColorSol: Sustainable product innovations with dye solar cells", which is supported by the German Federal Ministry for Education and Research (BMBF). The development of the monolithic cell concept is occurring together with partners from fundamental and applied research within a network project that is also supported by BMBF.

Development of Flexible Organic Solar Cell Modules

In addition to raising the efficiency value and developing flexible encapsulation materials, the development of efficient manufacturing technology is an essential pre-requisite for the cost-effective production of organic solar cells in future. Together with industrial partners, we made significant progress in developing coating and structuring processes for polymer films with a thickness of several ten to hundred nanometres.

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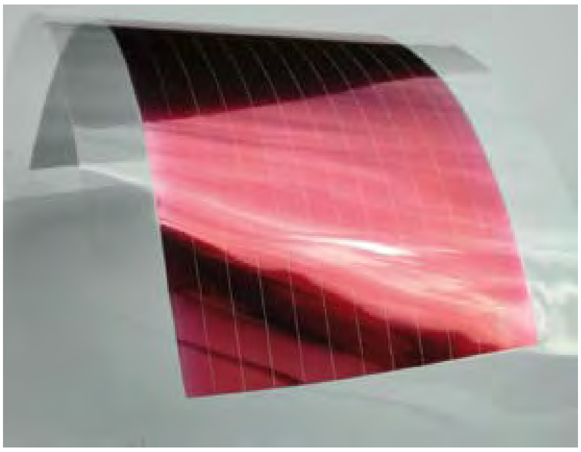

Fig. 1: Demonstration sample of a flexible organic solar cell module, which was produced within the project.

Together with industrial partners, we are developing procedures for manufacturing organic solar cells in a continuous roll-to-roll process. Aspects of the process include the development of wet-chemical coating technology for the polymer anode and the photoactive layer, and the development of techniques to structure the thin films for monolithic connection of the solar cell areas to form a module.

On the basis of rheological investigations and modelling, we were able to determine stability criteria for the coating processes. We carry out initial experiments on coating in our laboratory with a batch coating process. As the deposition system there is compatible with the roll-to-roll coaters of our project partners, the processes can be transferred quickly to their facilities. Depending on the sheet conductivity of the transparent electrode and the lighting conditions in the intended application (indoor or outdoor), we dimension the connection circuit to create a solar cell module from the individual cells with the appropriately adapted output voltage. To access the first application areas as soon as possible, we are co-operating with the developers of specific applications for organic solar cells. One concrete example of an application is the integration of a flexible, energy-autonomous measurement instrument in clothing to record data affecting comfort and health.

Fig. 2: Coating the polymer anode and the photoactive layer of organic solar cells. We are investigating the suitability of different coating methods for future roll-to-roll production.

This work is supported by the German Federal Ministry for Education and Research (BMBF).

Off-Grid Power Supplies

Around two thousand million people in rural areas, innumerable technical systems for telecommunications, environmental measurement technology or telematics, and four thousand million portable electronic devices all have one feature in common: They require off-grid electricity. Increasingly, regenerative energy sources or other innovative energy converters are being used to supply it.

Just on 20 % 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 electricity 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.

The quality of the components and systems for both rural electrification and technical power supplies has improved noticeably over the last few years, but there is still great potential for development. Thus, we support companies in developing components, planning systems and accessing new markets. Our special areas of competence encompass highly efficient power and control electronics, algorithms for battery monitoring, charging strategies for batteries, system operation management, energy management and system simulation.

Furthermore, we also offer analyses 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 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.

Village power supply systems are becoming increasingly important in rural electrification. Fraunhofer ISE monitors newly installed systems within international co-operation programmes. The acquired measurement data can be used to test the quality and reliability of the systems. The results are discussed with local staff during training courses on the monitoring procedures, so that the countries will be able to set up and operate the systems themselves on the medium term.

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 compared to conventional battery systems 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. Further activities in this area are presented in the section on "Hydrogen Technology".

The facilities for our development 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)
- 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
- testing and development laboratory for drinking water treatment systems

Off-Grid Power Supplies

Hybrid system as a power supply for a measurement station which continuously records the water level offshore from the North Sea island of Borkum. The hybrid system consists of a photovoltaic generator, a wind energy converter, a direct-methanol fuel cell, a battery storage unit and an energy management system. A grid connection is not usually available on such platforms. Reliable and cost-effective operation can be guaranteed by the modular construction of the power supply and the innovative energy management system.

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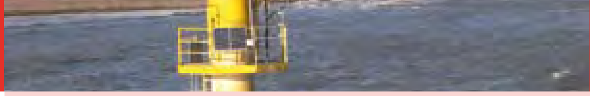


Concepts to Establish and Strengthen Local Electricity Suppliers in Ecuador and Peru

With the goal of disseminating village power supplies based on regenerative energy sources in rural areas of Ecuador and Peru, we are developing concepts to help local electricity suppliers to become established. Furthermore, we prepare recommendations on the integration of renewable energy sources into governmental programmes for rural electrification. Main aspects of the work are the preparation of technical specifications and guidelines on project financing, taking the legal boundary conditions in Ecuador and Peru into account. We hold seminars to train local operators of regenerative energy supply systems.

Brisa Ortiz, Matthias Vetter, Günther Ebert

Fig. 1: Village power supply with a small hydroelectric power plant. In Peru and Ecuador, systems based on renewable energy sources such as this have been successfully installed in a wide range of projects. However, there is still a need for a legal framework and technical specifications, before this type of energy supply concept can be disseminated on a large scale.

Access to electricity is essential for the development of rural areas. However, classic grid extension is often not economically viable in developing countries. Village power supplies based on renewable energy sources, by contrast, offer an economic, reliable and environmentally friendly electricity supply. This has already been demonstrated successfully in Peru and Ecuador in a wide range of diverse projects.

Nevertheless, the legal framework and technical specifications for this type of energy supply concept are still lacking in both countries. With this background, Fraunhofer ISE is co-operating with international project partners to develop concepts to establish and support local electricity suppliers in rural areas of Ecuador and Peru. We have gathered and analysed data on the current legal situation, the various environmental factors, the financial boundary conditions and technological options, as a basis for preparing solution models. We are writing a handbook for energy suppliers, which contains institutional, economic, financial and technical guidelines, taking the national and regional programmes for rural electrification into account. Seminars in Ecuador and Peru are intended to support the transfer of knowledge between the participating institutions, regions and enterprises.

The work is being carried out within the international joint project, "DOSBE", and is supported within the "Intelligent Energy Europe" programme, which is funded by the EU.

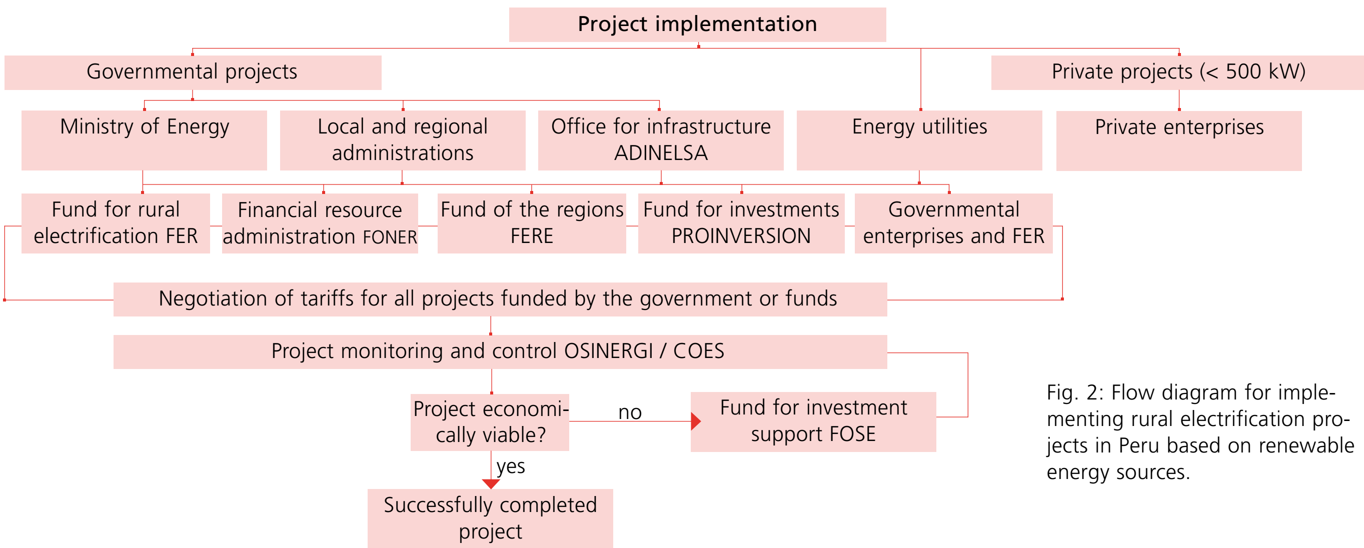


Fig. 2: Flow diagram for implementing rural electrification projects in Peru based on renewable energy sources.

Small PV Water Pumps with a Large Effect on Rural Income in Southern Africa

Increased application of renewable energy technology in the small and medium power range has the potential to reduce poverty in southern Africa. In a sociological field study, Fraunhofer ISE documented the living conditions of subsistence farmers in Zambia. Their income situation formed the basis for systematic photovoltaic solutions including financing models.

Frank Fleischhauer, **Sebastian Gölz**, Christof Weber, Günther Ebert

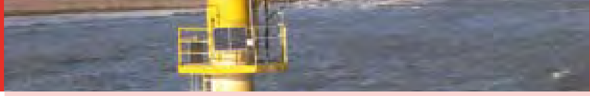
The rural population of the Katuba Region (a settlement area with 9631 residents in 1726 households) in Zambia is mainly engaged in agricultural activities – primarily subsistence farming. One source of income for most families, which offers potential for an increase, is fruit and vegetable farming in small gardens. The harvest is sold in the region or in the capital city of Lusaka, which is about 20 km away. This source of income could increase if the crops could be watered not only during the rainy season. In order to meet the demand for water during the dry season, we have developed a system based on photovoltaically (PV) powered water pumps (150 Wp PV for 4.2 m^3 per day with 10 m pumping height). In addition to technical and socio-economic parameters, the specific advantages of PV and diesel-fuelled water pumps respectively were taken into account in developing the system: Whereas the main advantages of PV water pumps are a low need for maintenance, simple installation and a long lifetime, the factors favouring diesel-fuelled pumps are their low investment costs, their existing wide dissemination and thus technical competence among their operators, and their suitability for mobile applications.

Mobility is a key factor to success due to the settlement and agricultural structure in Katuba, and also with regard to financing models. By hiring a PV water pump out to different farmers, effective use can be made of its pumping capacity. In this way, a "fee for service" approach can be developed, in which the hiring fees remain accessible for the small-scale farmers and the pump owner can build up a profitable business with the income.

The work is being carried out within the EU-funded project entitled "Renewable and Efficient Energy for Poverty Alleviation in Southern Africa (REEPASA)". The countries participating in the project are Zambia, Swaziland, Mozambique and South Africa.

Fig. 1: Drinking and domestic water is obtained in Katuba from wells, rivers and a small dam. The population is dependent on the location of the water sources and the means to draw the water – typically by hand.

Fig. 2: In a survey, we co-operated with Zambian farmers to analyse their existing activities in market gardening and the resulting income. Together with our partner, the "Centre for Energy, Environment, and Engineering Zambia (CEEEZ)", the exact energy demand was determined and possible organisational and financing approaches were developed and integrated into a new project in the area.



New Communication Standards for PV Hybrid Systems

The "Universal Energy Supply Protocol UESP", which we developed at Fraunhofer ISE for innovative energy management of PV hybrid systems, has been further standardised. We have equipped the "Energy Dispenser" devices, designed for load management and energy distribution in PV hybrid power supplies for villages, with an interface for manufacturer-independent communication with a higher-level energy management unit.

Georg Bopp, Matthias Vetter, Jakob Wachtel, Michael Zillgith, Günther Ebert

Fig. 1: "Tarom" PV charge controller from the Steca company for 24 V / 70 A with a UESP interface. The UESP interface consists of a small embedded system from the SSV company with a 32-bit coldfire processor (to the lower right of the photo). Fraunhofer ISE has implemented the UESP protocol including the network management under the Linux operating system in this interface. The same embedded system is used for the CANopen interface of the Energy Dispenser (Fig. 2).

Fig. 2: The Energy Dispenser distributes a certain amount of energy per day. If a large amount of energy is available to the system (e.g. during sunny periods), the users can consume twice as much energy for the same price. Conversely (e.g. during the night, when the battery capacity is almost exhausted), only half as much energy is supplied for the same price. We replaced its proprietary communication bus by a universal CANopen interface with standardised commands for input and output devices.

On the initiative of Fraunhofer ISE and several photovoltaic companies, the new Special Interest Group (SIG) on "Battery-Based Decentralised Energy Supply Systems" was founded within the CAN (Controller Area Network) in Automation (CIA) Organisation in 2007. The SIG is preparing a standardised and manufacturer-independent communication protocol for off-grid PV-hybrid systems. It is based on the Universal Energy Supply Protocol (UESP), which Fraunhofer ISE developed in co-operation with industrial partners including the Steca company. UESP allows the networking and optimal energy management of system components, simplifies the planning and installation of photovoltaic hybrid systems and simultaneously leads to cost-optimised and reliable system operation. UESP already communicates via the CAN bus, but still uses a manufacturer-specific network management system. Within the standardisation process, the network management system will be replaced by the industrial standard, CANopen, and the application scope will be extended to all types of off-grid energy supply systems with battery storage.

In 2007, we set up two PV hybrid systems with UESP and programmed a CANopen interface for the "Energy Dispenser" made by the Spanish company, TTA. The Energy Dispenser is an intelligent electricity meter and serves to distribute limited amounts of energy fairly and to optimise the usage of the available solar energy in PV hybrid systems. We replaced its proprietary communication bus by a universal CANopen interface. As a consequence, in future the Energy Dispenser can be used in every PV hybrid system, independent of the manufacturer.

The work is being carried out within projects that are supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the European Union.

On-Line Detection of Fouling Layers on Technical Surfaces by Ultrasonic Reflectometry

The development of suitable methods to detect undesired deposits (fouling) on technical surfaces, e.g. heat-transfer surfaces, particularly on membranes, is the objective of a current research project. On-line detection of fouling layers is the basis for analysing cleaning measures reliably and taking preventive measures in operation management. Optimised operation management is particularly important for solar-powered water purification processes. We are investigating the method of ultrasonic reflectometry for this purpose. The goal is a sensor system which is capable of detecting even microbiological deposits (bio-fouling) of only a few micrometres thickness during system operation.

Daniel Philippen, Matthias Vetter, **Joachim Went**, Günther Ebert

Within the context of solar-powered purification of drinking water, we are working on the implementation of small, autonomously powered membrane systems. Fouling presents the major problem to be solved in these systems. By developing a sensor for on-line detection of fouling, we aim to optimise the system management of membrane systems and apply effective cleaning measures.

With an initial operational prototype, we could already reliably detect coating thicknesses of less than 5 µm on the membrane surface. Together with the company, Gampt mbH, from the medical technology sector, we have begun to further develop an ultrasonic film thickness measurement instrument. At Fraunhofer ISE, we have developed special test cells, which allow defined fouling layers to be deposited on flat membranes. In this way, we can deliberately simulate different types of fouling. The transparent test cells are particularly advantageous, as coloured fouling layers can be deposited in them during operational cross-flow filtration. The layer growth can be observed visually and the layer thickness can be measured simultaneously with the new detection method. This method is particularly interesting because we have succeeded, even for a bio-fouling layer, in correctly measuring the layer thickness with a path difference of about 30 µm. Reliable detection of disturbing bio-fouling during continuous operation means that the consumption of biocides and anti-scaling chemicals can be considerably reduced. By developing the sensor system further, we have the opportunity to provide solutions for a range of technical processes which have problems with fouling. Beyond that, operation becomes more economical and environmentally friendly.

The work was supported by the Gampt mbH company and the German Federal Ministry for Economics and Technology (BMWi) within the ProInno II research programme.

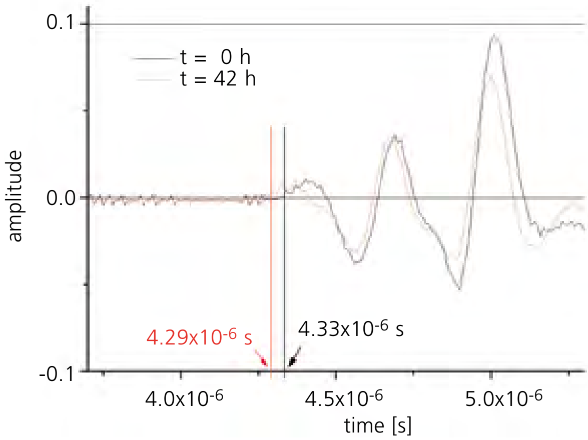


Fig. 1: Ultrasonic reflectance signal from the surfaces of the membrane and the fouling layer at a temperature of 24.8 °C (10 MHz transducer). The vertical lines indicate the point in time when the pulses are incident at the transducer. The reference pulse from the clean membrane (black) arrives at the transducer after 4.33 µs, whereas the pulse recorded after 42 h of filtration (red) already arrives after 4.29 µs. A layer thickness of 30 µm can be calculated from these values.

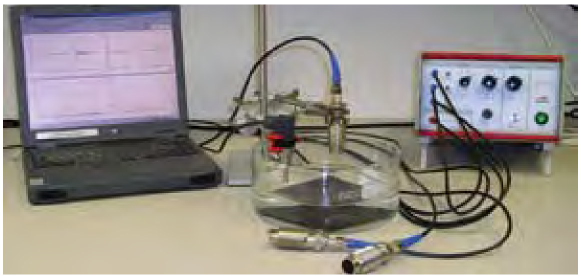
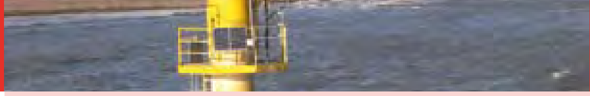


Fig. 2: Operational prototype of the fouling measurement instrument. In the centre of the photo and in the foreground are the ultrasonic transducers (blue connections) and the temperature sensors. To the right, the pulse generator with its integrated measurement amplifier is visible. On the left is the measurement computer with graphical measurement and analysis software.



Membrane Systems for Decentralised Water Purification Operating Autonomously due to Ultrasonic Cleaning

During the past three years, we have intensively investigated the possibilities for mechanically cleaning the membranes in water purification systems. Now we are able to offer systems which can be operated without needing additional chemicals for cleaning. The result of the developmental work is an ultrasonically supported cleaning system on a production scale. We have successfully operated the working prototype, which has a membrane module equipped with ultrasonic transducers, with water from the Dreisam River in Freiburg.

Simone Herold, Monika Gidt, Heiko Pawelczyk, **Joachim Went**, Günther Ebert

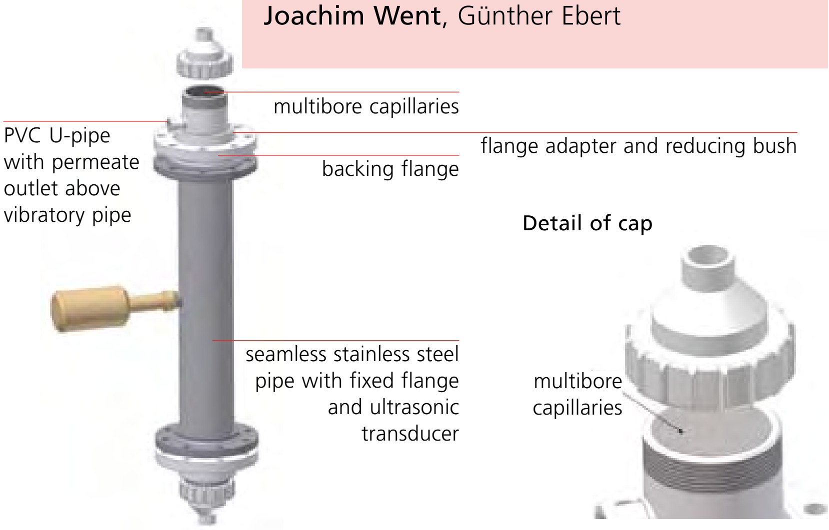
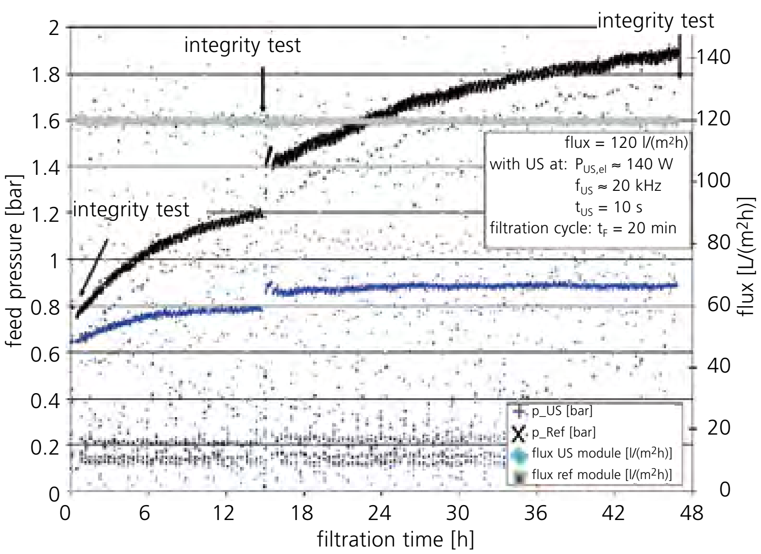


Fig. 1: Construction of an ultrasonic membrane module for the capillary module, dizzer 450, made by Inge AG. A commercially available ultra-filtration module is surrounded by an elastic stainless steel pipe to couple in ultrasonic pulses. This module operates with capillary membranes of polyether sulphone with a molecular weight cut-off of 150 kDa. The module has a total active membrane area of 4.5 m².



For the first time, we have successfully up-scaled an ultrasonic membrane cleaning system for small membrane systems from the laboratory to a production scale, which requires reliable calculation of the equipment and energy required. With long-term tests using natural surface water, we have also obtained reliable results on the cleaning performance of the system.

The concept of "Ultrasonically enhanced back-washing" is a practicable way to clean membranes ultrasonically. In addition, the anticipated costs for implementing it in a product can be calculated. This approach takes account of the advantages of larger membrane areas concerning both the energy balance and the deposition of fouling layers.

Long-term experiments, measurement of the ultrasonic field in the modules and the application of different membrane materials have revealed different approaches for optimising the product development. For the first time, the results of the research project offer an overview of the technical application of ultrasonic cleaning to sensitive surfaces and the effectiveness of "soft" cavitation (bubble formation in a liquid) for cleaning. When ultrasonic cleaning is applied to porous membranes, the aggressiveness of cavitation can be controlled by adjusting the pressure drop and specific usage of the backwash fluid.

The work was supported by three companies, ITN-Nanovation AG, Hielscher Ultrasonics GmbH and Grünbeck Wasseraufbereitung GmbH, and the German Federal Ministry for Economics and Technology (BMWi) within the InnoNet research programme.

Fig. 2: The graph shows a two-day interval within a long-term test. With an area-related flux of 120 l/(m²h) and a cleaning interval of 20 minutes, the change of pressure with time differs strongly between the ultrasonic module (blue symbols) and the reference module without ultrasonic equipment (black symbols). Whereas the pressure soon maintains a constant value with the ultrasonic module, the pressure in the reference module continues to rise due to the less effective cleaning.

Battery Management System for Stand-Alone Power Supply Systems in Practical Applications

Batteries form an essential component of off-grid power supply systems to compensate differences between the supply of and demand for electricity. Relatively inexpensive lead-acid batteries are most commonly used for this task, but their lifetime presents a critical factor. In order to lengthen this without restricting the availability and the autonomous operation duration of the power supply, we have developed a battery management system and tested it under real application conditions.

Rudi Kaiser, Simon Schwunk, **Robert Thomas**, Matthias Vetter, Günther Ebert

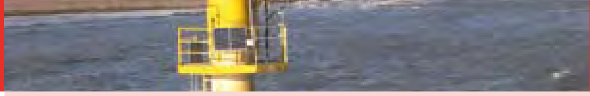
For optimised operation of photovoltaically powered, stand-alone systems, we have developed a battery management system, which accurately determines the state of the battery (state of charge and aging), applies optimised charging strategies and allows great flexibility concerning the operation management of the batteries due to the circuits implemented. In this way, we can significantly lengthen the lifetime of batteries in PV systems.

The algorithms for determining the state of charge and state of aging are distinguished by requiring only easily accessible measurement values and determining precise results for different types of technology without specific battery parameters. A further advantage is that in contrast to other algorithms, complete charging is not required as a recalibration point for determining the state of charge. Despite its functionality, the developed battery management system is compact enough to be applied with cost-effective hardware also in smaller systems.

At present we are subjecting the battery management system to a field test under real application conditions at the "Rappenecker Hof", a hikers' inn in the Black Forest without a grid connection (Fig. 2). This has been supplied for 20 years with a hybrid system consisting of a photovoltaic generator, a wind energy converter, a diesel generator and a battery storage unit, as well as a fuel cell for the last four years.

Fig. 1: Three of the four battery strings installed at the Rappenecker Hof. The implemented battery management system is able to determine the state of the batteries accurately (charge, aging), apply optimised charging strategies and react flexibly to consumer behaviour and generator performance. This is achieved by dividing the storage unit into several parallel strings, which can be connected independently of each other.

Fig. 2: The hybrid system at the Rappenecker Hof consists of a PV generator with 3.8 kWp, a fuel cell with 1.2 kW, a wind energy converter with 1 kW, a diesel generator with 9.6 kW and a battery storage unit with a capacity of 62 kWh. Within a field test, we are subjecting the battery management system that we have developed to the real operating conditions at the Rappenecker Hof.



Simulation-Based Development and Optimisation of PV Hybrid Systems

Simulation is essential as a rapid and cost-effective method to plan, investigate and optimise complex energy systems based on PV hybrid systems. We develop efficient models using the most modern simulation programs to carry it out. Beyond this, we use these models for simulation-based development of operation management strategies and component control, as well as for energy and battery management systems for PV hybrid systems.

Christian Friebe, **Matthias Vetter**,
Simon Schwunk, Günther Ebert

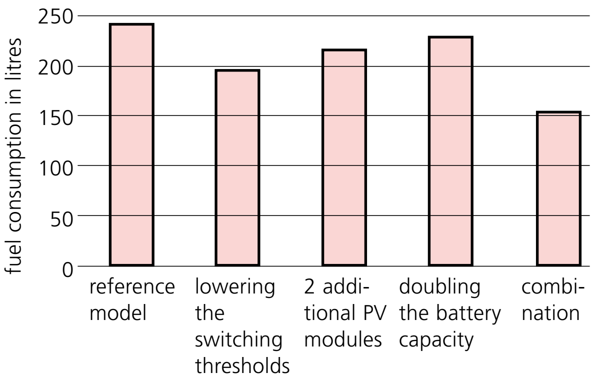
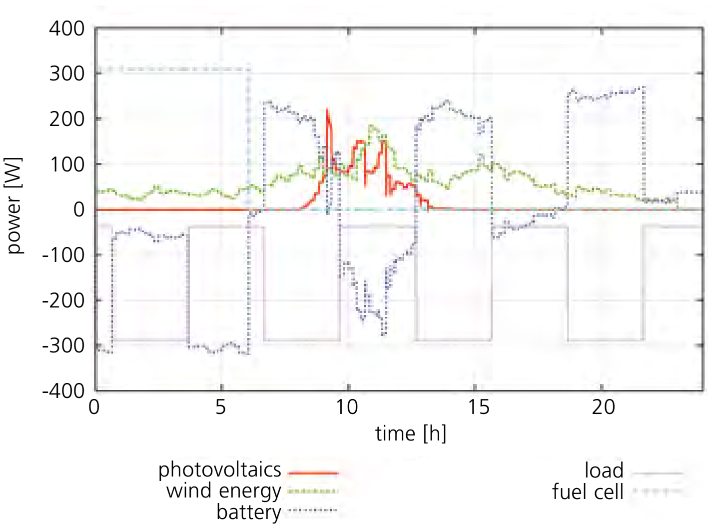


Fig. 1: Effect of different optimisation measures on the annual methanol consumption of a fuel cell in a PV hybrid system. The reference system consists of a PV generator (6 x 162 Wp), a wind energy converter (1 kW), a direct methanol fuel cell (325 W) and a battery (660 Ah). The largest effect on the methanol consumption is achieved by changing the switching thresholds in the energy management system. The right-most column represents the result of combining all of the optimisation measures.



PV hybrid systems are complex technical systems with widely varying behaviour, depending on the system configuration and the environmental conditions. They usually cannot be described adequately by general calculation estimates. For this reason, we carry out detailed system simulations, using the most modern simulation programs. With the dual aims of investigating control strategies and analysing the energy balance over the course of a year, we develop detailed but simultaneously efficient component and system models. With this approach, we are able to dimension systems, quantify the effect of individual parameters (Fig. 1), optimise systems, develop and improve controls, and investigate their effect on the system performance. We program the control algorithms in ANSI C, which can be ported directly to microcontrollers after successful testing.

Within the EVEREST project, we have applied this approach to develop an energy management system which correctly determines the system state (e.g. the state of charge of the battery), prepares a distribution plan for each day (Fig. 2) and ensures that the batteries are fully charged regularly.

We test whether the developed control algorithms on the microcontroller are operating correctly with the help of the so-called "hardware in the loop" method. This uses models for the process to be controlled, which provide simulated values to the microcontroller. In this way, we are able to shorten development processes appreciably, particularly error detection.

This development work is supported within the InnoNet Programme by the German Federal Ministry for Economics and Technology (BMWi).

Fig. 2: Simulated power profiles during a typical day in winter for the individual components of a PV hybrid system, consisting of a PV generator (6 x 162 Wp), a wind energy converter (1 kW), a direct methanol fuel cell (325 W) and a battery (660 Ah), which is designed to supply a stand-alone measurement station. The fuel cell was switched on during the early hours of this day so that as much energy as possible could be used directly, and not stored intermediately in the battery..

Energy-Autonomous Preparation of Drinking Water from Seawater or Brackish Water

At Fraunhofer ISE, solar-thermally driven water desalination systems are developed that are based on the principle of membrane distillation. We distinguish between two categories, very simply constructed and completely energy-autonomous compact systems for daily capacities of app. 150 litres per system, and two-loop systems for daily capacities exceeding 2000 litres. After successful testing in pilot systems, we are now concentrating on developing a marketable product.

Joachim Koschikowski, Georg Mülhöfer, **Matthias Rommel**, Marcel Wieghaus, Hans-Martin Henning

Membrane distillation (MD) is a separation process in which water vapour is removed from an aqueous solution and is driven through a micro-porous membrane. The driving force is the temperature-induced difference in water vapour partial pressure between the two sides of the membrane. For small systems in the capacity range from several 100 litres per day up to 100,000 litres per day, which can be operated with solar energy or waste heat, MD offers decisive advantages compared to other processes. One essential aspect for decentrally installed, solar-driven systems is that membrane distillation requires only relatively simple systems technology and practically maintenance-free operation can be well achieved. Fraunhofer ISE has operated solar-driven MD pilot systems since 2004 to desalinate seawater and brackish water. Based on the experience that we have gained from continuous monitoring of the five compact systems and two two-loop systems under real operating conditions, we are now able to further develop both the MD modules and the complete system with respect to increasing yields, operational safety and ease of installation.

We are able to validate simulation models with the measured data and use them to optimise the systems. Furthermore, we have concentrated on developing the compact system with a daily capacity of 100 to 150 litres to a marketable product. We installed the first system with the new design for a client on Tenerife in November 2007.

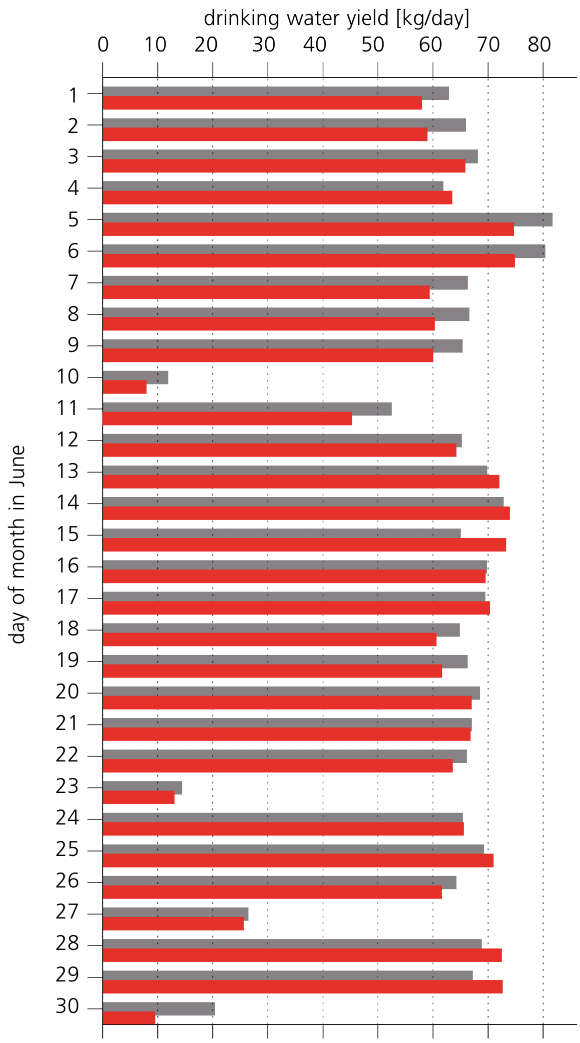


Fig. 1: Comparison of simulated (grey) and measured (red) drinking water yields per day during the month of June for a compact system that was installed on Gran Canaria in 2004.

Fig. 2 : Energy-autonomous compact system that was installed in November 2007 on Tenerife for seawater desalination. The daily capacity is about 120 litres.


SIC-SAFCO
SNAPSIC
105 4P
1000µF ±20%
500 Vcc .LL.
-55+105°C
05 49 326
CGS SBCHE15
15K J KP KE
TML 05105
In/ph: 8.33A Pn: 5.75kW

Grid-Connected Renewable Power Generation

Construction of grid-connected systems is the largest global market of the photovoltaic branch today. Well-implemented market introduction programmes, particularly in Japan, Germany and some States of the USA, but also in European countries such as Spain, Italy, Greece, France and Portugal, are ensuring high growth rates. To maintain this market growth while subsidies are decreased, 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 today. 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, particularly for large, commercial photovoltaic systems. 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 large-area photovoltaic systems but also concentrating photovoltaic systems and solar thermal power stations can make an important contribution to environmentally friendly generation of electricity. To achieve higher steam temperatures, we are conducting research to improve both the concentrator optics, including Fresnel lenses and reflector systems, and the absorber coatings for solar thermal power stations. We support the industry with our optical and thermal measurement services for quality control of the collector fields and with simulations to dimension and optimise complete systems. Together with our partner, PSE GmbH, we also prepare new concepts to control the reflectors for Fresnel collectors. We optimise the operation of concentrator PV and tracker controls with modern power electronics and controls technology.

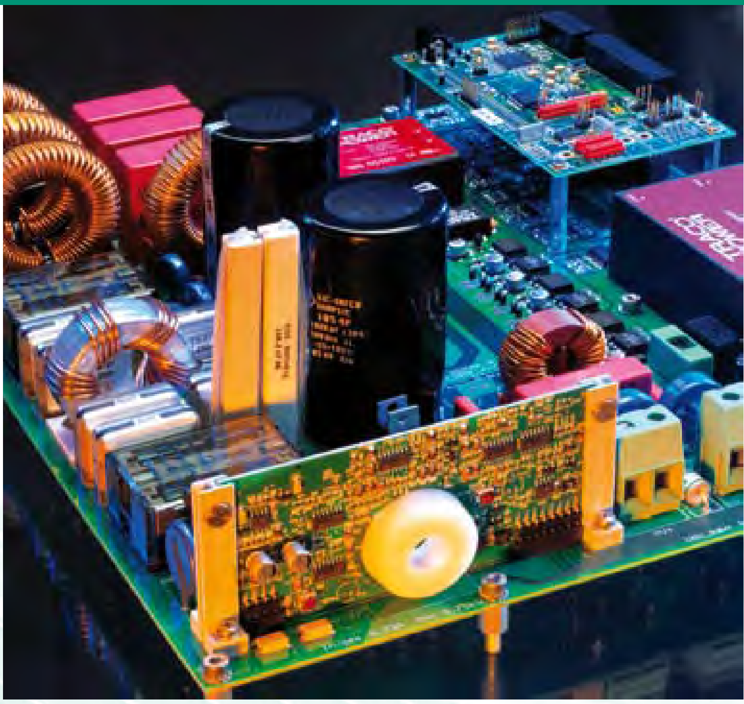
Optically concentrating photovoltaic systems offer the potential to reduce the price of solar electricity from large power stations in sunny regions. We are developing high-efficiency solar cells for concentrator modules that are mounted on dual-axis solar trackers. In combination with inexpensively manufactured Fresnel lenses, module efficiency values of 26 % are achieved. Concentrix Solar GmbH, a spin-off company from Fraunhofer ISE, is currently constructing the first 500 kW power station based on this technology.

The liberalisation of the electricity markets and the entry of climate-protecting technology to the electricity-generation market mean that the proportion of PV systems and other distributed generators such as combined heat and power plants is increasing continuously. Many small generators and controllable loads 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.

The facilities for our work on grid-connected renewable power generation 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



Triple-phase 6 kW inverter without a transformer, designed for grid connection of PV systems. Its construction principle without a transformer means that high efficiency values are achieved. This inverter needs only passive cooling with cooling fins. Comparable devices are often equipped with active cooling, i.e. an additional fan, which must usually be replaced during the inverter lifetime. By dispensing with a transformer, the mass and volume of the inverter can be decreased, which in turn leads to cost savings.

The triple-phase grid input has the advantage of loading the grid symmetrically – this avoids undesirable unbalanced loads on the grid. In addition, the number of electrolyte condensers can be clearly reduced in comparison to single-phase inverters, which also has a positive effect on the lifetime and costs.

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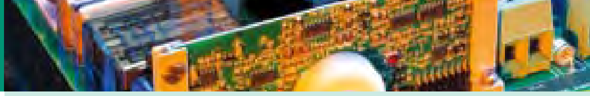


Process Optimisation and Quality Assurance for Yield Predictions

Yield predictions are essential for the preparation of financing concepts for larger photovoltaic systems. Scientific studies can provide reliable information within the specified accuracy on the long-term average of the system yield. To validate the quality of our predictions, the measurement data from our quality-control monitoring for 15 locations in Germany were compared with the predictions that had been made originally.

Thomas Erge, Klaus Kiefer, Björn Müller, Christian Reise, Nicole Römer, **Andreas Steinhüser**, Günther Ebert

	G/L	PR
1 solar radiation (horiz.)	100%	
2 solar radiation (module plane)	113%	100%
3 shading	110%	97%
4 soiling	109%	96%
5 reflection	106%	93%
6 spectrum	105%	92%
7 module	99%	86%
8 elec. interconnection	98%	85%
9 cabling	97%	85%
10 inverter	93%	80%

Fig. 1: Typical calculation steps, ratio of gains to losses (G/L) and effect on the performance ratio (PR) during the course of yield prediction.

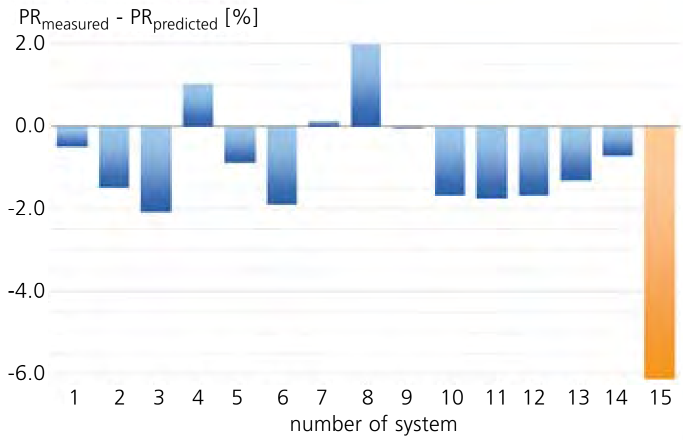


Fig. 2: Comparison of the performance ratio as predicted with pyranometer measurement data: positive values mean that the measured value was higher than the prediction. System 15 had technical problems.

The main information from the yield prediction for a photovoltaic system is the anticipated annual energy yield, expressed both as an absolute value in kWh and related to the system dimensions as kWh per kWp. To assess the quality of a system and also to compare the operating data from installed systems, the performance ratio (PR) or system efficiency value is an important parameter and should be included in a yield prediction report.

For the 15 locations in Southern Germany, for which we not only prepared yield predictions but have carried out quality-control monitoring, the predictions agree very well with reality. For all systems without technical problems, the value of the predicted performance ratio agrees within ± 2 % with that measured with a pyranometer (solar radiation instrument) and is thus well within the tolerance range specified in the prediction report. Larger deviations can be observed in individual systems which had technical problems.

Pyranometer measurements must be analysed for a direct comparison between the predicted and measured PR. The results show that the system performance of PV power plants can be simulated very well.

There is more uncertainty in determining the long-term averages of the direct and diffuse radiation on a horizontal plane and calculating the radiation incident on the module plane. The total uncertainty for yield predictions, including the uncertainty for the solar radiation, is between 4 and 5 %, depending on the location and the technical concept.

Performance Analysis and Optimisation of Photovoltaic Power Plants

Automated operation monitoring is necessary in order to guarantee that a photovoltaic system supplies constant yields over a planned lifetime of 20 years. It ensures that a system error such as an inverter failure is detected immediately. Data is acquired on the solar radiation with calibrated radiation sensors and on the generated electricity with a calibrated meter, and is used to accurately calculate the so-called performance ratio (system efficiency value). Good quality pays for itself, not only regarding the photovoltaic components. Accurate and reliable measurement technology should also be included in the complete system.

Alfons Armbruster, Wolfgang Heydenreich, **Klaus Kiefer**, Frank Neuberger, Peter Raimann, Eberhard Rössler, Günther Ebert

Fig. 1: PV system on the Solar Info Center in Freiburg: The 50 kWp system, which was installed in 2003, has consistently delivered optimal yields since then.

Year	Annual solar radiation	Yield	Performance ratio
2004:	1240 kWh/m²;	1026 kWh/kWp;	82.7%
2005:	1252 kWh/m²;	1091 kWh/kWp;	87.2%
2006:	1279 kWh/m²;	1097 kWh/kWp;	85.8%
2007:	1300 kWh/m²;	1151 kWh/kWp;	88.6%

Photo: Andreas Weindel

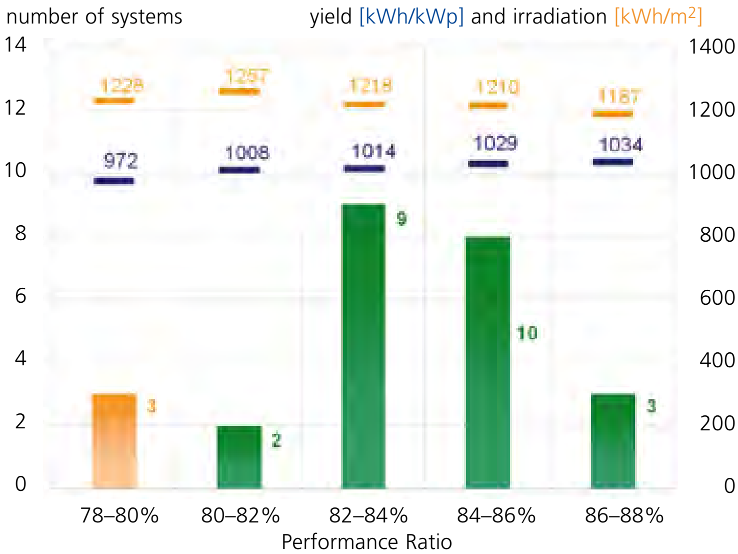


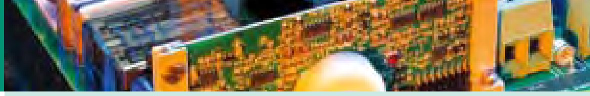
Fig. 2: Frequency distribution of the performance ratio for 27 systems in Southern Germany (green or orange). The systems with a PR from 78 to 80 % are partially shaded. The average yield for the systems in a given PR range is indicated in blue; the average annual solar radiation total is shown in dark yellow. The close correlation between yield and performance ratio is evident. By contrast, the solar radiation total and PR are independent of each other.

In very good systems, the performance ratio is around 80 % and above. Long-term measurements have demonstrated that the individual monthly values are subject to slight deviation but the annual value remains practically constant if the system does not develop technical faults. Thus, the performance ratio is an important parameter for assessing the system quality during operation. It can already be recognised during the first few months whether the performance corresponds to that determined in the yield prediction. In this way, immediate feedback is obtained on whether the solar power station is meeting expectations.

The quality of photovoltaic systems has risen continually over the past years. The number of systems in Bavaria and Baden-Württemberg which bring annual yields exceeding 1000 kWh per kWp installed power (corresponding to a module area of app. 8 m^2 for the present state of the art) is increasing steadily. In large, megawatt solar power stations, where Fraunhofer ISE was responsible for all aspects of quality management from the yield prediction through to monitoring, the performance ratio in 2006 was consistently around 80 % or even well above (Fig. 2).

The measured total annual radiation on the tilted solar generator plane was about 1220 kWh m^{-2} on average. The highest total radiation value in 2007 of 1300 kWh m^{-2} was measured in Grünstadt in Southern Palatinate. All systems with yields below 1000 kWh/kWp are partly shaded and not optimally oriented. Maximum yield can be obtained only from non-shaded sites, even with optimal technology.

The best systems gained yields on the order of 1050 kWh/kWp and 1100 kWh/kWp.



Inverter with SiC MOSFET's

Silicon carbide (SiC) is a semiconductor material which has been used increasingly in power electronics due to its excellent properties. Silicon carbide was first used in diodes, then also in bipolar transistors and JFET's, and most recently in MOSFET's. We recognised the possibilities which it offered for PV inverters. The CREE® company was convinced by our ideas and provided us, as the only research institute outside the USA, with the first SiC power MOSFET's.

Bruno Burger, Dirk Kranzer,
Sascha Lehrmann, Olivier Stalter,
Günther Ebert

Apart from reliability, efficiency is the main criterion for PV inverters. It is determined predominantly by switching losses in the transistors used. The new MOSFET's of SiC combine low forward resistance and short switching times, so are better suited for PV inverters than comparable IGBT's of silicon. The samples which the CREE® company provided to us were laboratory prototypes, such that the data sheet did not include complete specifications. In effect, the MOSFET was a "black box" for us. With our measurement equipment, which was designed for characterising transistors, we determined the switching times, switching energy levels and the forward resistance at different temperatures and gate voltages. This measurement procedure allows us to model transistors accurately, and we gain informative comparisons of different semiconductor components from it in topology investigations.

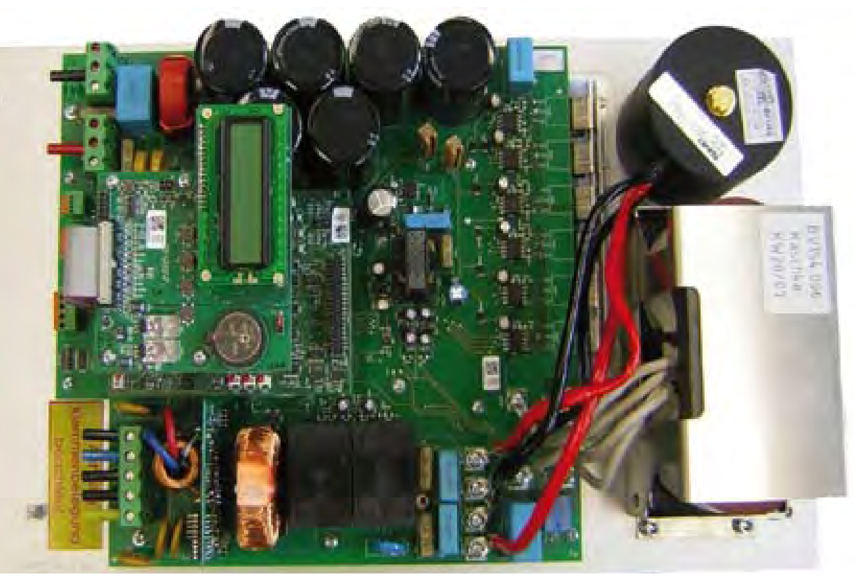


Fig. 1: Single-phase PV inverter with HERIC® topology, 5 kW rated power, 350 V intermediate circuit voltage and 16 kHz switching frequency. The development was commissioned by an industrial partner.

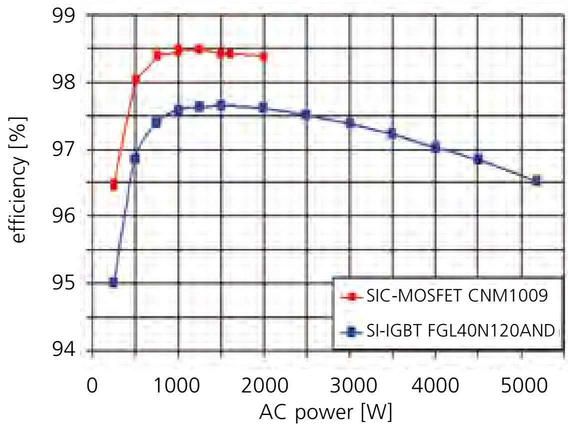


Fig. 2: Comparison of efficiency values for the single-phase HERIC® PV inverter. As the MOSFET's are not specified for the complete power range of the inverter, the curve was not determined up to the rated power in this case. With a maximum efficiency value of 98.5 %, we have again set a world record for PV inverters.

Silicon carbide, in comparison to silicon, is a very expensive semiconductor material due to its complicated production process. Thus, it is found in very few applications of commercial power electronics, despite its excellent properties. However, specifically the application here in PV inverters opens up new possibilities for the mass market. Due to the feed-in tariff, the added value gained by a higher efficiency value over the lifetime is significantly higher than the additional costs which are caused by the expensive semiconductor material. In order to demonstrate this, we replaced the installed IGBT's by prototypes of the SiC MOSFET's in a single-phase PV inverter (Fig. 1) and a triple-phase PV inverter (Fig. 4). Both inverters were models which we had developed for industrial partners. No other changes were made.

The single-phase HERIC® topology, with up to 850 V operating voltage, already has a high efficiency value, so that the maximum efficiency gain of 0.8 % may appear to be small. However, when it is known that often entire development departments are occupied with raising the efficiency value by one or two tenths of a percent, it represents a major advance, as we only replaced the transistors here. With this approach, a new efficiency value record of 98.5 % has been made for PV inverters, which can be increased further when the system is adapted appropriately.

The increase was still clearer for a triple-phase inverter with an operating voltage of 750 V. The increase in the European efficiency value of 2.4 % was appreciable (Fig. 3). What initially does not sound very spectacular actually represents a halving of the power losses. Furthermore, this increase was again achieved without adaptation of the whole system! We assume that with a new development, a maximum efficiency value of 98.5 % with a reduced total volume can also be achieved for the triple-phase inverter, setting new standards for PV inverters.

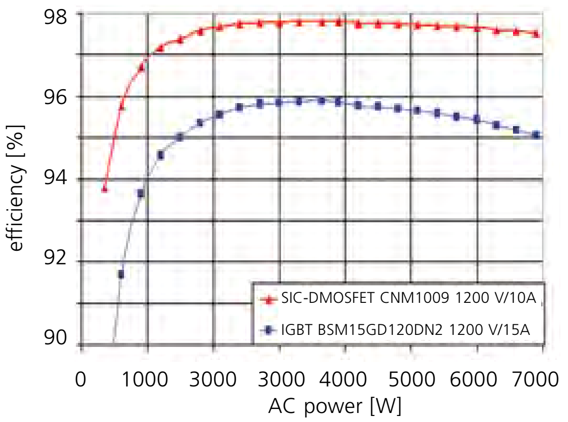


Fig. 3: Comparison of efficiency values for the triple-phase inverter when equipped with IGBT's and SiC MOSFET's. Maximum values of 95.1 % with IGTB's and 97.5 % with MOSFET'S were achieved. This represents an increase of 2.4 %! The measurement of the efficiency value includes all the losses of the inverter including the power demand of the control electronics.

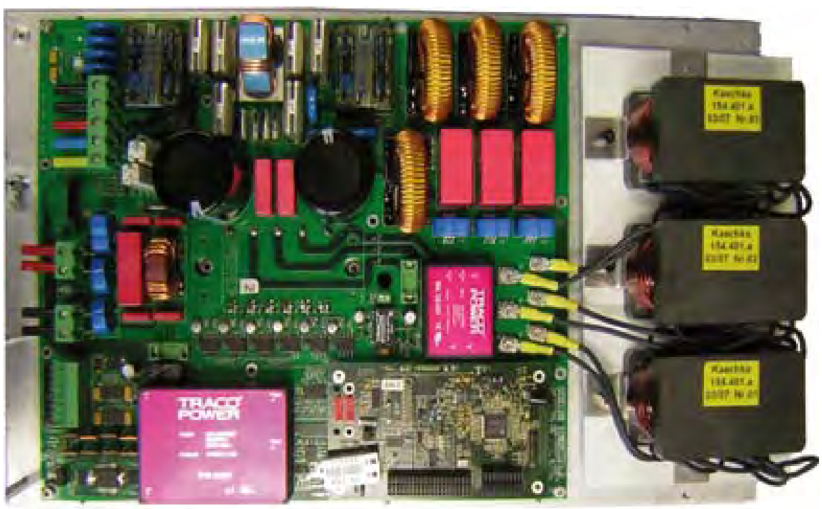
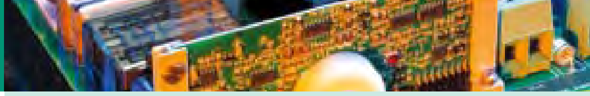


Fig. 4: Inverter developed at Fraunhofer ISE for triple-phase input to the grid. Specifications: 7 kW rated power at 750 V intermediate circuit voltage and 16.6 kHz switching frequency.



Scalable Monitoring System based on Embedded Systems for Energy Analyses

Monitoring systems allowing remote access to operating data are being used increasingly often to control the operation of energy supply systems. At Fraunhofer ISE, we have developed a scalable monitoring system, based on embedded systems, which allows on-line access. It makes use of the GSM M2M mobile radio service, which allows distributed computers to be integrated into a single network.

Rainer Becker, Cedric Buerfent, Rico Werner, Michael Zillgith, **Christof Wittwer**, Günther Ebert

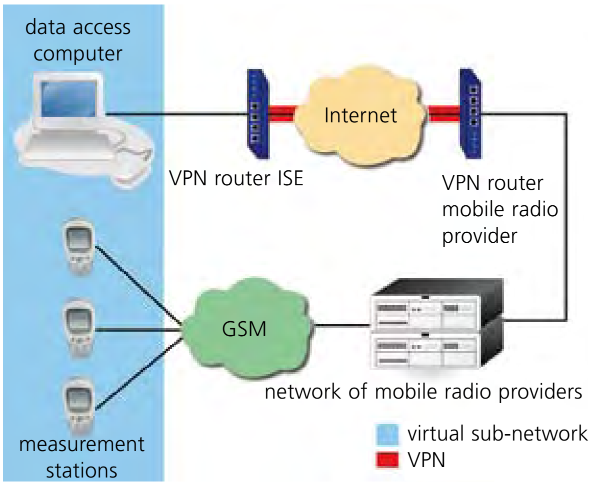
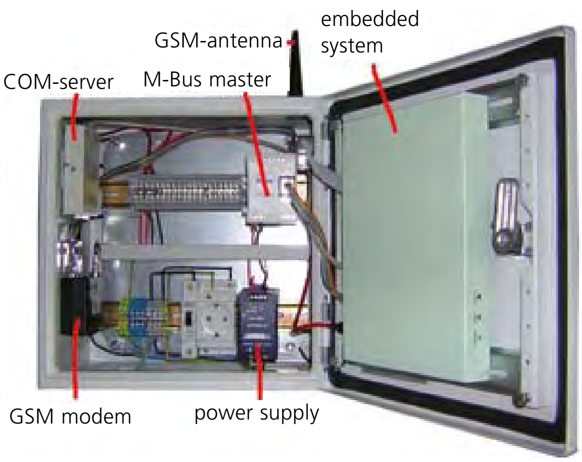


Fig. 1: M2M communications infrastructure for scalable monitoring systems based on GSM technology: The measurement computers establish an IP connection to the network provider via a GSM modem. A VPN connection ensures safe access by the access server to the target computer.



The newly developed monitoring system to control the operation of energy supply systems allows energy-technological systems to be measured in the field over long periods. On site, embedded systems operate with flash-based storage media and without fans. Use is made of the open-source Linux operating system. The systems acquire measurement data continuously and store these in the form of daily data sets. Each day, the data sets are copied, via a VPN Internet connection to a mobile radio network operator, onto a central server. The embedded systems can be accessed at all times via the Internet, so that maintenance work and software updates can be carried out remotely at any time.

We conceived the system to be scalable, so that a large number of systems can be integrated into the network and also so that the system can be serviced automatically. At present, already more than 100 heat pumps located all over Germany are being measured with this technology in a large monitoring project. The system can be extended very simply to accommodate additional measurement stations.

The system hardware has been designed such that any type of field bus system or measurement system can be integrated. The software framework was developed at Fraunhofer ISE. Flexible and robust measurement software is used, which allows extension with embedded systems. The access mechanisms were mainly implemented with software packages from the Linux community which meet high demands on availability and remote maintenance options. Systems of this type will be obtainable already for app. € 100 in future.

Fig. 2: System photo: Installation unit of the measurement system with an embedded system. The monitoring systems are tailored to individual specifications, so that also field bus systems, e.g. M-bus meters can be integrated.

Field Test for Linear Fresnel Collectors

The promising technology of the linear Fresnel collector for solar-thermal power stations was optimised at Fraunhofer ISE. At the Plataforma Solar de Almería, a 100 m long demonstration collector was installed by the project commissioners, MAN Ferrostaal Power Industries and the Solar Power Group. Our contributions included key components such as the absorbers and secondary reflectors, as well as optical quality control and advice on component dimensioning and measurement data acquisition.

Andreas Georg, Wolfgang Graf, Anna Heimsath, Christina Hildebrandt, Nico Lemmertz, Gabriel Morin, Thomas Schmidt, Josef Steinhart, Markus Tscheche, **Werner Platzer**, Andreas Gombert

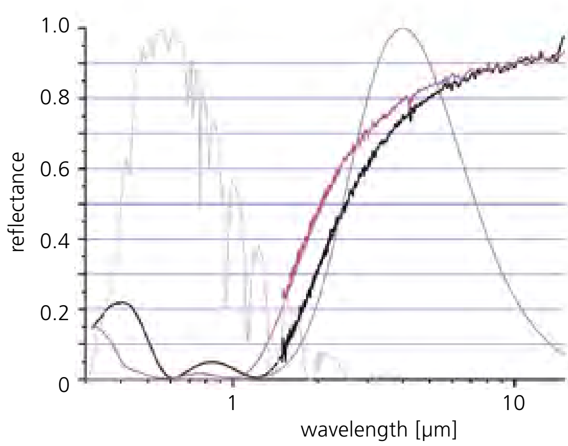


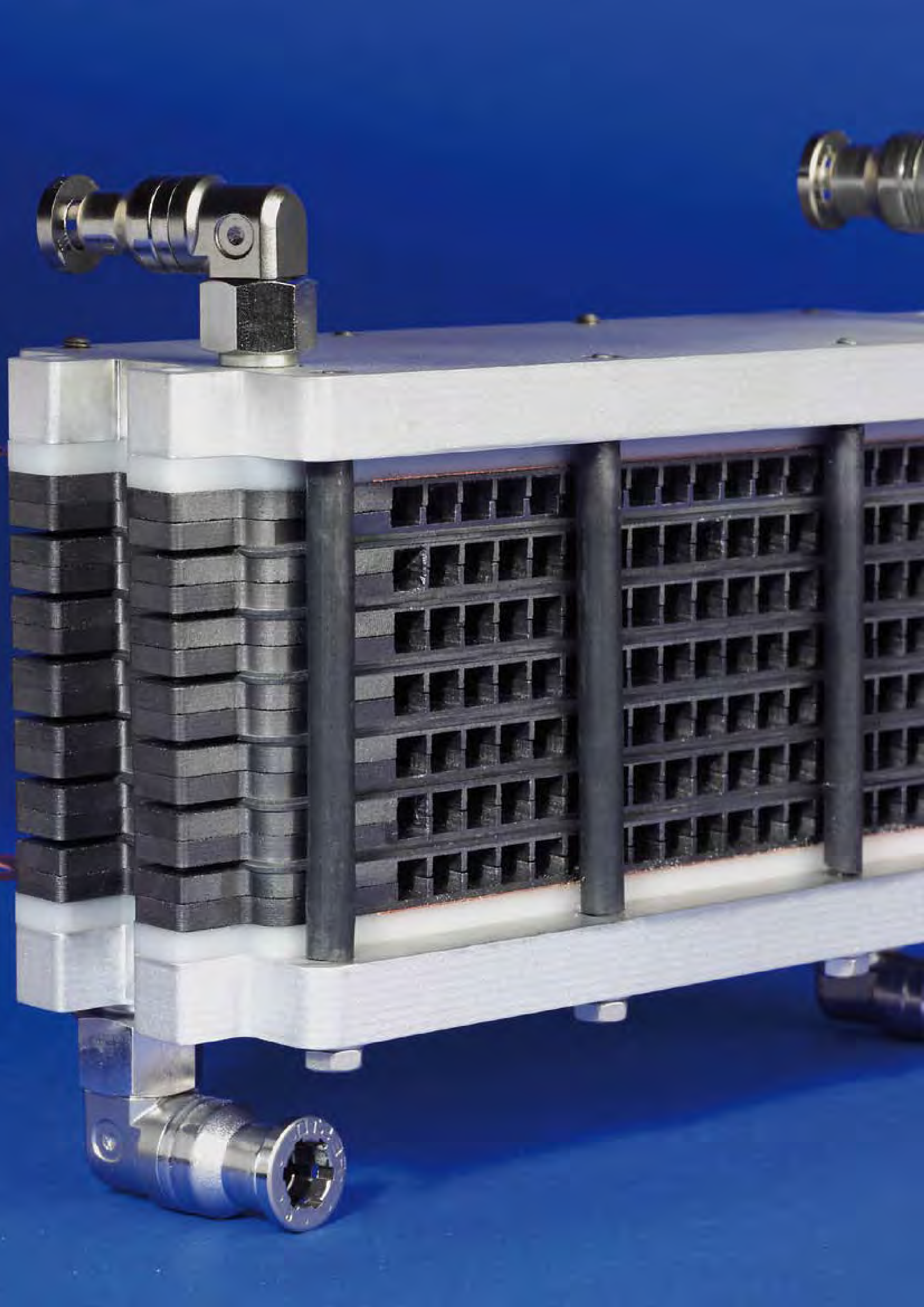
Fig. 1: Reflectance spectra of a sputtered absorber immediately after coating (black) and after heating (magenta). The relative intensity distribution of direct solar radiation (grey, left) and a Planck black-body radiator at 450 °C (grey, right) are also plotted.

For solar-thermal power stations, in which steam for a turbine is produced with concentrated solar radiation, we have developed an alternative to the parabolic troughs which have been used up to now – the linear Fresnel collector. Long rows of flat reflectors are oriented such that they focus the direct solar radiation onto the linear receiver which is mounted above the reflectors.

Absorber coatings which are stable at high temperatures in air were sputtered onto a steel pipe for the demonstration system. A thermally stable reflective coating was deposited onto the secondary reflectors of curved glass. The absorber pipe is dimensioned for superheated steam at 450 °C, as the advanced direct evaporation technology was applied. There is then no need for oil-water heat exchangers. During the installation of the reflector field, the exact form of the primary reflectors was tested on site by fringe reflectometry (see also article on p. 40). Spectrometric investigations and determination of the receiver acceptance range completed the preliminary characterisation. The efficiency values of the collector as a function of solar position and operating temperatures can be determined from the temperatures and energy fluxes that are measured during operation. The first field results agree excellently with the results of simulation.

Fig. 2: Demonstration collector in Almería. The hydraulic connection of the collector to the direct evaporation trough is variable, so that different operating conditions of the collector (pre-heating, evaporation and overheating) can be investigated without difficulty.

Our project partners were MAN Ferrostaal Power Industries, Solar Power Group GmbH, German Aerospace Centre (DLR) and PSE GmbH.



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 extracted from its diverse chemical compounds. This is achieved by applying energy. Ideally, regenerative energy is used in the form of renewably generated electricity for electrolysis. A second approach is the reforming of gaseous or liquid fuels, so-called hydrocarbons or alcohols.

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. For example, a long-term perspective is that hydrogen be used to store fluctuating forms of renewable energy, so that all desired energy services can be provided with the accustomed reliability. 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 and aeroplanes. Finally, miniature fuel cells are excellent alternatives or supplements to rechargeable batteries in off-grid power supplies or electronic appliances, due to the high energy density of hydrogen or methanol. Even though this application does not immediately represent a large contribution to our total energy supply, it is important in paving the way for the introduction of hydrogen systems.

Innovative technology to obtain hydrogen and convert it efficiently 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 fuel-cell systems, mainly for off-grid, portable and mobile applications.

We develop reformer systems to convert liquid hydrocarbons or alcohols. The systems consist of the actual reforming reactor and, depending on the type of fuel cell connected, gas treatment to raise the hydrogen concentration and reduce the amount of catalyst-poisoning carbon monoxide in the reformate gas. Such systems can be used in applications ranging from stationary combined heat and power plants, through auxiliary power units, to off-grid power supplies.

To obtain hydrogen from water, we construct controlled membrane electrolysis systems supplying power from a few watts up to several kW, corresponding to the production of several hundred litres of hydrogen per hour. To gain deeper understanding of the processes occurring at the electrodes, we apply different characterisation methods, including scanning electron microscopy and cyclovoltammetry.

The membrane fuel cell, operating with hydrogen or methanol, is our favoured energy converter in the power range from milliwatts to several hundred watts, being efficient, environmentally friendly, quiet and requiring little maintenance.

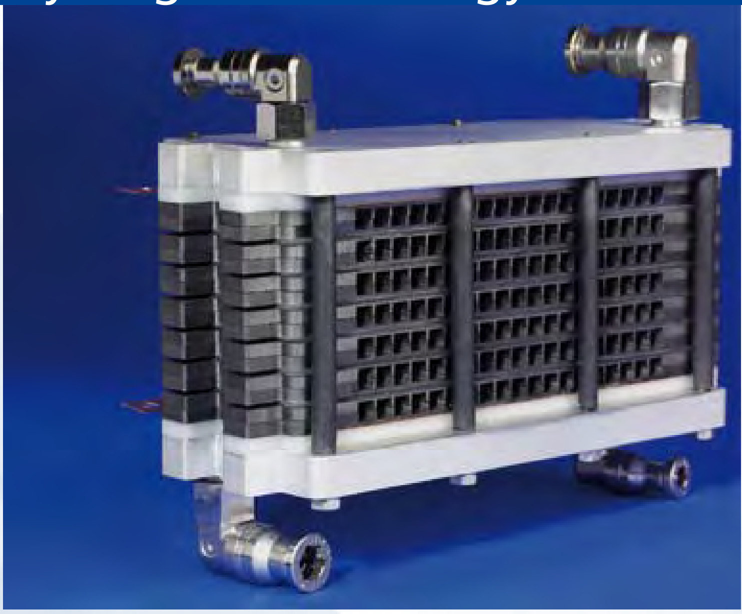
In addition to the well-known system configuration based on fuel cell stacks, we have focussed on flat, series-connected fuel cells in a single plane. This design is very suitable for integration into the surface of a casing or as part of a hybrid system in combination with the battery.

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 commercially viable fuel cell systems. We offer fuel-cell systems for power supply aboard cars, trucks, ships or aeroplanes, as well as stand-alone power supplies for off-grid applications and small portable electronic systems.

In our portable fuel-cell systems, we are aiming to achieve air cooling of the fuel-cell stack to improve the energy efficiency and reduce the system dimensions. The figure shows an air-cooled test stack designed to allow investigation of the temperature distribution during operation. The goal is to minimise temperature differences between the individual cells, to optimise the water management and to maximise performance.

The test stack is operated in a fuel-cell test stand with an integrated climatic chamber under exactly defined environmental conditions. Comparison between the measured and modelled temperature distribution provides information on how cooling structures, fan positions and other important parameters can be optimised.

Hydrogen Technology



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Characterisation of PEM and Direct Alcohol Fuel Cells

Fraunhofer ISE is equipped with seven test stands for in-situ characterisation of single-cell polymer electrolyte membrane (PEM) fuel cells, four test stands to investigate direct alcohol fuel cells and four system test stands. With these, we cover the complete spectrum of competence in the low power range from fundamental investigation through to development of controls for complete systems. By reinforcing our facilities for ex-situ analysis, we are extending our portfolio with regard to materials and durability characterisation.

Carsten Agert, Steffen Eccarius, Dietmar Gerteisen, Thomas Jungmann, Timo Kurz, Julia Melke, **Michael Oszcipok**, Christopher Hebling

Fraunhofer ISE has developed portable PEM fuel cell systems in the power range from a few 100 mW to several 100 W for many years now. Our goal has been to continually optimise the developments. A pre-requisite is thorough understanding of the processes which occur within our fuel cell systems.

The fundamental insights gained allow us, on the one hand, directly to further develop our technology. On the other hand, we obtain important parameters which serve to validate the theoretical models. Modelling of the electrochemical processes in the catalytically active zones, fluid-dynamic dimensioning of fuel-cell modules through to simulation-based control of complete PEM fuel-cell systems have supported the system developments for many years from the first development step on.

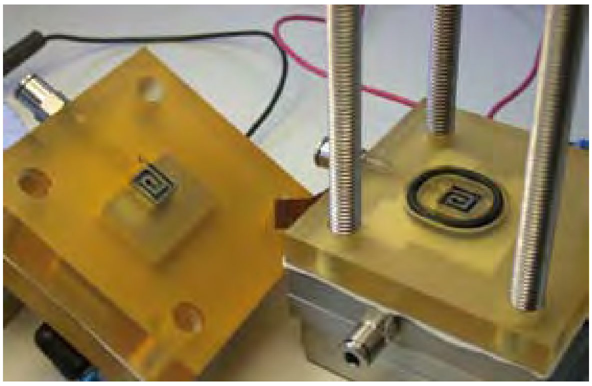


Fig. 1: Fuel cells with a reference electrode and a very small area (1 cm^2) allow us to investigate electrochemical, catalytic electrode processes without gradients.

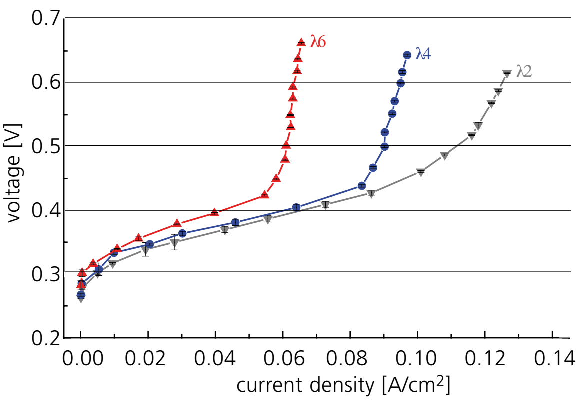


Fig. 2: Reference cell measurements are used to identify the losses from a direct-methanol fuel operated at 50 °C in the vapour phase with a 50 mass % solution of methanol and water. From this we have learned that high air stoichiometry permanently affects the fuel concentration at the anode, and how the configuration of such fuel cells should be optimised.

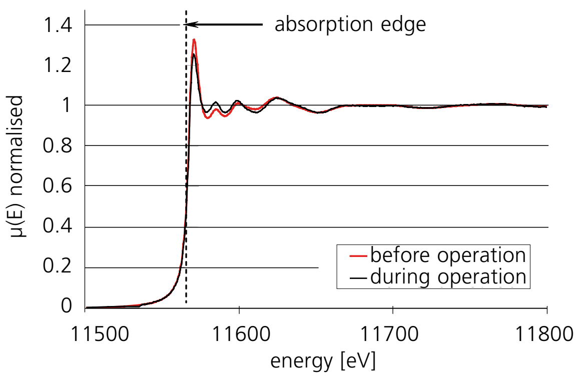


Fig. 3: X-ray absorption spectrum for a PtRu catalyst on a carbon substrate before and during operation with ethanol. The region behind the absorption edge provides data on the particle size and morphology of the catalyst, as well as its modification during operation. The region directly adjacent to the absorption edge contains information on the available adsorbate capacity.

The predictive power of every fuel-cell model is determined by its validation. For this reason, at Fraunhofer ISE we characterise fuel cells in situ and ex situ, and do not confine ourselves to the state of the art – with our innovative approaches, we go far beyond it.

We investigate electrochemical processes such as anodic oxidation of methanol and ethanol in situ with the help of fuel cells which are equipped with reference electrodes (Fig. 1). With reference cell measurements, we are able to analyse losses during operation. Figure 2 shows the anodic losses of a direct-methanol fuel cell for varying air stoichiometry. The high air flow rate dries out the fuel cell. The decreasing water concentration on the fuel-cell side and the associated mass-transport losses lead to a reduction in the maximum current density which can be achieved.

X-ray absorption spectroscopy (XAS), which we conduct at the Hamburg Synchrotron Radiation Laboratory, provides with still deeper insights into the reaction processes of our fuel cells in operation (Fig. 3). It gives us information on catalyst kinetics, adsorbate formation and partial reactions which take place at the electrodes.

We complement our knowledge of fuel-cell operation with the most modern ex-situ analytical methods. With the help of environmental scanning electron microscopy (ESEM) in a water vapour atmosphere and energy-dispersive X-ray analysis (EDX), we are able to analyse the morphology and elementary composition of fuel cell components on a microscopic scale under environmental conditions of 0 – 100 % relative humidity and temperatures between -40 °C and 200 °C (Fig. 4). Furthermore, we can visualise and quantify contamination, catalyst migration and other degradation phenomena with the integrated EDX unit (EDAX Genesis).

As a complementary approach, we apply our inductively coupled plasma mass spectrometer, currently the most accurate method for trace analysis (Fig. 5). With it, we can detect contaminating material compounds or corrosion residues from operating hydrogen or alcohol-fuelled fuel cells down to the ppt range.

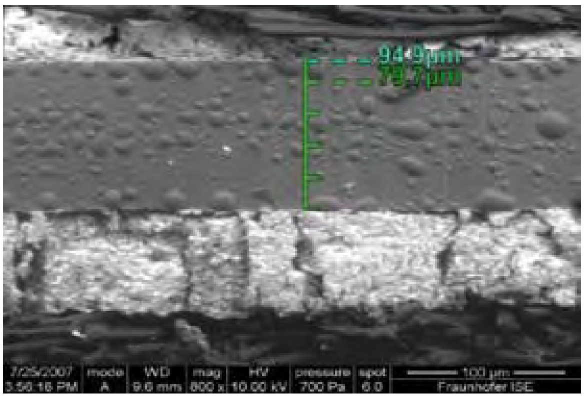


Fig. 4: When we analyse samples near the triple point of water, we can use our ESEM (environmental scanning electron microscope) to study the swelling behaviour of membrane electrode assemblies (MEA). A MEA with Nafion 115 can swell by up to 20 %. Ice formation in the electrode can lead to its destruction.

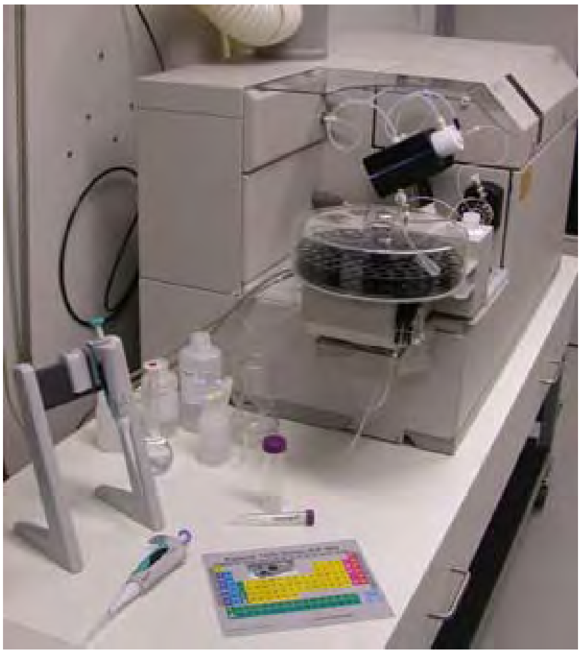
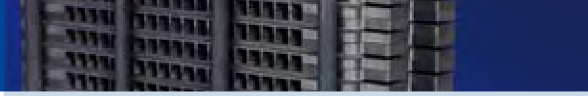


Fig. 5: We can detect corrosion products or catalyst particles from fuel-cell operation with our inductively coupled plasma (ICP) spectrometer, in order to characterise optimised materials.



Reformer Fuel-Cell Module for 350 W

Independence from the public electricity grid, with a lightweight, efficient power supply that is fuelled by a renewable, biological fuel – this is our goal in developing a reformer / fuel-cell module based on bio-ethanol. The intended power of 350 W is sufficient, e.g. to supply electricity to medical equipment, repeaters or base stations for telecommunications, or a camping van.

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Philipp Wemhöhner, Christopher Hebling

At Fraunhofer ISE, we are currently developing a compact power supply consisting of a hydrogen generator and a fuel cell, with a rechargeable battery as a buffer. The advantage of this concept, compared to fuel-cell systems with hydrogen tanks or metal hydride storage cartridges, is its significantly higher gravimetric energy density. For a daily energy quantity of 8400 Wh, our system weighs only about 50 % as much as a system with a hydrogen tank or a system based exclusively on batteries, and has only 35 % of the mass of a system with metal hydride storage (see Fig. 1). This is possible because the environmentally friendly bio-ethanol is stored in the liquid state.

On the other hand, the system also becomes more complex by inclusion of the reformer. We are working on solutions based on our long and extensive experience in the reformation of hydrocarbons. In our present work, we are optimising the reactor concept by testing different flow configurations, geometrical configurations and reforming processes.
The starting point was a flat reactor with an integrated burner, heat exchanger and gas purification steps. In the next step, the integrated heat exchanger was replaced by a miniature heat exchanger prepared by the Forschungszentrum Karlsruhe. In addition, we implemented the concept of a cylindrical reactor with an internal burner and an integrated heat exchanger. When the series of measurements has been completed, we will decide on the concept which will be implemented as a prototype.

We obtained the low-temperature fuel cell which is used in the system from the Schunk company. It is designed for use with reformate. We were also able to benefit from long years of experience concerning integration of the fuel cell and operation management. At Fraunhofer ISE, we have already developed numerous low-temperature fuel cells in stack and planar configurations, and have gained wide-ranging experience in operation management.

In July 2007, we operated a reformer together with a fuel cell for the first time. A graph for the fuel cell, which shows the current and voltage of this combined circuit, can be seen in Fig. 2. At the time of the experiment, the fuel was not yet injected via the dosing system developed by our project partner, the Institut für Mikro- und Informationstechnik of the Hahn-Schickard-Gesellschaft (HSG-IMIT), but with a pulsed pump. The resulting flooding and gas starvation effects can be seen clearly in the voltage plot. We anticipate that these effects will be greatly reduced by applying the new dosing systems and adapting the thermal management of both systems.

A further important task is system integration, i.e. the connection of all system components, and operation management of the complete system, including the initialisation and ending procedures and a safety concept. The safety concept was preceded by a PAAG process, in which possible risks are described and potential counter-measures are listed. The microcontroller-based controls for the whole system, which we also developed, ensure autonomous, safe operation of the complete system.

Our project partners, EGO, Lifebridge, Umicore, HSG-IMIT, DMT, Elbau, Intratec and Magnum are future users of the system or support us in designing the housing, constructing the reactor, preparing the dosing technology and developing electronics.

The work is supported by the German Federal Ministry of Economics and Technology (BMWi) within the InnoNet programme.

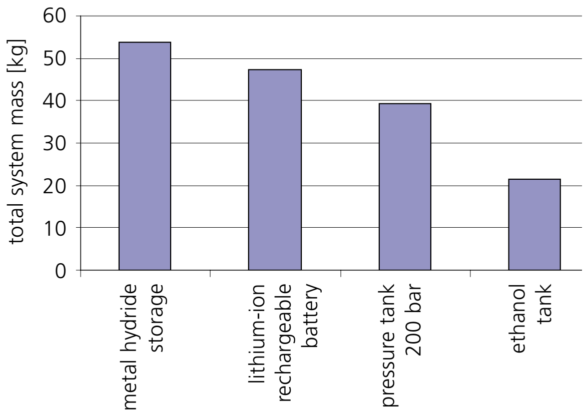


Fig. 1: The graph shows the total mass of a reformer / fuel-cell system with different concepts for the fuel storage. The tank is dimensioned such that the system can be operated for 24 h with 350 W output power. A system based solely on rechargeable lithium-ion batteries is also shown for comparison.

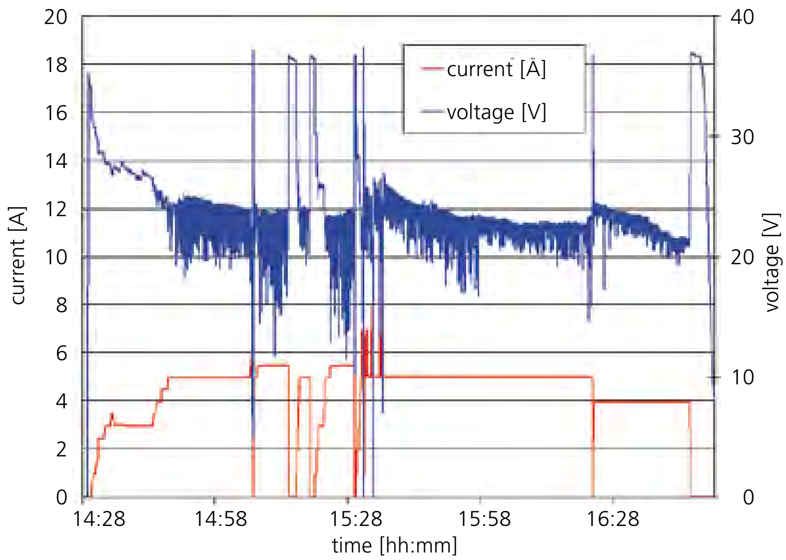
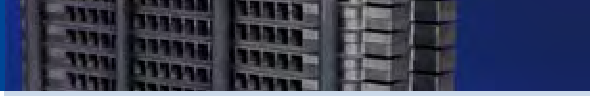


Fig. 2: The graph shows the current and voltage profiles of our test system, consisting of a reformer and a fuel cell, in partial-load operation. Values are shown for different operating points and load conditions. The fluctuations in the voltage values are caused by pulsed fuel dosing and thus a pulsed hydrogen supply to the fuel cell.



Spatially Resolved Characterisation of High-Temperature PEM Fuel Cells

We have developed a segmented test cell for spatially resolved characterisation of high-temperature polymer-electrolyte membrane (HT-PEM) fuel cells, in which measurements can be made up to 200 °C. During operation, local impedance, current density and cell temperature can be measured. This test stand thus offers us unique opportunities for developing HT-PEM fuel cells.

Carsten Agert, Zoran Canic,
Tobias Hutzenlaub, **Timo Kurz**,
Marco Zobel, Christopher Hebling

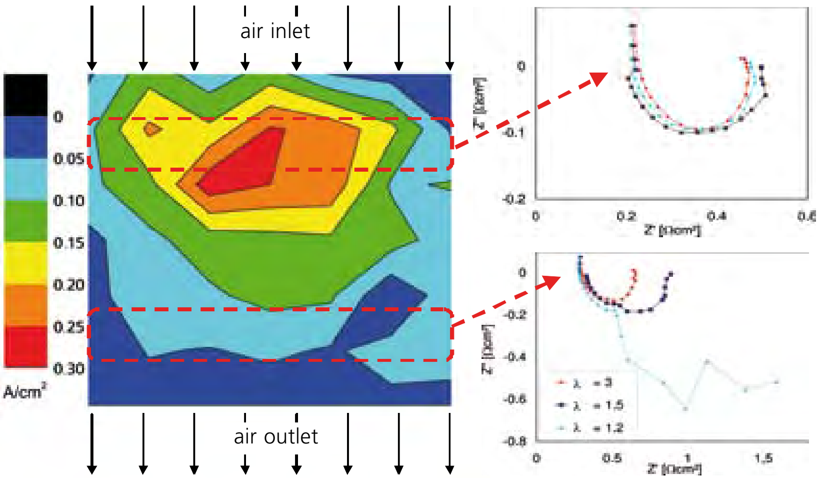


Fig. 1: Spatially resolved measurement of the local current density in the cell at 160 °C and low air flow-rates in a parallel flow-field channel. The reduction of the current density toward the outlet indicates that the air is consumed along the channel by the cell reaction. This lack of oxygen can be clearly recognised in the extended impedance spectra (lower right).

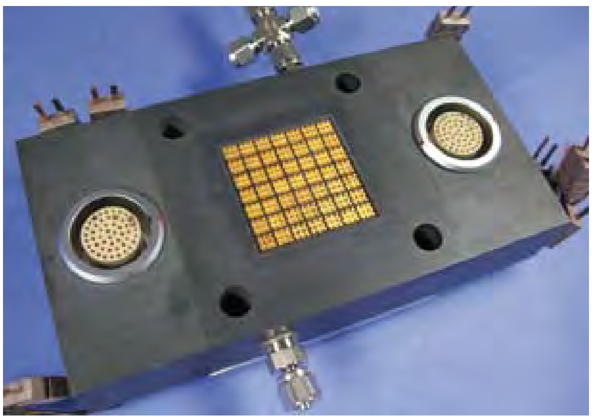


Fig. 2: Segmented end-plate of the cell: The photo shows 49 gold contacts (centre), two round connectors for measurement instruments (left and right), gas connection (top and bottom) and thermo-element plugs (perimeter).

The high-temperature polymer-electrolyte membrane (HT-PEM) fuel cell is a further development of the PEM fuel cell. With its higher operating temperature exceeding 100 °C, the formation of liquid water is avoided, which can lead to flooding of channel structures and thus power losses in low-temperature PEM fuel cells. In addition, the tolerance of common catalysts to carbon monoxide is clearly increased, which makes this cell type particularly suitable for hydrogen-rich reformate gas from the conversion of hydrocarbons such as methanol, ethanol or natural gas.

In order to identify an optimal design, temperature-resistant materials and the best possible operation management strategies for the HT-PEM fuel cell, we have developed a novel, segmented test cell. This allows the spatially resolved characterisation of membrane electrode assemblies (MEA's) over an active area of 25 cm^2 at temperatures of up to 200 °C. One end-plate of the cell consists of 49 segments, on each of which the current density and impedance – two decisive quantities – are measured. In addition, the temperature distribution in the cell is recorded. With the help of these measurement results, information can be gained on local loss mechanisms and an optimum gas distribution in the cell. The test cell is operated in a furnace in a nitrogen atmosphere, so that homogeneous heating of all components is ensured.

The work is supported by a doctoral scholarship awarded by the Deutsche Bundesstiftung Umwelt (DBU – German Federal Environmental Foundation).

Hydrogen Storage on the Basis of Chemical Hydrides

Chemical hydrides have high energy storage densities due to their large proportion of hydrogen and are thus highly suitable storage materials for portable fuel-cell systems, where a low total mass is important. We use the advantages of these materials to provide hydrogen for electricity generation safely and simply. At Fraunhofer ISE, we are currently developing a hydrogen storage / generator system for the low power range (20 W_{el}), based on the chemical hydride, ammonia borane.

Thomas Aicher, Johannes Kostka, **Tom Smolinka**, Oliver Wolf, Christopher Hebling

Efficient and safe storage of hydrogen with high gravimetric and volumetric storage densities has gained urgency with respect to market introduction of small, portable fuel-cell systems in the near future. In chemical hydrides, the hydrogen is chemically bonded to the host material, so that these materials achieve very high storage densities. At the same time, the risks of storing elementary hydrogen are avoided. Thus, they are suitable candidates above all for portable fuel-cell systems. However, the high temperatures at which hydrogen is released at adequate flow rates, well above 100 °C, pose technical challenges for the application of these materials.

Therefore, at Fraunhofer ISE, we are developing a process in which the temperature for releasing hydrogen is below 100 °C. These moderate conditions are promising for a simple, and thus light and powerful, system for hydrogen generation. To achieve them, we exploit the advantageous solution behaviour of the potent hydrogen storage material, ammonia borane (H_3B-NH_3) in various solvents. Similarly, we are testing different reactor concepts to improve the thermal integration and thus increase the efficiency value.

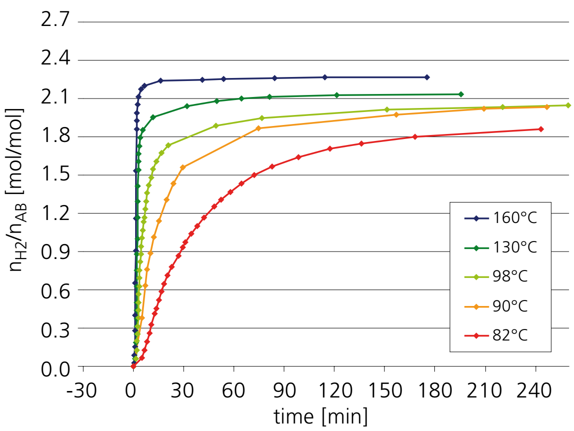
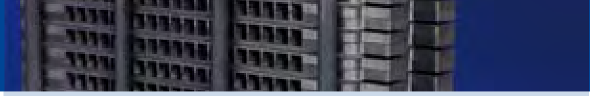


Fig. 1: Hydrogen release rate of a 20% ammonia borane-triglyme solution at different temperatures. The kinetics are sufficiently rapid for temperatures of 90 °C and higher. Up to 2.2 moles of hydrogen are released per mole of ammonia borane. This corresponds to a storage density of 13 wt.-% relative to the initial state of the material.

Fig. 2: Experimental set-up to test different reactor types in a hydrogen generator based on chemical hydrides. It consists of a storage vessel, a dosing pump, a thermally insulated reactor and a collection vessel. Exact knowledge of the possible reaction paths during the release of hydrogen is needed for optimal dimensioning of the system.



Development of a Catalyst for a Pyrolysis System

Pyrolysis of hydrocarbons offers an alternative to conventional reforming to generate hydrogen for portable or stationary PEM fuel-cell systems. During pyrolysis, the hydrocarbon compounds are cracked, producing carbon and hydrogen. The essential advantage of the pyrolysis system is its simple configuration. The hydrogen-rich product gas can be fed directly from the pyrolysis reactor into a high-temperature PEM fuel cell and be converted to electricity there.

Thomas Aicher, Johannes Schuth,
Alexander Susdorf, Robert Szolak,
Christopher Hebling

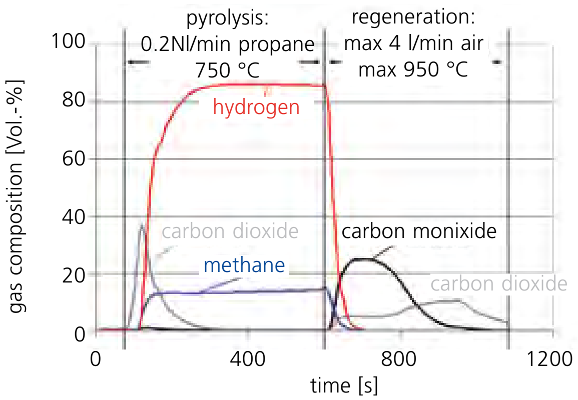
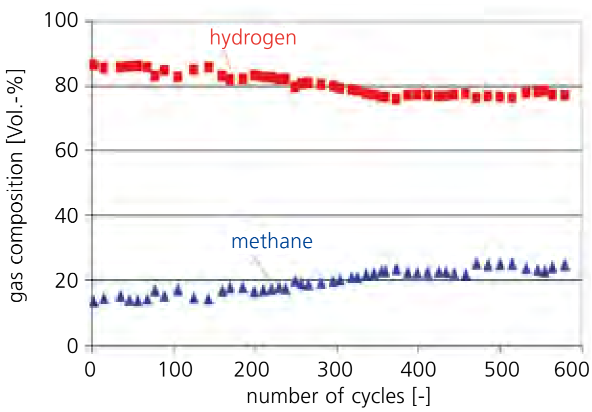


Fig. 1: Gas composition during propane pyrolysis with subsequent regeneration. The hydrogen and methane concentration during pyrolysis is almost constant after the maximum has been reached. The carbon monoxide concentration remained below < 1 vol. % throughout the process. An overlap between the regeneration and pyrolysis processes is possible with the selected parameters, so two reactors can be operated alternately with the developed catalyst. A constant gas flow-rate for the fuel cell can be achieved in this way.



No water is needed for pyrolysis. The product gas consists predominantly of hydrogen (> 80 vol. %) and methane. The carbon monoxide concentration is so low that gas purification is not needed.

During pyrolysis, propane is catalytically converted into hydrogen, methane and carbon. The produced carbon is deposited onto the catalyst and must be burnt off with air in a second step. Thus, two reactors are needed to produce a continuous flow of hydrogen-rich gas, which alternately switch between pyrolysis and regeneration. The constantly changing operating conditions and the high temperatures which occur during regeneration (> 950 °C) represent demanding conditions for the catalyst. At present, there are no commercially available catalysts which are suitable for a pyrolysis system.

At Fraunhofer ISE, we have developed a catalyst for this process which is thermally stable and durable. We avoided the use of expensive precious metals in developing the catalyst. A suitable substrate was coated with nickel alloy as the active component. The composition of the active components, the preparation method and the substrate have a large influence on the gas composition and the stability of the catalyst. The catalyst that we have developed has already progressed to the stage of being included in a prototype.

The catalyst development was commissioned by the Voller Energy company.

Fig. 2: Catalyst aging. The figure shows the measured gas composition at the end of pyrolysis. The gas composition remains constant after about 250 cycles. Even after 580 cycles (1 cycle comprises one pyrolysis process with subsequent regeneration), the hydrogen concentration is still > 77 vol. %. The aging test was carried out with the operating parameters shown in Fig. 1.

Fluid Dynamic Simulation as an Aid to Reactor Design

In designing our reactor chambers, we have been using "Fluent", a computational fluid dynamics (CFD) software package, for some time. The great advantage of this approach is the visualisation of flow-rates, pressure gradients and concentration of the materials involved during the planning phase. This information saves us valuable time and allows a detailed view into the reactors, which would not be possible otherwise.

Bettina Lenz, Christopher Hebling

Hydrogen-rich gases to feed fuel cells can be generated by reforming of fuels. The chemical reaction occurs at catalysts. Optimal mixing and treatment of the reaction partners before the catalyst is a central criterion to avoid soot formation or "hot spots". Depending on the process, the reaction partners we consider include almost all hydrocarbons as well as water and air or pure oxygen.

The reactors can be divided into different zones: the zone in which the reactants are introduced, a mixing and evaporation zone, the honeycomb catalyst on which the actual chemical reactions take place and the outlet of the product gas. Different boundary conditions (e.g. thermal losses via the reactor wall) are defined for the different zones in the simulation, depending on the temperature, mass flow and geometrical configuration. In this way, depending on the degree of detail, we can generate a highly complex image of the reformer.

The geometrical data can be transferred directly from a drawing program. We use commercially available, 3-dimensional, technical drawing programs (CAD programs). Discretisation of the geometrical information, i.e. segmentation into finite volume elements, requires great care to keep the calculation time as short as possible and yet still lead to a stable result.

Fig. 1: The discretised reactor geometry, with its mixing chamber, reaction zone (catalyst) and outlet zone, serves as an input file for the actual CFD simulation. The image shows the grid over an auto-thermal kerosene reformer, in which a mixture of air and water vapour is introduced via the upper pipe. This mixture is fed into the reactor chamber via an annular gap. We feed liquid kerosene centrally in the annular gap via a single-component injector.

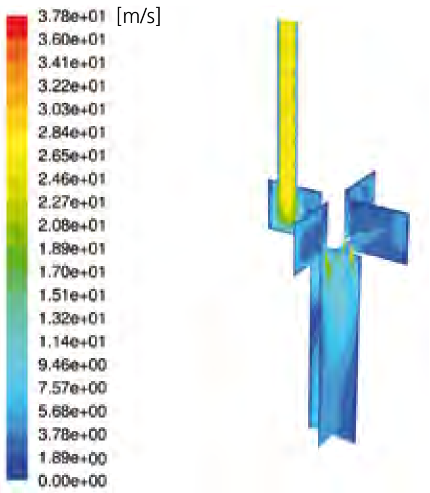


Fig. 2: The calculated flow-rate profile provides information on the degree of mixing, zones with very low flow-rates, and pressure drops, as a basis for optimising the geometrical configuration. The flow-rate is shown, which can assume values up to 40 m s^{-1} in the annular gap.

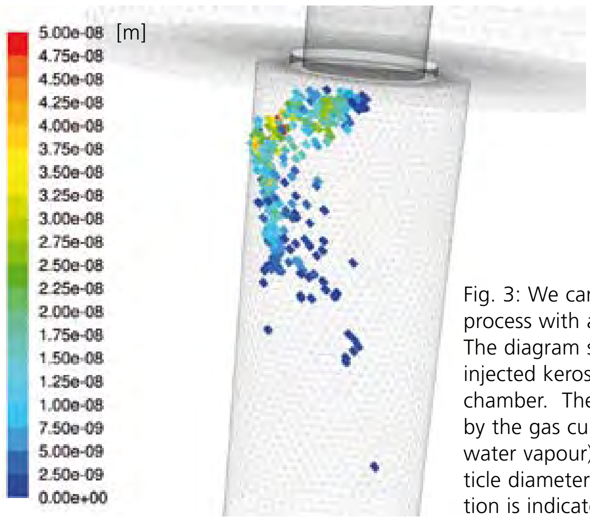
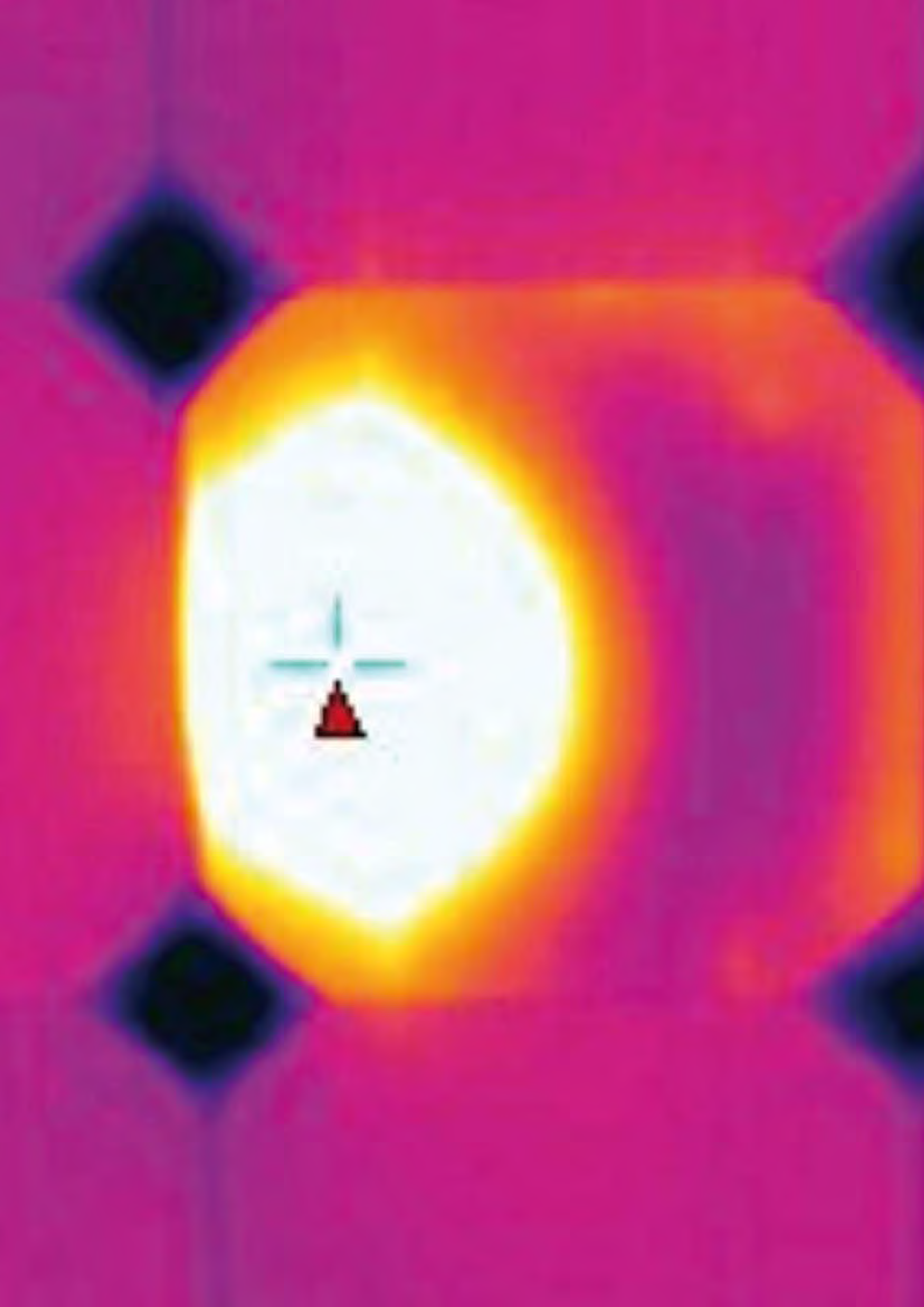


Fig. 3: We can model the fuel injection process with a non-stationary simulation. The diagram shows the path taken by injected kerosene particles in the reactor chamber. The particles are transported by the gas current (air and super-heated water vapour) and evaporated. The particle diameter up to complete evaporation is indicated by the colour coding.



Quality convinces

Service Units

In the booming solar industry, the role of materials testing, certification and quality control is becoming increasingly important. As a complement to our research and development work, we offer our clients related testing and certification services. At present, Fraunhofer ISE has four accredited testing units: the Testing Centre for Thermal Solar Systems, the Thermal-Optical Measurement Laboratory, the Test Centre for Photovoltaics and the ISE Calibration Laboratory CalLab. Further service units include a test facility for compact heating and ventilation units, a laboratory for quality control of phase change materials (PCM), a test stand for thermally driven heat pumps and a battery testing laboratory.

Beyond the service aspect, these units also have a research function for us. The insights gained during characterisation, certification or testing can become the kernel for new research topics, be it in product development or improvement, further development of testing methods and standards, or theoretical development, for example in model-based prediction of aging.

The Testing Centre for Thermal Solar Systems has been accredited by DAP (Deutsches Akkreditierungssystem Prüfwesen GmbH) since May 2005. The testing facilities include:

- outdoor test stand with a tracker
- indoor test stand with a solar simulator (max. aperture area 3 m x 3.5 m)
- collector test stand up to 200 °C
- system and storage tank test stand

Most of the work involves commissions from the industry to test collectors according to European collector standards such as the SOLARKEYMARK label. A unique feature is the possibility to test collectors at temperatures up to 200 °C. This makes it feasible to test new applications such as process-heat generation and to conduct stagnation tests (see article on p. 103).

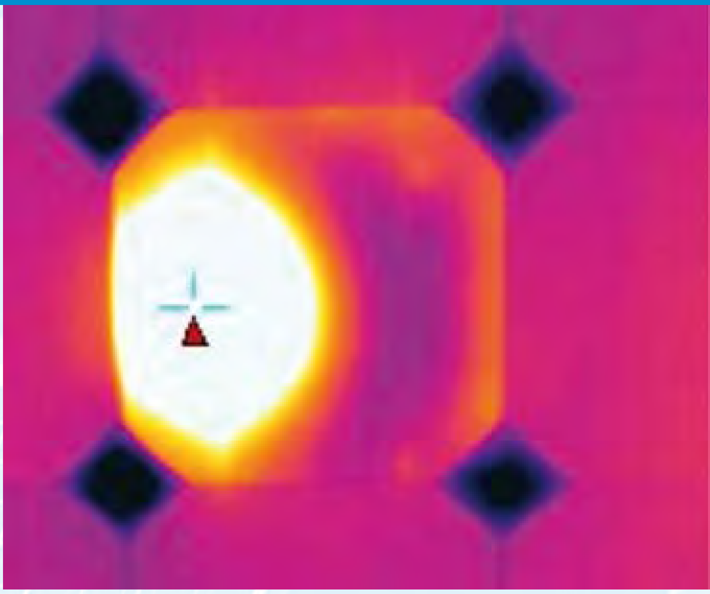
The Thermal-Optical Measurement Laboratory TOPLAB was accredited according to DIN EN ISO/IEC 17025 in 2006. It offers a comprehensive range of characterisation for innovative building components and materials to developers and planners of façades, façade components and windows, including shading devices (see article on p. 104).

The following properties can be tested:
- g value: calorimetric measurement
- transmittance: spectral and broadband measurements
- reflectance: spectral and broadband measurements
- U value

The Test Centre for Photovoltaics was also accredited in 2006, including testing for product type approval of PV modules according to IEC 61215 and 61646. The Test Centre is part of an entire complex concentrating on durability analysis of PV modules. The goal of the facility is to ensure the quality and reliability of PV modules. It is closely linked to ISE CalLab-Modules and to module development at the Institute. Tests are carried out to accompany the development of modules and module components. Similarly, quality assurance is carried out in co-operation with module producers. The co-operating "Certification Body" is the VDE (see article on p. 101).

The fourth accredited laboratory, having gained this status in November 2006, is ISE CalLab, which is one of the international leaders in this field. The calibration of solar cells and modules plays an important role in product comparisons and for quality assurance of PV systems. The cell calibration serves as a reference for industry and research. The module calibration is part of the module certification process, on the one hand. On the other hand, it serves to control the quality of systems and to support development (see article on p. 100).

Service Units



Thermographic image of a partly shaded solar cell in a PV module. The white zone indicates overheating at a "hot spot". To identify faulty PV modules, e.g. with hot spots, we measure them with a high-resolution thermocamera. With this procedure, the temperature distribution within a module or over larger module fields can be visualised.

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	Test stand	Dr Benoît Sicre	Tel.: +49 (0) 7 61/45 88-52 91 E-mail: Benoit.Sicre@ise.fraunhofer.de
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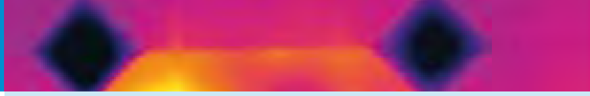
Qualification testing and optimisation of PV systems			
	Battery testing laboratory	Robert Thomas	Tel.: +49 (0) 7 61/45 88-54 19 E-mail: Robert.Thomas@ise.fraunhofer.de



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.

Patrick Blattert, Jochen Hohl-Ebinger, Astrid Ohm, Jürgen Ketterer, **Klaus Kiefer**, Frank Neuberger, Peter Raimann, Edgar Wolf, Wilhelm Warta

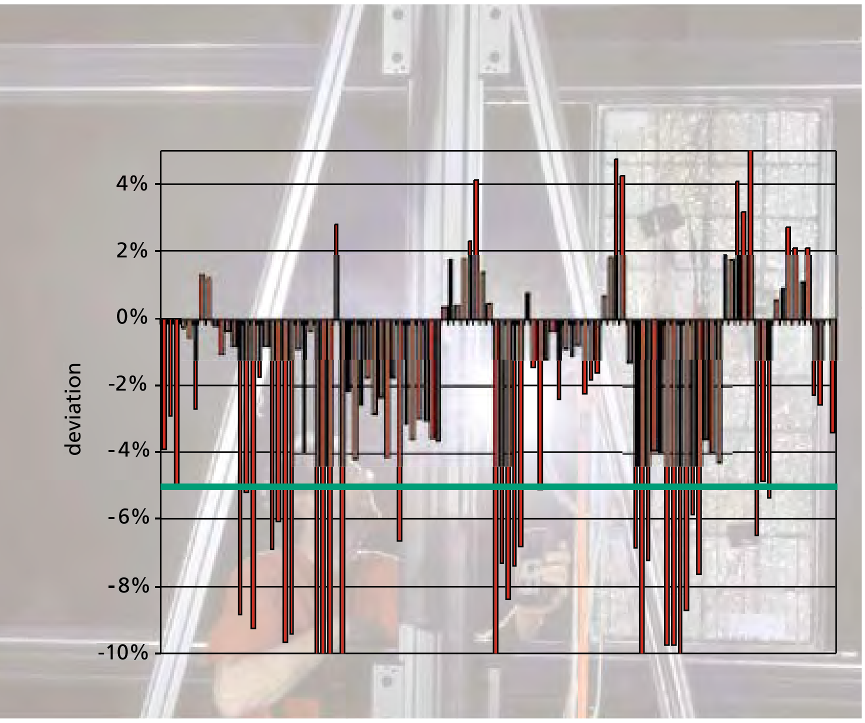


Fig. 1: The performance of photovoltaic modules with an area of up to 4 m^2 can be measured at Fraunhofer ISE with a new high-precision, pulsed solar simulator. The measurement accuracy is ± 2 % for precision measurements of the power under standard test conditions STC. A measurement test series of 100 PV modules demonstrated 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 rated value.

ISE CalLab is one of the internationally leading photovoltaic calibration laboratories. Module and cell manufacturers commission us to calibrate their reference modules and cells for production. 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 16 x 16 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
- determination of the NOCT temperature and power
- measurement of the angular and temperature dependence of the module parameters
- measurement of the dependence of module parameters on the radiation intensity

In November 2006, ISE CalLab - Modules was accredited according to DIN EN ISO/TEC 17025:2005. The accreditation of ISE CalLab – Cells will be completed soon.

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

Quality Assurance for PV Systems

Good planning, high-quality components and careful monitoring are decisive for the investment returns on a photovoltaic system. We understand comprehensive quality assurance for photovoltaic systems to mean a complete package of measures which ensure that the predicted yield is obtained throughout the entire lifetime of the system. We offer services from planning to operation to maximise the quality of photovoltaic systems.

Klaus Kiefer, Frank Neuberger,
Andreas Steinhüser

Our services include:

Yield prediction

Reliable yield predictions can be made only when the site is taken into account with its specific boundary conditions. After determining all relevant data, we carry out a scientific yield analysis. In addition, the client obtains information on the following points:
Error analysis: How accurate are the results?
Risk analysis: What can reduce the yield?
Performance Ratio: What is the system efficiency of the planned system? Evaluation of the system technology: How good are the components and their dimensioning?
Reliability indicators: How can initial controls, authorisation measurements and monitoring additionally help to ensure that the predicted yield is obtained?

Quality-control monitoring

Not only good planning and high-quality components are decisive for optimal operation and thus also returns from a photovoltaic system, but also automated operation monitoring. Our monitoring service offers quality assurance and maximum system yields. We measure systems and determine their potential for optimisation.

System authorisation

To control the performance of large solar power stations, on-site measurements of the characteristics of partial generators or individual strings of the solar generator are necessary. Faulty modules and defects in the generator circuit can be identified with our mobile measurement equipment. In this way, corrective measures can be taken in time to prevent major losses.

Test Centre for Photovoltaics

A new centre to test the reliability of photovoltaic modules has been established. Since its accreditation in 2006 according to ISO 17025, it has been an authorised "Testing Laboratory" for the "Certification Body", VDE, and carries out tests for product type approval complying with IEC 61215 and 61646.

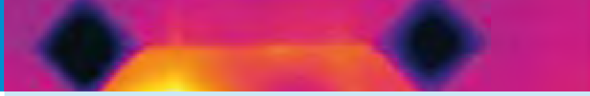
Michael Köhl, Stefan Brachmann,
Markus Heck

The enormous growth in the photovoltaic industry has greatly increased the need to test the performance and durability of photovoltaic modules, to guarantee quality for consumers in a global market. Thus, Fraunhofer ISE has extended its relevant testing facilities and offers its services to module manufacturers in co-operation with VDE, which is a "Certification Body" of the IEC EE.

The following module tests are conducted in the Test Centre:
- insulation resistance
- wet leakage currents
- mechanical loads
- temperature cycling
- damp heat
- humidity-freeze cycling
- UV irradiation
- nominal operating cell temperature (NOCT, fig. 1)
- hot spot endurance
- bypass diode thermal test
- robustness of connection box
- outdoor exposure

ISE CalLab (see p. 100), one of the leading laboratories for power measurements of modules, carries out the STC (standard test conditions) power measurements after the individual tests.

Fig. 1: Outdoor test stand to determine the "nominal operating cell temperature" (NOCT). The single-axis tracker allows the required testing times to be shortened.



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 not only inverters and charge controllers, but also DC components such as lamps, batteries or television sets.

Robert Thomas, Bruno Burger,
Heribert Schmidt

Battery Testing Laboratory
We test and qualify all common technological types and designs of batteries for manufacturers, system integrators and users. 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 and charging devices can have their equipment tested and optimised in connection with the corresponding batteries.

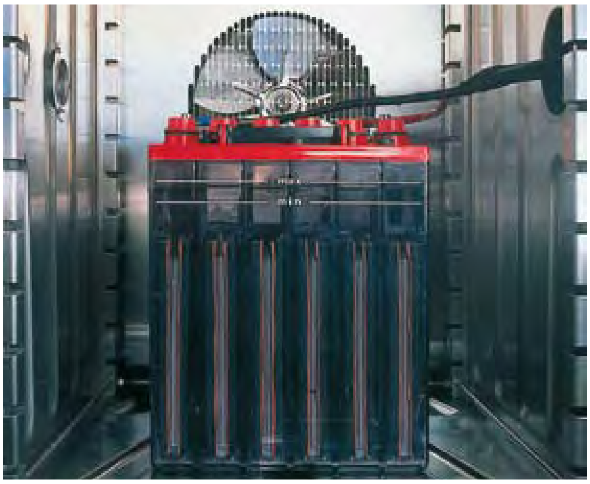


Fig. 1: In the climatic chamber, not only efficiency and capacity but also the aging and charging performance of storage batteries can be investigated under variable conditions.

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.

Benoît Sicre, Jeannette Wapler*,
Thore Oltersdorf, Sebastian Herkel

* PSE GmbH Forschung Entwicklung Marketing, Freiburg

Test facility for compact ventilation and heating units
With our automated test facility, we measure the energy efficiency of complete units and their components. We can choose from a wide spectrum of testing conditions. From the measurements, we derive recommendations to optimise the components and their interaction. We support our clients in implementing new developments. Skilled staff with expertise on cooling technology and the necessary technical equipment are available.

Monitoring
In numerous occupied houses, we are measuring the performance of ventilation equipment with heat pumps from various manufacturers in practice. Possible fault causes are identified and corrected. From these measurements, we prepare proposals to optimise the equipment and controls.

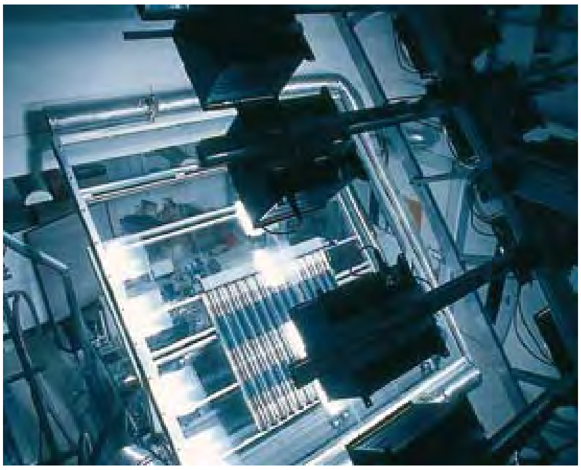
Measurements of air tightness and air exchange rate
We measure the air tightness of ventilation units under real operating conditions with the help of a tracer gas, applying the constant injection method. This can be done either with the test stand or in situ in the building. We use the same equipment to determine the air exchange rate in buildings according to the concentration decay method.

Testing Centre for Thermal Solar Systems

We operate an outdoor test stand for thermal solar collectors. Our testing centre is authorised by DIN CERTCO and is fully accredited by DAP (Deutsches Akkreditierungssystem Prüfwesen). We test solar collectors and complete systems, thereby supporting 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.

Korbinian Kramer*, **Stefan Mehnert, Matthias Rommel,** Thorsten Siems

* PSE GmbH Forschung Entwicklung Marketing, Freiburg



Indoor test stand with solar simulator.

Testing of solar collectors

We test solar collectors and complete systems according to national or international standards and standard procedures:
- SOLAR KEYMARK Scheme Rules
- collector testing according to DIN EN 12975:2006, 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
- system test according to DIN EN 12976:2006, parts 1 and 2

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' for absorbers of flat-plate collectors
- optimisation and calculation of the reflector geometry for collectors

Indoor collector test stand with a solar simulator

We operate an indoor test stand with a solar simulator. We designed it to imitate outdoor conditions as closely as possible. Its great advantage, particularly for collector development, is the high reproducibility of the measurement conditions. This allows us to carry out targeted 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 °

High-Temperature Testing Unit up to 200 °C

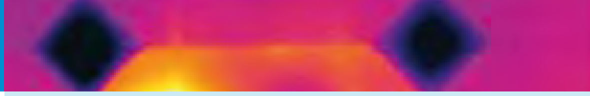
We have set up a new test rig, with which we can measure efficiency curves for temperatures up to 200 °C. This means that it is now feasible to carry out experimental development of process heat collectors.

Test stand for solar air collectors

We operate 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.

Our services for solar air collectors:

- measurement of the pressure loss of solar air collectors as a function of 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



Measurement of Building Façades and Transparent Components

We offer a comprehensive range of characterisation for innovative building components and materials to developers and planners of façades, façade components and solar components. Special laboratories, which have been accredited according to DIN EN ISO IEC 17025, are available to determine the optical and thermal properties of transparent components and sun-shading systems. Further facilities include a daylighting measurement container and an outdoor test unit.

Ulrich Amann, Angelika Helde, **Tilmann Kuhn**, Werner Platzer, Jan Wienold, Helen Rose Wilson

Thermal-Optical Measurement Laboratory and Lighting Laboratory

Existing measurement procedures such as those specified in DIN EN 410 or DIN EN 13363 do not describe the properties of advanced glazing and façade constructions sufficiently reliably. Thus, we have developed testing and evaluation 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 such as switchable transmittance (photochromic, thermotropic or electrochromic)
- air flow within the façade
- integrated photovoltaics

Different user profiles can also be taken into account in the evaluation procedures.

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

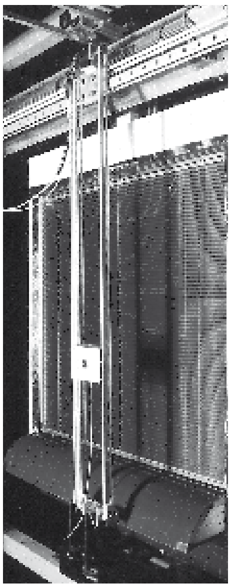


Fig. 1: Solar calorimeter to determine the total solar energy transmittance (g value). The corresponding methodology developed by Fraunhofer ISE has been accredited according to DIN EN ISO IEC 17025 since 2006.

Examples of equipment

- solar calorimeter to determine the total solar energy transmittance of transparent components and sun-shading devices
- thermal resistance measurements on glazing units according to EN 674
- angle-dependent transmittance and reflectance measurements with a large integrating sphere
- measurement of the angular distribution of transmitted and reflected light with a photogoniometer

The laboratory has been accredited according to DIN EN ISO IEC 17025 since 2006. It is a so-called "flexible accreditation", which encompasses not only standard procedures but also the further-reaching procedures which we have developed at Fraunhofer ISE to determine g value, transmittance, reflectance and U value. 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 façade orientation can be chosen. Meteorological data and the global illuminance on the vertical plane of the façade is measured and recorded. The following investigations are conducted in the measurement rooms:

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

Façade testing facility

In addition to laboratory measurements, we offer the measurement of complete façades under real climatic conditions. Long-term investigations provide information on the stability, switching performance and loads on the façade. The optimisation of controllers can be experimentally validated.

Facts and Figures

Visiting Scientists

Kevin Beard
University of South Carolina
Columbia, South Carolina USA
1.3.2007–15.4.2007
Research area: Miniature fuel cells

Benjamin Gonzales Diaz
Universidad de La Laguna
Tenerife, Spain
31.1.2005–31.12.2007
Research area: Solar cell technology

Francesco Frontini
Politecnico di Milano
Milan, Italy
1.6.2007–31.12.2008
Research area: Building technology

Darja Markova
Technical University of Riga
Riga, Latvia
1.2.2006–31.1.2007
Research area: Micro-reformers

Douglas Bressan Riffel
Universidade Federal da Paraíba UFPB
Paraíba, Brazil
16.4.2007–15.4.2008
Research area: Solar cooling

Prof. Ricardo Rüther
Universidade Federal de Santa Catarina UFSC
Florianópolis-SC, Brazil
16.6.2007–30.7.2007
Research area: PV systems technology

Isabel Salamoni
Universidade Federal de Santa Catarina UFSC
Florianópolis-SC, Brazil
1.5.2006–31.3.2007
Research area: Potential for renewable energy in Brazil

Prof. Bifen Shu
Sun Yat-Sen University
Guangzhou, China
11.12.2006–11.12.2007
Research area: Thermal storage

John Weidner
University of South Carolina
Columbia, South Carolina, USA
1.9.2007–30.9.2007
Research area: Fuel-cell simulation

Dr Noboru Yamada
Nagaoka University of Technology
Nagaoka, Niigata, Japan
16.7.2007–31.8.2007
Research area: Thermal applications of solar energy

Participation in National and International Organisations

Allianz SysWasser
- Mitglied

Bavaria California Technology Center (BaCaTec)
- Board of Governers

BERTA AK – Brennstoffzellen: Entwicklung und Erprobung für stationäre und mobile Anwendungen (Arbeitskreis des BMWi)
- Mitglied

Brennstoffzellen-Allianz-Baden-Württemberg (BzA-BW)
- Mitglied und Vorstand

BSW Arbeitskreis Ländliche Elektrifizierung
- Mitglied

Bundesverband Kraft-Wärme-Kopplung (B.KWK)
- Mitglied

CAN in Automation (CiA)
- member

Deutsche Elektrotechnische Kommission (DKE)
- Komitee 373: »Photovoltaische Solarenergiesysteme«
- Komitee 384: »Brennstoffzellen«
- Arbeitsgruppe »Portable Fuel Cell Systems«
- Ad-hoc-Arbeitskreis »Blitz- und Überspannungsschutz für Photovoltaik-Anlagen«

Deutsche Gesellschaft für Sonnenenergie e.V. (DGS)
- Mitglied

Deutsche Meerwasserentsalzung e.V. (DME)
- Mitglied

Deutscher Wasserstoff- und Brennstoffzellen-Verband e.V.
- Mitglied

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

Fachnormenausschuss Lichttechnik (FNL 6) »Innenraumbeleuchtung mit Tageslicht«
- Mitglied

Normenausschuss Bau NABau 00.82.00 »Energetische Bewertung von Gebäuden«
- Mitglied

Gemeinschaftsausschuss NABauNHRS »Energetische Bewertung von Gebäuden«
- Mitglied

EU PV Technology Platform, Steering Committee
- Vice-Chairman

EU PV Technology Platform, Working Group Science, Technology & Applications (WG3)
- member

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

European Center for Power Electronics e.V. (ECPE)
- member

European H2/FC Technology Platform
- member

European Photovoltaic Industry Association (EPIA)
- associate member

European Solar Thermal Industry Federation (ESTIF)
- member

Evergreen Solar, Marlboro, USA
- scientific advisory board

Expertenkommission der Bundesregierung »Forschung und Innovation«
- Mitglied

Fachausschuss Tageslicht der Lichttechnischen Gesellschaft (LitG)
- Mitglied

Fachinstitut Gebäude-Klima (FGK) Arbeitskreis »Expertenkreis Klimaschutz«
- Mitglied

Fachverband Transparente Wärmedämmung e.V.
- Mitglied
- Fachausschuss »Produktkennwerte«

FIT Mikroenergietechnik
- Mitglied und Leitung

FitLicht – Fördergemeinschaft innovative Tageslichtnutzung
- Mitglied

ForschungsVerbund Sonnenenergie (FVS)
- Mitglied und Sprecher

Fraunhofer-Allianz Energie
- Geschäftsführung und Vorsitzender

Fraunhofer-Netzwerk Intelligente Energienetze
- Koordination

Fraunhofer-Netzwerk Windenergie
- Mitglied

Freiburger Verein für Arbeits- und Organisationspsychologie
- Vorstand

Fuel Cell Europe
- member

German Scholars Organization (GSO)
- President

GVEP Global Village Energy Partnership
- member

IEC TC82 WG7 for IEC Qualification Standards: Concentrator Photovoltaic (CPV)
- member

Institut für Solare Energieversorgungstechnik (ISET)
- Wissenschaftlicher Beirat

International Advisory Committee of EUPVSEC
- member

International Advisory Committee of SIMC
- member

International Commission on Glass (ICG) TC10 "Optical Properties of Glass"
- member

International Energy Agency IEA, Paris, France:
Solar Heating & Cooling Programme SHCP
- Task 33/4 »Solar Heat for Industrial Processes«
- Task 37 »Advanced Housing Renovation«
- Task 38 »Solar Air-Conditioning and Refrigeration«
- Task 39 »Polymeric Materials for Solar Thermal Applications«

Energy Conservation in Buildings and Community Systems Programme ECBCS
- Annex 47 »Cost Effective Commissioning«

Energy Conservation through Energy Storage Programme ECES
- Annex 18 »Transportation of Energy utilizing Thermal Energy Storage Technology«

Heat Pump Programme HPP
- Annex 32 »Economical Heating and Cooling Systems for Low Energy Houses«
- Annex 34 »Thermally driven Heat Pumps«

International Program Committee of GADEST
- member

International Science Panel on Renewable Energies (ISPRE)
- Chairman

Kompetenzfeld Photovoltaik NRW
- Mitglied

Kompetenznetzwerk Brennstoffzelle NRW
- Mitglied

Lichttechnische Gesellschaft
- Mitglied

M&EED Monitoring and Evaluation Working Group by Global Village Energy Partnership (GVEP) and European Union Energy Initiative (EUEI)
- member

Mikrosystemtechnik (MST)
- Beirat

Scientific Commission to the ENI Science and Technology Award
- member

Semi® Standards – Photovoltaic Equipment Interface Specification Task Force (PV-EIS)
- (Task Force) member

Stiftung Solarenergie
- Beirat

Strategierat Wasserstoff – Brennstoffzellen
- Mitglied
- AK Wasserstoffbereitstellung
- AK Wasserstoffspeicherung

Symposium Photovoltaische Solarenergie
- Wissenschaftlicher Beirat

VDE-ETG Fachausschuss V.I.I. Brennstoffzellen
- Mitglied

VDI-Gesellschaft Technische Gebäudeausrüstung
- Richtlinienausschuss 6018

VDMA – The German Engineering Federation Productronics Association / Dachverband Deutsches Flachdisplay-Forum (DFF) Arbeitsgemeinschaft Organic Electronics Association (OE-A)
- Mitglied

VDMA Arbeitsgemeinschaft Brennstoffzellen
- Mitglied

Verband zu Energieeffizienz in Gebäuden
- Gründungsmitglied

Verein Deutscher Elektrotechniker
- ETG-Fachausschuss »Brennstoffzellen«

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

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

Weiterbildungszentrum WBZU »Brennstoffzelle«, Ulm
- Mitglied im Aufsichtsrat

Zentrum für Sonnenenergie- und Wasserstoff-Forschung ZSW
- Kuratorium

Congresses, Conferences and Seminars organised in Cooperation with the Institute

22. Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein, 7.–9.3.2007

13. Symposium Licht und Architektur
Kloster Banz, Bad Staffelstein, 8.–9.3.2007

Workshop SiliconFOREST 2007
Fortschritte in der Entwicklung von Solarzellen-Stukturen und Technologien
Falkau, 12.–14.3.2007

17. Symposium Thermische Solarenergie
Kloster Banz, Bad Staffelstein, 9.–11.5.2007

Low-power Microtrigeneration for the Residential and Commercial Sector
Conference organised by Cluster de Energia, Enerlan and Polysmart
Bilbao, Spain, 12.6.2007

Local Renewables Freiburg 2007
Freiburg, 13.–15.6.2007

estec 2007
3rd European Solar Thermal Energy Conference
Freiburg, 19.–20.6.2007

Power Electronics for Renewable Energies
Freiburg, 19.–20.6.2007

Intersolar 2007:
»PREHEAT – Symposium on Heat Storage Technologies«
»New Generation of Solar Thermal Systems – NEGST«
Congress and Convention Center Freiburg, 21.–22.6.2007

ISES Solar Academy 2007
Solar & Energy Efficient Renovation Strategies for Multi-Family Housing
Solothurn, Switzerland, 4.–11.8.2007

22nd European Photovoltaic Solar Energy Conference and Exhibition
Milan, Italy, 3.–7.9.2007

Semi® Standards – PV-EIS Task Force, Kick-Off Meeting
Milan, Italy, 6.9.2007

Jahrestagung 2007 des ForschungsVerbunds Sonnenenergie
Leibniz Universität, Hannover, 26.–27.9.2007

Effiziente Fernwärmenutzung für Low-Ex-Gebäude – Statusseminar von BMWi und PTJ
Berlin, 4.–5.10.2007

Netzferne Stromversorgung mit Photovoltaik
Freiburg, 10.–11.10.2007
VDI Wissensforum
Solarthermie – Heizen und Kühlen mit der Sonne
Stuttgart, 17.–18.10.2007

Semi® Standards – PV-EIS Task Force, 1st Meeting
Messezentrum Stuttgart, 11.10.2007

2nd International Conference Solar Air-Conditioning
Tarragona, Spain, 18.–19.10.2007

Solartechnik: Aktuelle technische Entwicklungen und Perspektiven
DECHEMA-Haus, Frankfurt/Main, 25.10.2007

Bauphysik und TGA in der Baupraxis
Wuppertal, 30.10.2007

Investmentforum 2007
Fraunhofer Haus, München, 8.11.2007

2nd Fraunhofer Symposium Micro Energy Technology
Freiburg, 27.11.2007

PowerMEMS 2007
The 7th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications
Congress and Convention Center Freiburg, 28.–29.11.2007

EMV, Blitz- und Brandschutz für Solaranlagen
Freiburg, 4.–5.12.2007

Trade Fairs and Exhibitions

Bau 2007
Munich, 15.–20.1.2007

Nanotech 2007
Tokyo, Japan, 21.–23.2.2007

Hanover Trade Fair, HMI 2007
Hanover, 16.–20.4.2007

ECOTEC 2007 – Der Wissensmarkt für Umwelttechnologie
Essen Zollverein, 1.–3.6.2007

Intersolar 2007
International Trade Fair and Congress for Solar Technology
Freiburg, 21.–23.6.2007

22nd European Photovoltaic Solar Energy Conference and Exhibition
Milan, Italy, 3.–7.9.2007

f-cell 2007
Stuttgart, 24.–25.9.2007

2nd Fraunhofer Symposium Micro Energy Technology
Freiburg, 27.11.2007

Lecture Courses and Seminars

Dr. Dietmar Borchert
"Photovoltaik"
Vorlesung SS 07
TFH Georg Agricola zu Bochum
Fachbereich Maschinentechnik

Dr. Bruno Burger
"Leistungselektronische Systeme für regenerative Energiequellen"
Vorlesung WS 07/08
Universität Karlsruhe
Fakultät für Elektrotechnik und Informationstechnik

Priv. Doz. Dr. Andreas Gombert
"Optische Eigenschaften von Mikro- und Nanostrukturen"
Vorlesungen SS 06 und WS 06/07
Albert-Ludwigs-Universität Freiburg
Fakultät für Angewandte Wissenschaften

Dr. Jens Pfafferott
"Solares Bauen"
Präsenzveranstaltung SS 07 und WS 07/08
Fernstudiengang Energiemanagement
Universität Koblenz-Landau

Dipl.-Ing. Norbert Pfanner
"Photovoltaische Systemtechnik"
Vorlesung SS 07
Hochschule Offenburg

Dr. Werner Platzer
"Thermische Solarenergie"
Präsenzveranstaltung WS 07/08
Fernstudiengang Energiemanagement
Universität Koblenz-Landau

Prof. Dr. Roland Schindler
"Halbleitertechnik I (Technologie)"
Vorlesung WS 07/08
"Halbleitertechnik II (Bauelemente)"
Vorlesung SS 07
"Photovoltaik I"
Vorlesung WS 07/08
"Photovoltaik II"
Vorlesung SS 07
Fernuniversität Hagen
Fakultät für Mathematik und Informatik
Fachrichtung Elektrotechnik und Informationstechnik

Dr. Heribert Schmidt
"Photovoltaische Systemtechnik"
Vorlesung SS 07
Universität Karlsruhe
Fakultät für Elektrotechnik und Informationstechnik

Prof. Dr. Eicke R. Weber
Dr. Stefan Glunz
"Photovoltaische Energiekonversion"
Vorlesung SS 07
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof. Dr. Eicke R. Weber
"Photovoltaische Energiekonversion"
Oberseminar WS 07/08
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof. Dr. Eicke R. Weber
Dr. Werner Platzer
Dr. Ferdinand Schmidt
"Solarthermie"
Vorlesung WS 07/08
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof. Dr. Gerhard Willeke
Priv. Doz. Dr. Giso Hahn
"Aktuelle Solarzellenkonzepte in der Photovoltaik"
Seminar SS 07
"Halbleitertechnologie und Physik der Solarzelle"
Vorlesung WS 07/08
Universität Konstanz
Fachbereich Physik

Prof. Dr. Volker Wittwer
Dr. Stefan Glunz
"Stromversorgung im kleinen Leistungsbereich"
Vorlesung WS 07/08
Albert-Ludwigs-Universität Freiburg
Fakultät für Angewandte Wissenschaften

Doctoral Theses

Carsten Baur
"Entwicklung und Charakterisierung von III-V Weltraumsolarzellen"
(Development and characterisation of III-V space solar cells)
University of Constance
Constance, 2007

Steffen Eccarius
"Passive Konzepte der Direktmethanolbrennstoffzelle"
(Passive concepts for the direct-methanol fuel cell)
University of Karlsruhe
Karlsruhe, 2007

Jürgen Ell
"Gasinduziertes optisches Schaltverhalten dünner MgNi-Schichten"
(Gas-induced optical switching behaviour of thin MgNi films)
Technical University of Darmstadt
Darmstadt, 2007

Markus Glatthaar
"Zur Funktionsweise organischer Solarzellen auf der Basis interpenetrierender Donator/Akzeptor-Netzwerke"
(On the function of organic solar cells based on interpenetrating donor/acceptor networks)
University of Freiburg
Freiburg, 2007

Rüdiger Löckenhoff
"Neue Aufbau- und Integrationstechniken für die hoch konzentrierende Photovoltaik"
(New design and integration technology for highly concentrating photovoltaics)
University of Freiburg
Freiburg, 2007

Ansgar Mette
"New Concepts for Front Side Metallization of Industrial Silicon Solar Cells"
University of Freiburg
Freiburg, 2007

Peter Schossig
"Mikroverkapselte Phasenwechselmaterialien in Wandverbundsystemen"
(Micro-encapsulated phase change materials in composite wall systems)
University of Karlsruhe
Karlsruhe, 2005

Malte Christian Thoma
"Optimierte Betriebsführung von Niederspannungsnetzen mit einem hohen Anteil an dezentraler Erzeugung"
(Optimised operation management of low-voltage grids with a high proportion of distributed generation)
ETH Zurich, Switzerland
Zurich, 2007

Patent Applications

Oliver Schultz, Marc Hofmann
"Semiconductor component and procedure for its production and its application"

Frank Dimroth, Andreas Bett, Hansjörg Lerchenmüller, Christoph Schmidt
"Photovoltaic concentrator module with multi-functional frame"

Dietmar Gerteisen
"Procedure to produce gas diffusion layers, gas diffusion layers produced in this way and fuel cells containing these gas diffusion layers"

Robert Szolak, Tom Smolinka, Felix Bailatow, Florian Mertens
"Hydrogen generator and procedure to generate hydrogen"

Rüdiger Löckenhoff
"Front-surface series-connected solar module"

Ferdinand Schmidt, Andreas Häberle, Michael Hermann
"System for solar energy utilisation with device to release heat to the surroundings, procedure to operate the system and application"

Kuno Mayer, Mónica Alemán, Daniel Kray, Stefan Glunz, Ansgar Mette, Ralf Preu
"Procedure for precision processing of substrates and its application"

Thorsten Siems, Kurt Schüle
"Solar tubes, solar tubular collector and application"

Michael Oszcipok, Steffen Eccarius
"Fuel cell and procedure for its production"

Matthias Schicktanz
"Device and procedure for thermostatting and for heat recovery"

Kuno Mayer, Mark Schumann, Daniel Kray, Teresa Orellana Peres, Jochen Rentsch, Martin Zimmer
"Procedure and device for processing wafer surfaces"

Stefan Janz, Stefan Reber
"Reflectively coated semiconductor component, procedure for its production and its application"

Jan Christoph Goldschmidt, Philipp Löper, Marius Peters
"Solar element with increased efficiency and procedure for efficiency increase"

Frank Dimroth, Jara Fernandez, Stefan Janz
"Semiconductor element, procedure for its production and its application"

Frank Dimroth, Jan Schöne
"Multiple-junction solar cell"

Kuno Mayer, Mark Schumann, Daniel Kray, Teresa Orellana Peres, Jochen Rentsch, Martin Zimmer
"Texturing and cleaning medium for surface treatment of wafers and its application"

Giso Hahn, Helge Haverkamp, Bernd Raabe, Felix Book, Amir Dastgheib-Shirazi
"Novel screen-print type of procedure to create a selective emitter structure on industrially manufactured solar cells"

Michael Köhl, Karl-Anders Weiß, Axel Müller, Hannes Franke
"Thermal collector of polymer material with inserted absorber body"

Tilmann Kuhn, Peter Nitz, Christoph Meyer
"Giant fin of translucent substrate material with opaque inserts"

Beatrice Hacker, Thomas Jungmann, Ursula Wittstadt, Tom Smolinka
"Bipolar plate for a PEM electrolyser"

Adolf Goetzberger, Jan Christoph Goldschmidt, Philipp Löper, Marius Peters
"Light trap to concentrate light, particularly solar radiation"

Frank Dimroth, Jan Schöne
"Semiconductor component and its application"

Meinrad Spitz, Stefan Rein
"Procedure for inductive measurement of a sheet resistance of a doped layer introduced into a multi-crystalline semiconductor wafer"

Rüdiger Löckenhoff
"Photovoltaic module with adapted solar cell width"

Patents Granted

Ralf Preu, Erik Schneiderlöchner, Stefan Glunz, Ralf Lüdemann
"Procedure to produce a semiconductor-metal contact through a dielectric layer"

Robert Hahn, Andreas Schmitz, Christopher Hebling
"Miniature fuel-cell system"

Robert Hahn, Stefan Wagner, Andreas Schmitz
"Proton-conducting polymer membrane and procedure for its production"

Alexander Hakenjos
"Procedure and circuit configuration to measure electrochemical cells in a series circuit"

Anders Ødegård, Christopher Hebling
"Device and procedure to increase the fuel concentration in a fuel-containing liquid fed to the anode of a fuel cell"

Sarmimala Hore, Peter Nitz, Rainer Kern
"Procedure to produce the photoelectrode of a solar cell"

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

Bruno Burger, Jan Hesselmann, Mario Zedda
"Device and procedure for heating a fuel cell or a fuel cell stack"

Stefan Reber, Albert Hurrle, Norbert Schillinger
"Device and procedure for continuous chemical vapour deposition under atmospheric pressure and its application"

Bruno Burger, Heribert Schmidt
"Protective switching device for a solar module"

Andreas Georg, Wolfgang Graf, Josef Steinhart, Volker Wittwer
"Optically transparent, lightweight construction element"

Ansgar Mette, Stefan Glunz, Ralf Preu, Mónica Alemán
"Procedure to apply electric contacts to semi-conductive substrates, semi-conductive substrate and application of the procedure"

Press Releases

www.ise.fraunhofer.de/english/press/index.html

28.03.2007
Professor Joachim Luther appointed to German government's commission of experts on research innovation

04.04.2007
Solar Electricity on a Large Scale – Linear Fresnel Collectors for Solar Thermal Power Stations in a Practice Test

04.04.2007
Hydrogen from Diesel: efficient, residue-free, reliable – Diesel vaporizer for combustion motors, burners and fuel cells

04.04.2007
A Boost of Energy for Service Robots – 350 Watt Fuel Cell System for grid-independent electricity supply

20.08.2007
New Design and More Energy – Solar Cells with "Metal Wrap Through" Technology

04.10.2007
Solar cells brave desert heat and snow

05.11.2007
Fraunhofer Event for Micro Energy Technology in Freiburg

Publications in reviewed journals

Aicher, T.; Griesser, L.
»Novel Process to Evaporate Liquid Fuels and its Application to the Catalytic Partial Oxidation of Diesel«, in: Journal of Power Sources, Vol. 165/2007 1, pp. 210-216

Alink, R.; Gerteisen, D.; Oszcipok, M.
»Degradation Effects in PEM Fuel Cell Stacks by Sub-Zero Operation – an In-situ and Ex-situ Analysis«, in: Journal of Power Sources, submitted

Antón, I.[1]; Silva, D.[1]; Sala, D.[1]; Bett, A. W.; Siefer, G.; Luque-Heredia, I.[2]; Trebst, T.[3]
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([2]: Inspira S.L., Madrid, Spain)
([3]: CeramOptec GmbH, Bonn, Germany)

Banat, F.[1]; Jwaied, N.[1]; Rommel, M.; Koschikowski, J.; Wieghaus, M.
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([1]: Department of Chemical Engineering, Jordan University of Science and Technology, Irbid, Jordan)

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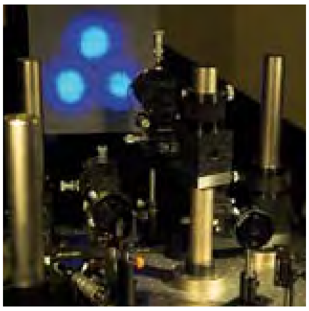



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