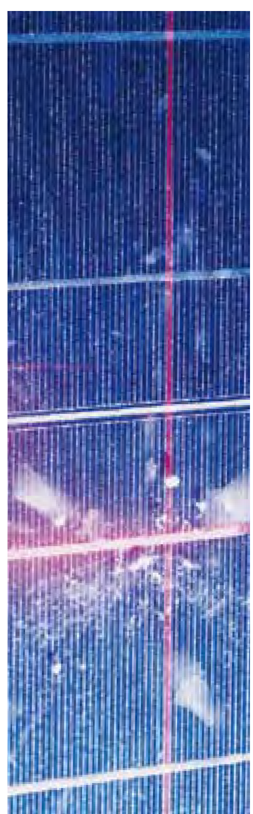
Fraunhofer Institut Solare Energiesysteme

Annual Report 2008

Achievements and Results


Solar Summits Freiburg

The "Solar Summits Freiburg" will be held for the second time from 14th to 16th October, 2009. This time, the scientific conference will address the topic of "Solar Building". Leading representatives from science and industry will present the latest technological developments from solar energy research, as well as innovative building concepts and project ideas from the solar and energy-efficient building sectors. Fraunhofer ISE is responsible for the scientific programme of the conference. With its numerous, high-quality lectures and discussions, the conference will offer a comprehensive overview of the diverse applications of solar technology in buildings.

Further information including registration details can be found under

www.solar-summits.com

The Fraunhofer Institute for Solar Energy Systems ISE is committed to promoting energy supply systems which are sustainable, economic, safe and socially just. It creates technological foundations for supplying 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: energy-efficient buildings and technical building components, applied optics and functional surfaces, silicon photovoltaics, alternative photovoltaic technology, renewable power generation and hydrogen technology. Beyond the solar sector, it also has expertise on display technology, lighting technology, water purification and electromobility.

With activities extending well beyond fundamental scientific research, the Institute is engaged in the development of production technology and prototypes, the construction of demonstration systems and the operation of testing centres. The Institute plans, advises, tests and provides know-how and technical facilities as services. Fraunhofer ISE has been certified according to DIN EN ISO 9001:2000 since March, 2001.

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Facts and Figures

Foreword

2008 was by far the most successful year to date for Fraunhofer ISE. I would like to express my admiration and sincere gratitude to all colleagues for this achievement.

With a total budget for 2008 (including investments) that exceeded 50 million euros for the first time, our Institute experienced an increase of 20 percent compared to 2007. Only 12 percent of the income was from Fraunhofer base funding. The staff numbers have increased even more rapidly – from over 600 to more than 800 now. This vigorous growth demanded that the administration also be strengthened and restructured. Our new Business Manager and COO, Dr Holger Schroeter, and our new Human Resources Manager, Thomas Arnsberg, have approached the substantial tasks associated with this growth with fresh enthusiasm.

There has also been a change in the scientific leadership team. Dr Andreas Gombert left the Institute to become the CTO of our spin-off company, Concentrix Solar GmbH. The new Head of the Department for "Materials Research and Applied Optics" is Dr Werner Platzer.

Among the many excellent research results (see pages 12 and 13), the new world efficiency record of 41.1 percent for III-V multi-junction solar cells on a germanium substrate deserves special mention. This result, which was presented just after the end of the year, is particularly pleasing, as Concentrix Solar GmbH will exploit these solar cells commercially in its concentrator modules. In 2008, this spin-off company from Fraunhofer ISE inaugurated its first production facility, with an annual capacity of 25 MW.

The entire year 2008 brought Fraunhofer ISE a series of inaugurations. Among them, the new Silicon Material Technology and Evaluation Centre SIMTEC has special prominence. Here, we have established a complete wafer-processing line – from crystallisation through sawing to cleaning of the wafers. Above all, our development work on alternative ("dirty") silicon for solar cells will be concentrated in SIMTEC. This topic has become particularly significant due to the commercial introduction of purified or „upgraded" metallurgical grade (umg) silicon this year.

The new VDE-Fraunhofer ISE Test Centre for Photovoltaics (TZPV), which we operate jointly with VDE, was able to move into new laboratories in autumn, allowing it to double its testing capacity. The close co-operation with the industry in all of our testing centres (see page 99 ff) is of great benefit both to our industrial partners and to Fraunhofer ISE. In addition to pure testing services, we are able to offer knowledge-based advice as a result of our research work in the relevant technologies.

In future, the work of Fraunhofer ISE will expand beyond Freiburg even more strongly, as our clients desire access to nearby laboratories – within Germany and internationally. Our Laboratory and Service Centre (LSC) in Gelsenkirchen continues to grow satisfyingly. The Technology Centre for Semiconductor Materials THM in Freiberg, which was founded jointly with Fraunhofer IISB Erlangen, has made decisive progress, so that we expect the complete range of work to begin in 2009. A major success for the Fraunhofer Centre for Silicon Photovoltaics CSP in Halle/Saale was its substantial contribution that led to the selection of the "Solar Valley Mitteldeutschland" as a German Cluster of Excellence (see pages 60 and 61). Fraunhofer ISE is involved both via Fraunhofer CSP in Halle and as an external partner from Freiburg. I would like to acknowledge specifically Prof. Gerhard Willeke (Fraunhofer ISE) and Dr Jörg Bagdahn (Fraunhofer IWM, Halle) for their successful efforts in building up CSP.

In the USA, we initiated the establishment of the the Fraunhofer Center for Sustainable Energy Systems CSE at MIT in Boston. Fraunhofer ISE has sent a prominent expert in the person of Prof. Roland Schindler to the CSE to support the initial establishment phase. In April, the German Federal Minister for Foreign Affairs, Frank-Walter Steinmeier, and the President of MIT, Dr Susan Hockfield, attended the ceremony where a Memorandum of Understanding (MOU) on the establishment of the Fraunhofer CSE was signed.

My predecessor as the Director of Fraunhofer ISE, Prof. Joachim Luther, became the Founding Director of the Solar Energy Research Institute of Singapore SERIS, with which we plan close co-operation. An initial step, taken in co-operation with VDE, is intended to be the establishment of a certified testing centre for solar modules in Singapore. The topic of energy-efficient building technology, a research focus at Fraunhofer ISE, has attracted appreciable interest from both Singapore and Korea. In May, the Lord Mayor of Seoul and I signed a MOU regarding co-operation on this subject.

A particular success for us was the first "Intersolar North America" Trade Fair in San Francisco, which was held which was held co-located with SEMICON WEST. As newly appointed member of SEMI International, I have been asked to represent the interests of the rapidly growing PV branch in this important global association with more than 2000 member companies.

We started a new series of conferences in 2008, the "Solar Summits Freiburg". The conferences will be held annually on different topics, with guidance and strong participation from Fraunhofer ISE. The initial event on "Silicon Materials for Photovoltaics" in October attracted participants from 23 nations. In October 2009, the focus will be on "Solar Buildings". The German Federal Minister for Foreign Affairs, Frank-Walter Steinmeier, visited Fraunhofer ISE in November 2008, in connection with a Climate Conference held in Freiburg.

Finally, I would like to mention an event with a special nature: Silicon FOREST (FORtschritte in der Entwicklung von Solarzellen-Strukturen und Technologien – Progress in the Development of Solar Cell Structures and Technology), which Dr Stefan Glunz has already organised for the fourth time, together with Dr Giso Hahn (Fraunhofer ISE and University of Constance) and Dr Jan Schmidt (ISFH Hameln). Silicon FOREST brings together undergraduates, post-graduates and post-docs from all regions of Germany, allowing them to present and discuss results from current research on silicon solar cells. These events promote networking among young scientists who will later be working in a wide range of companies and research institutions.

We were very pleased to learn of the appointments of Dr Bruno Burger as an Honorary Professor at the Technical University of Karlsruhe and Matthias Rommel as a Professor and Director of the Institut für Solartechnik SPF at the Hochschule für Technik, Rapperswil (HSR), Switzerland. The departure of Matthias Rommel will leave a large gap at Fraunhofer ISE, but we share his pleasure over the notable distinction accorded to him as a member of our staff. Since October 2008, scientists from Fraunhofer ISE have been teaching courses as part of the new Master's Programme on "Renewable Energy Management" at the Centre for Renewable Energy (ZEE), University of Freiburg.

This year again, staff members of Fraunhofer ISE have been honoured with prestigious awards. Dr Bruno Burger, Dr Frank Dimroth, Michael Köhl and Dr Harry Wirth each received a Fraunhofer Bonus for Excellence. Dr Michael Hermann received the international Bionic Award of the Schauenburg Foundation, which was awarded by the VDI and DBU for the first time. He was distinguished for his work on the FracTherm© procedure to optimise thermal solar collectors and other heat exchangers, applying biomimetic principles. Dr Stefan Glunz and his colleagues, Dr Oliver Schultz, Dr Daniel Kray and Dr Ansgar Mette, received the international Eni Award 2008 in the presence of the Italian President for their work on thin, highly efficient silicon solar cells.

Finally, I would like to sincerely thank our Board of Trustees and 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 development, for their sustained co-operation and support.

Organisational Structure

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: Scientific departments and a grouping according to business areas.

The scientific departments of the Institute are responsible for the research and development (R & D) in the laboratories, project work and concrete organisation of work. Most members of the scientific and technical staff are based in the individual departments.

The external presentation of our Institute, our marketing activities on R & D, and above all, our strategic planning are structured according to the six business areas which reflect the main research topics addressed by the Institute.

Eicke R. Weber　Hans-Martin Henning　Christopher Hebling　Günther Ebert　Werner Platzer　Holger Schroeter

Institute Director	Prof. Eicke R. Weber	+49 (0) 7 61/45 88-51 21
Deputy Director	Prof. Volker Wittwer	+49 (0) 7 61/45 88-51 40
Departments	Electrical Energy Systems Dr Günther Ebert	+49 (0) 7 61/45 88-52 29
	Energy Technology Dr Christopher Hebling	+49 (0) 7 61/45 88-51 95
	Materials Research and Applied Optics Dr Werner Platzer	+49 (0) 7 61/45 88-59 83
	Materials – Solar Cells and Technology Dr Andreas Bett	+49 (0) 7 61/45 88-52 57
	PV Production Technology and Quality Assurance Dr Ralf Preu	+49 (0) 7 61/45 88-52 60
	Silicon Solar Cells – Development and Characterisation Dr Stefan Glunz	+49 (0) 7 61/45 88-51 91
	Thermal Systems and Buildings Dr Hans-Martin Henning	+49 (0) 7 61/45 88-51 34
Business and Technical Services	Dr Holger Schroeter	+49 (0) 7 61/45 88-56 68
Press and Public Relations	Karin Schneider	+49 (0) 7 61/45 88-51 47
Strategic Planning	Dr Thomas Schlegl	+49 (0) 7 61/45 88-54 73
Technical Manager	Thomas Faasch	+49 (0) 7 61/45 88-52 03

Institute Profile

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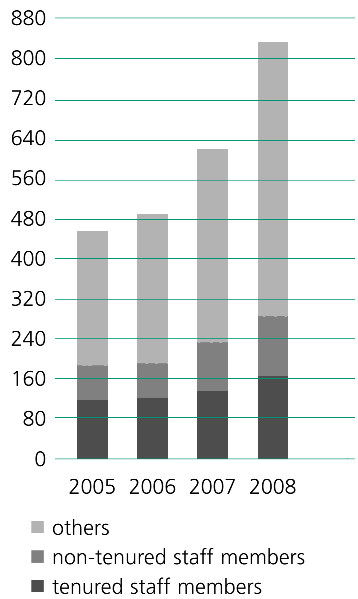
Personnel

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 2008, 94 doctoral candidates, 102 undergraduate students, 45 trainees, 5 apprentices and 234 scientific assistants were employed at the Institute. In this way, Fraunhofer ISE makes an important contribution toward educating researchers in this important field of work.



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. It conducts application-oriented research to benefit the economy and society at large. Fraunhofer ISE finances itself to more than 80 percent with contracts for applied research, development and high-technology services. 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 Erneuerbare Energien (FVEE – German Research Association for Renewable Energy) and the European Renewable Energy Centres (EUREC) Agency. The Institute can draw on expertise from other Fraunhofer Institutes, so that complete interdisciplinary solutions can be offered. There is particularly close co-operation with the University of Freiburg.

Networking within the Fraunhofer-Gesellschaft

- member of the Fraunhofer Thematic Associations for Building, Energy, Nanotechnology, Optically Functional Surfaces and Water Systems
- member of the Institute Association for "Materials, Components" (materials research)
- guest member of the Institute Association for "Surface Technology and Photonics"
- co-ordination of the Fraunhofer Innovation Topic of Microenergy Technology, in the context of "Perspectives for Tomorrow's Markets"

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/about-us/our-partners.

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 on large-area heterojunction solar cells of amorphous and crystalline silicon. LSC Gelsenkirchen also offers training sessions on characterisation procedures and solar cell technology.

The youngest external branch, the Fraunhofer Centre for Silicon Photovoltaics CSP in Halle/Saale, is operated jointly by the Fraunhofer Institute for Mechanics of Materials IWM, Freiburg and Halle, and Fraunhofer ISE. In Halle, a centre for crystallisation and materials analysis is being established, in which targeted research and development on silicon materials is being conducted together with industrial partners. Beyond this, concepts for silicon thin-film cells and module integration are being developed. Following the start signal in 2007, Fraunhofer CSP, together with other research institutions and commercial enterprises, won the Federal Government competition for Clusters of Excellence with its "Solar Valley Mitteldeutschland" application.

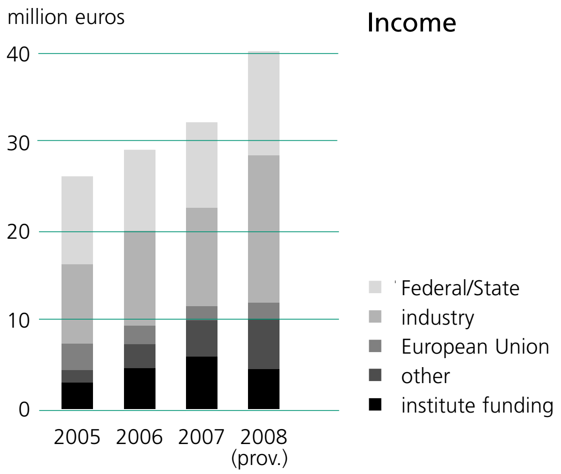
The Fraunhofer Center for Sustainable Energy Systems CSE in Boston was initiated in 2008. At CSE, know-how and technology for renewable energy that is already established in Europe is to be further adapted and introduced to the American market. The activities will concentrate on solar technology and energy-efficient building. Close co-operation is planned between researchers from Fraunhofer ISE and the scientists at Fraunhofer CSE and the Massachusetts Institute of Technology MIT.

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. THM supports companies in research and development on materials 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.

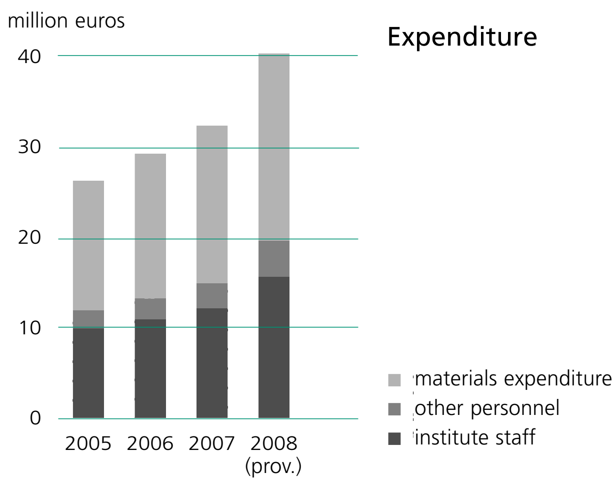
A photovoltaic project group has been run jointly by Fraunhofer ISE and the Department of Physics at the University of Constance since 2006.

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. In addition to the expenditure documented in the graph, the Institute made investments of 14.4 million euros in 2008 (not including investments for building modifications and expansion).

Income



Expenditure



Research and Development

- initial operation of a chilled ceiling with integrated phase change material (PCM) in combination with heating and electricity co-generation, to optimise the load on a combined heat and power (CHP) plant
- vacuum insulation panels (VIP) introduced to the market by industrial partners as a practicable form of thermal insulation
- COP's (Coefficient of Performance) for the whole year determined for the first time in a comprehensive monitoring project on heat pumps
- large European project to develop solar technology for high-rise buildings ("Cost-Effective" Project) started under the leadership of Fraunhofer ISE
- new test stand for thermal solar systems developed and commissioned, with which up to four systems can be measured simultaneously according to EN12976
- "inHaus2" research platform inaugurated in Duisburg
- measurement of Fresnel demonstration collector for direct evaporation at the Plataforma Solar de Almería, Spain
- demonstration façade with switchable gasochromic solar control
- development of a high-T stable absorber coating for use in Fresnel collectors
- spectral simulation and optimisation of single and two-stage concentrator optics
- 23.2 % efficiency for an n-type silicon solar cell with a boron front-surface emitter
- 15.1 % efficiency for a large-area wafer-equivalent solar cell on an mc-Si substrate with a porous reflector (IMEC), 20 µm coating thickness
- 20.3 % efficiency for a p-type silicon solar cell with printed contacts (aerosol + Ag galvanisation)
- 20.1 % efficiency for an n-type silicon solar cell with an aluminium back-surface emitter
- 20.3 % efficiency for a p-type silicon solar cell with contacts of deposited nickel (Ni-plating and Ag galvanisation)
- 20.4 % efficiency for a solar cell with laser-chemical processing LCP
- 21.1 % efficiency for a back-surface contacted solar cell on n-type silicon with industrially relevant masking technology (laser ablation and screen printing)
- analytical REM commissioned for materials analysis with EBSD, EDX, T-EBIC and CL
- first demonstration of a quantitative measurement procedure for spatially resolved series resistance determination for in-line production control (measurement times of less than 1 s)
- demonstration of a quantitative, spatially resolved measurement procedure for in-line classification of hot spots with measurement times of less than 10 ms
- 18.1 % efficiency for a 130 µm thin, screen-printed Cz-Si solar cell (125 x 125 mm^2) with LFC contacts demonstrated on production systems, most of them in PV-TEC
- 16.6 % efficiency for an mc-Si solar cell (125 x 125 mm^2, R_{sh} emitter = 80 Ω/sq) with in-line galvanised, fine screen-printed linear contacts, processed completely in PV-TEC
- MWT solar cell process transferred to renowned German cell manufacturer, efficiency increase of 0.3–0.4 % demonstrated in comparison to Al BSF reference cell
- 20 µm fine seeding layer produced on inkjet-opened silicon nitride film and 50 µm fine screen-printed seeding layer produced on textured silicon wafers
- in-line measurement of the chemicals in an acidic texturing solution demonstrated on the basis of random sampling of 10,000 wafers
- laser-fired contact process (app. 15,000 contacts per s) transferred from 2 µm thin evaporated films to 30 µm thick screen-printed layers
- in-line high-rate evaporation facility developed and constructed together with Applied Materials GmbH & Co. KG, dynamic deposition rate of 5 µm m/min demonstrated
- 41.1 % world record efficiency for a III-V concentrator solar cell with 454 x solar radiation
- 37.6 % efficiency for a III-V concentrator solar cell with 1700 x solar radiation
- 28.5 % efficiency for concentrator modules
- production of a 60 cm x 100 cm dye solar cell module for an industrial workshop
- flexible organic solar cell modules produced with technology suitable for upscaling
- world record electrical efficiency of 6.7 % for fluorescent collectors
- efficiency of 98.8 % for photovoltaic inverter with silicon carbide components

- commissioning of an innovative communications gateway to acquire measured data from electricity and gas meters (EWE Box) by the project partner
- development of technical and economic concepts for market introduction of distributed electricity generators (MASSIG)
- Fraunhofer ISE co-ordinates the "intelliekon" project to investigate intelligent measurement and feedback systems for the energy consumption of households
- investigations on the integration of photovoltaics in urban areas within the European research project, "PV-UPSCALE"
- application demonstrated of intelligent co-munications and energy management systems for the electricity grid (DEMAX)
- concept developed for reliable and efficient desalination on the basis of PV-operated reverse-osmosis systems without batteries
- system models developed for different types of battery technology
- testing procedures developed for quality control of PV-LED systems
- co-operation started between Fraunhofer ISE and VDE to certify fuel cell systems
- passive miniature fuel cell of injection-moulded polymer presented with vapour-phase methanol supply
- direct ethanol fuel cell demonstrated
- Fraunhofer "Attract" Programme started on the topic of passive miniature fuel cells/water management
- VDE-Fraunhofer ISE Test Centre for Photovoltaics (TZPV) opened for standardised quality assurance, testing and certification of photovoltaic modules according to the internationally recognised IEC standards
- SIMTEC – Silicon Material Technology and Evaluation Centre opened. Main subjects: Silicon crystallisation, wafer technology and crystalline thin-film technology
- ConTEC – Concentrator Technology and Evaluation Centre fully operational. Main subjects: Testing of concentrator solar cells and modules, development of contacting technology, accelerated aging tests

Professorships, Awards and Prizes

Dr Stefan Glunz, Head of the Department for Silicon Solar Cells – Development and Characterisation, and his colleagues, Dr Oliver Schultz, Dr Daniel Kray and Dr Ansgar Mette received the international Eni Award 2008. In May 2008, the award in the "Science and Technology" category was presented to them in Rome by the Italian utility, Eni, in the presence of the Italian President, for their work on thin, highly efficient silicon solar cells.

Dr Michael Hermann was honoured for his bionic research work to develop commercially viable technology with the international Bionic Award. The Bionic Award was presented in 2008 for the first time on behalf of the Schauenburg Foundation by the VDI and DBU in the German Association of Foundations for Science.

Prof. Eicke R. Weber was appointed to the Board of Directors for the SEMI International industrial association.

Prof. Joachim Luther was selected as a "Hero of the Environment 2008" by the "Time" Magazine.

Matthias Rommel was appointed as a Professor and Director of the Institut für Solartechnik SPF at the Hochschule für Technik, Rapperswil (HSR), Switzerland.

Dr Bruno Burger was appointed an Honorary Professor at the Technical University of Karlsruhe in December 2008.

Dr Tom Smolinka received the 2nd Prize for his poster on "Highly Efficient Solar Hydrogen Production by Combining PV Concentrator Solar Cells with PEM Electrolysis Cells" at the f-cell 2008 in Stuttgart.

Xiaohui Tian was presented the Best Poster Award 2008 in the "Fuel Cells, Science & Technology" category at the Grove Fuel Cell Symposium in Copenhagen. His poster was entitled "Computational Geometry Design and Modeling of a Vapor-fed Direct Methanol Fuel Cell".

Gerhard Peharz[1], Gerald Siefer[1], Kenji Araki[2] and Dr Andreas Bett[1] received the Best Student Presentation Award of the IEEE 2008 in the "Concentrator Cells and Systems" category for their presentation on "Spectrometric Outdoor Characterization of CPV Modules".

[1] Fraunhofer Institute for Solar Energy Systems ISE
[2] Daido Steel Co. (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, 2008

Energy-Efficient Buildings and
Technical Building Components

Applied Optics and
Functional Surfaces

Silicon Photovoltaics

Alternative Photovoltaic
Technology

Renewable Power Generation

Hydrogen Technology

Service Units

Energy-Efficient Buildings and Technical Building Components

Energy-efficient buildings not only protect the atmosphere, but are also easier to market. In particular, the marketing aspect will become more important now that the European "building energy certificate" has been introduced, which allows the user 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 percent 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, convert 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 the development of fundamentals 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. We offer advice, planning and concept development as well as the implementation of new approaches to energy-efficient operation management and controls regarding energy and user comfort issues within the framework of advanced building projects. 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.

In collaboration 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 develop the international frameworks 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.

An extraordinary building was officially opened on 5th November, 2008 in Duisburg: "inHaus2". For about eighteen months, this had been a hive of activity for research and development on the intelligent building site, new materials or energy-saving systems. More than 50 partners from industry and research participated in the project implementation. Fraunhofer ISE was responsible for co-ordinating the research activities on building operation and facility management (see article on page 27).

Contacts

Energy-Efficient Buildings and Technical Building Components	Dr Hans-Martin Henning	Tel.: +49 (0) 7 61/45 88-51 34 E-mail: Hans-Martin.Henning@ise.fraunhofer.de
Building concepts, analysis and operation	Sebastian Herkel	Tel.: +49 (0) 7 61/45 88-51 17 E-mail: Sebastian.Herkel@ise.fraunhofer.de
Solar façades	Tilmann Kuhn	Tel.: +49 (0) 7 61/45 88-52 97 E-mail: Tilmann.Kuhn@ise.fraunhofer.de
Durability analysis	Michael Köhl	Tel.: +49 (0) 7 61/45 88-51 24 E-mail: Michael.Koehl@ise.fraunhofer.de
Lighting technology/ building applications	Jan Wienold Dr Werner Platzer	Tel.: +49 (0) 7 61/45 88-51 33 E-mail: Jan.Wienold@ise.fraunhofer.de Tel.: +49 (0) 7 61/45 88-59 83 E-mail: Werner.Platzer@ise.fraunhofer.de
Energy supply units for residential buildings	Dr Benoît Sicre	Tel.: +49 (0) 7 61/45 88-52 91 E-mail: Benoit.Sicre@ise.fraunhofer.de
Heat storage for heating and cooling	Dr Peter Schossig	Tel.: +49 (0) 7 61/45 88-51 30 E-mail: Peter.Schossig@ise.fraunhofer.de
Thermal solar collectors and applications	Matthias Rommel	Tel.: +49 (0) 7 61/45 88-51 41 E-mail: Matthias.Rommel@ise.fraunhofer.de
Monitoring and demonstration projects	Sebastian Herkel Klaus Kiefer	Tel.: +49 (0) 7 61/45 88-51 17 E-mail: Sebastian.Herkel@ise.fraunhofer.de Tel.: +49 (0) 7 61/45 88-52 18 E-mail: Klaus.Kiefer@ise.fraunhofer.de

Energy Supply Units for Residential Buildings (heat pumps, micro-CHP)

The importance of supplying heat and electricity efficiently to residential buildings is constantly increasing. In this sector, we evaluate the efficiency and support manufacturers of heating and ventilation systems in the development of new equipment or system components. The services we offer include system and component simulation, prototype development and characterisation in the laboratory, as well as evaluation of zero series.

Lukasz Kaczmarek, Thomas Kramer, **Marek Miara**, Nidal Mustapha, Thore Oltersdorf, Michael Platt, **Christel Russ**, Kurt Schüle*, **Benoît Sicre**, Jeannette Wapler**, Jakub Wewior, Xiaolong Zhang, Hans-Martin Henning

* Kollektorfabrik GbR, Freiburg
** PSE AG, Freiburg

Efficient energy conversion – including renewable energy sources to an increasing extent – plays a central role in achieving the announced goals for CO_2 reduction.

At Fraunhofer ISE, we are currently carrying out a broadly based field measurement campaign covering about 200 heat pump systems on commission to manufacturers and energy utilities. The heat and electricity fluxes are recorded every minute, allowing the energy efficiency of the systems and their operating behaviour to be analysed. The large number of systems and their geographic distribution over the entire area of Germany means that we gain comprehensive insight from these measurements into the state of the art under widely varying meteorological conditions, user profiles and heat sources. From this basis, we derive recommendations for further development of the equipment and system optimisation.

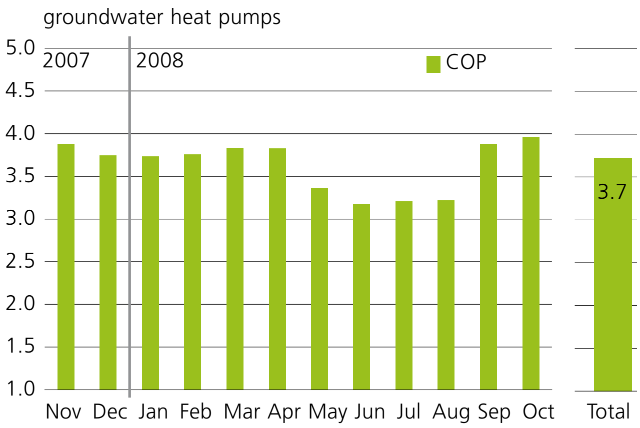


Fig. 1: In a monitoring programme, we measure, analyse and evaluate a large number of heat pump systems in new buildings and the existing building stock with regard to efficiency and optimisation potential. In new buildings, average seasonal performance figures (SPF) for heating and domestic hot water of 3.7, 3.0 and 3.5 are achieved when the ground, air and groundwater respectively are used as the heat source. (November 2007 to October 2008, 53 heat pump systems, 43 with the ground, 6 with air and 4 with water as the heat source).

Our activities concerning small combined heat and power plants (micro-CHP) include the investigation of wood pellets as a fuel and the analysis of new structural concepts and operating strategies to increase the fuel conversion efficiency and electricity yield. As part of the "PeStiS" project, the interaction between a 1 kW Stirling engine and a 15 kW pellet burner was simulated and characterised in the laboratory. The operation management was then optimised according to energy-relevant and economic criteria.

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

Fig. 2: Conception and control of a miniature micro-CHP system using wood pellets as the fuel. The goal was to maximise the electricity yield with a sophisticated energy management concept and flexible use of waste heat with highly efficient heat storage and supply. The photo shows the Stirling engine and the pellet burner in the laboratory. (Photo: Stirling Power Module GmbH).

Component Development for New and Established Heat Pump Concepts

Both electrically and thermally driven heat pumps exploit the potential to save energy in the building sector, as ambient heat is integrated into the process in addition to the source of driving energy. Our work is dedicated to the targeted development and optimisation of components. Beyond the intrinsic energy-saving potential of both types of technology, further increases in the efficiency can be achieved by improving the internal heat and mass transfer processes.

Jörg Dengler, Gerrit Füldner, Thore Oltersdorf, Ferdinand Schmidt*, **Lena Schnabel, Benoît Sicre**, Kai Witte, Ursula Wittstadt, Hans-Martin Henning

* University of Karlsruhe

Among thermally driven heat pumps, component development is focused on zeolite/water systems, particularly the development of new composite sorbent/metal structures. In co-operation with Fraunhofer IFAM (Dresden/Bremen), Fraunhofer ITWM and Fraunhofer IVV, we are currently developing heat-transfer materials, in which the adsorbent is deposited directly by crystallisation on a fibre or foam structure. The materials and structures are analysed on the basis of experimentally determined equilibrium data, measurement of the heat and mass transfer dynamics on the microscopic and macroscopic scale, and investigation of cycling stability. The described adsorber concepts promise to increase the power density significantly. This work is being carried out as part of the Fraunhofer-financed project on "Thermally driven high-performance cooling processes (THOKA)". At the same time, we are pursuing new evaporator concepts within the "SORCOOL" joint project that is supported by the German Federal Ministry for Economics and Technology (BMWi). Characteristic curves for the evaporation process are measured on horizontal heating surfaces to identify suitable evaporator surfaces. Transfer to small-scale evaporator units is investigated in a further experimental set-up.

Our work on electrically driven heat pumps is concentrating on the development of evaporators for using air-based heat sources. Here, we are investigating alternative materials and new concepts for directing the flow of both the air and the cooling medium. We characterise these components and integrate them into clients' systems, such as air-to-air and air-to-water heat pumps.

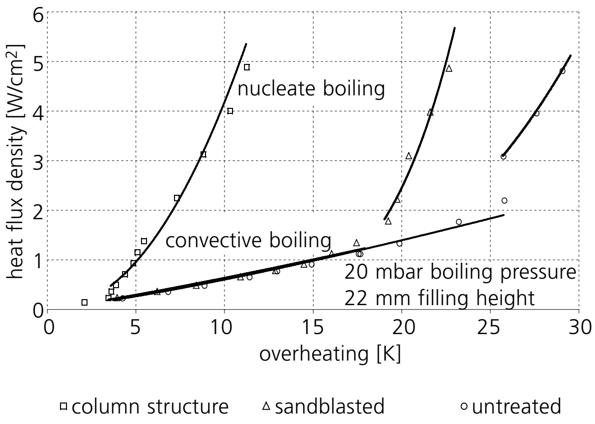


Fig. 1: Heat transfer characteristic curves for three different heating surfaces (copper with rectangular column structures, a sand-blasted and an untreated copper surface). The change in the gradient of the heat flow density as a function of the driving temperature difference indicates the evaporation range. The aim is to achieve the highest possible heat transfer density with only a slight temperature increase (< 5 K). This succeeds best with the column structure.

Fig. 2: The photo shows the column structure during measurement. The screws in the centre serve to fasten the sample. An ascending bubble can be seen clearly above the right-hand side of the heating surface.

Fig. 3: Illustration of a heat-transfer structure for compression heat pumps using air as the heat source. The applied manufacturing process combines advantages from flat-pipe heat exchangers with lateral flow and conventional fin-pipe heat exchangers with longitudinal flow.

Low-Exergy Surface Cooling Systems with Phase Change Materials (PCM)

Innovative low-exergy surface cooling systems operate with small temperature differences between the cooling medium and the intended room temperature. The potential to use regenerative energy sources for air-conditioning can be significantly increased by additional integration of a very efficient thermal storage element in the form of phase change materials (PCM). The goal of our work is to develop such surface cooling systems up to implementation in demonstration buildings.

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

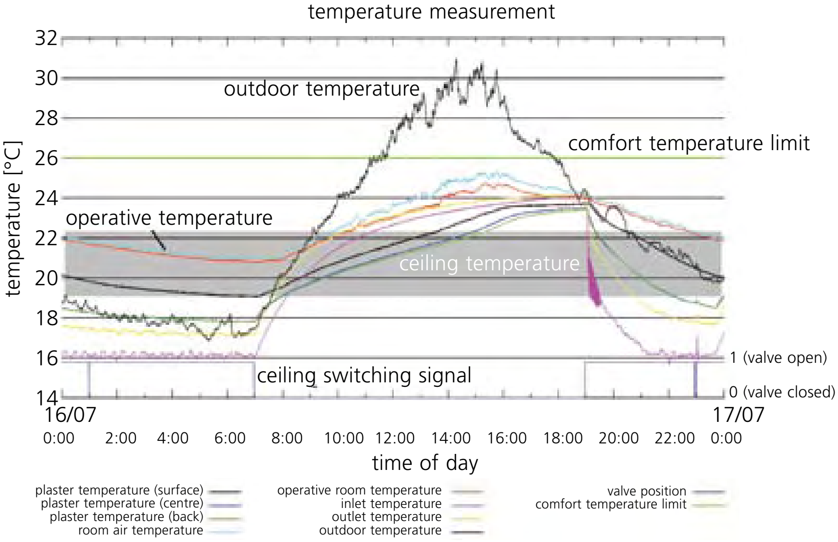


Fig. 1 shows examples of temperature profiles in an office equipped with a demonstration PCM chilled ceiling (measured at Fraunhofer ISE) on a summer day. Room temperatures of more than 26 °C were reliably prevented without operating the chilled ceiling actively, despite high outdoor temperatures approaching 30 °C. During the night, the PCM is regenerated by a connected CCHP (combined cooling, heat and power) plant.

Drawing on building materials with integrated PCM which had previously been developed at Fraunhofer ISE together with the industry, we have now developed actively water-cooled surface cooling systems with integrated PCM. An essential advantage of this new technology is that the generation of cooling power is decoupled in time from the cooling demand by inclusion of the storage element. As a result, not only can the cooling system be operated more efficiently, but it can be dimensioned appreciably smaller, as it no longer has to meet the peak demand in the daily profile. This particularly favours energy-efficient low-exergy cooling concepts.

Central aspects of our work included:

- identifying a suitable PCM, particularly concerning the melting range
- developing a technically practicable system design
- carrying out suitable demonstration projects
- investigating the control strategy and determining the efficiency gains of the PCM surface cooling system

Following the installation of two chilled ceilings, they are now being monitored, analysed and optimised.

Development of a simulation tool to support the market introduction of PCM building materials was another major focus of our work. This simulation-based calculation tool, "PCM-Express", has been available free of charge since March 2008 from our project partner, Valentin Energiesoftware.

The work was supported by the German Federal Ministry for Economics and Technology (BMWi) within the "PCM-Aktiv" project.

Fig. 2: A simulation-based calculation tool was developed for interested building owners, planners and users within the "PCM-Aktiv" project. It allows the potential thermal and economic advantages of cooling buildings with PCM to be determined simply and compared with conventional solutions. The tool can be obtained free of charge from our project partner, Valentin Energiesoftware (www.valentin.de).

Research on Solar Cooling accompanying the "Solarthermie2000plus" Funding Programme

Fraunhofer ISE is responsible for the research on solar-thermal cooling systems accompanying the "Solarthermie2000plus" funding programme of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The research is focused on support for the project management organisation in selecting the projects, assistance during the planning phase and analysis of the operating performance of the installed systems. The project applications cover a wide range of concepts and nominal cooling power. The first system started operation at the end of 2007.

York Tiedtke*, Jakub Wojciech Wewiór, **Edo Wiemken**, Hans-Martin Henning

* PSE AG, Freiburg

Up to the end of 2008, three systems for solar-thermal cooling had started operation. These first three systems already indicate the diverse possibilities for applying solar cooling:

- solar-assisted air-conditioning at FESTO AG & Co. KG in Berkheim/Esslingen with 1218 m^2 evacuated tubular collectors (operation since the end of 2007). The collector array increases the regenerative share of heat supplied to the adsorption chillers with a total of 1.05 MW rated cooling power. Waste heat from the factory and gas-fired boilers are further sources of heat.
- solar process cooling in the radiological practice of Dr Reichel and Dr Gehrmann in the "Ärztehaus Berlin". An absorption chiller with a rated cooling power of 10 kW is thermally driven by 40 m^2 evacuated tubular collectors. During the day, the system reduces the amount of cooling power drawn from the building cooling grid to cool the tomography equipment (in operation since summer 2008).
- autonomous solar air-conditioning in Butzbach Technical College. Two absorption chillers, each with a rated power of 10 kW, supply cooling power to the chilled ceilings and ventilation equipment. Evacuated tubular collectors with a collector area of 60 m^2 have been installed and were commissioned at the end of 2008.

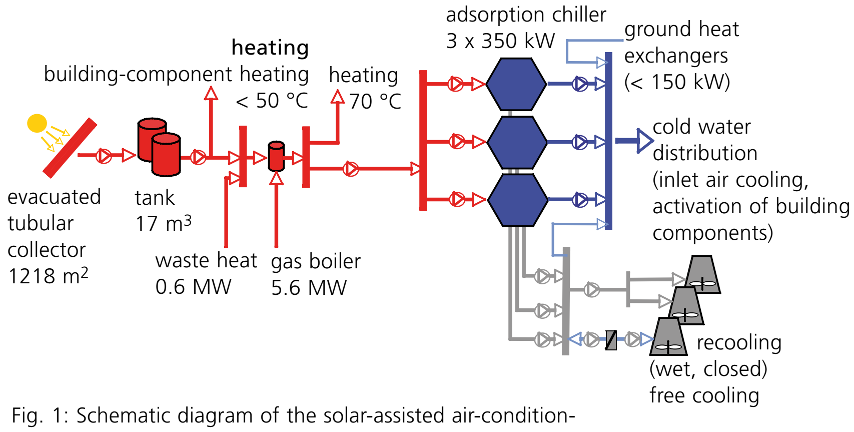


Fig. 1: Schematic diagram of the solar-assisted air-conditioning system for the technological centre of FESTO AG & Co. KG. An office area of about 26 000 m^2 is air-conditioned with water-based cooling from three adsorption chillers, each with a rated cooling power of 353 kW. The system was originally installed in 2001. Since the end of 2007, a solar-thermal system with a collector area of 1218 m^2 has reduced the amount of heat supplied by gas-fired boilers.

Fig. 2: Photo of the low-energy building of Butzbach Technical College, in which an autonomous solar air-conditioning system has been installed (i.e. solar air-conditioning for summer, without additional auxiliary heating or cooling sources). Two absorption chillers, each with 10 kW rated cooling power and manufactured in Berlin by the Sonnenklima company, supply cold water for the air-conditioners and chilled ceilings for a seminar area of 335 m^2.

Data acquisition equipment is installed by the corresponding monitoring partners as part of the funding programme. After sufficient data on operating performance has been collected, a comprehensive energy balance will be prepared.

The project is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).

Evaluation Methods for Building Envelopes

Modelling complex façades in building energy simulation programs and the perceived colour of façades are relevant issues concerning current building practice. At Fraunhofer ISE, we address these topics with the aim of increasing planning certainty in the building process.

Francesco Frontini, Sebastian Herkel, **Tilmann Kuhn, Helen Rose Wilson**, Hans-Martin Henning

Fig. 1: Insulating glazing units from different product families have been mounted in front of a black wall of the rotatable container on the roof of Fraunhofer ISE. At an incidence angle of 20 °, the colour difference between the various windows is just perceptible.

Fig. 2: The same insulating glazing units as in Fig. 1 are viewed here under an incidence angle of 75 °. The colour differences between the different product families are now clearly visible. Such colour differences can be evaluated quantitatively with a colorimetric camera and a measurement and analysis method which was developed at Fraunhofer ISE.

Modelling of complex façades in building simulation programs

Current façade models describe complex façades as a stack of flat, homogeneous layers in which optical absorption occurs. Heat transfer takes place between the layers. Light-redirecting, air-permeable, angle-selective IR-transparent and geometrically complex structures can be treated only with greatly simplified approximations. We have thus developed a new methodological approach for the ESP-r building simulation program, which allows measured values for transmittance, reflectance and g value to be used directly as input data for the simulation. The implementation has been completed and validated. The model is available in the official version of ESP-r. The work was partly financed by the Velux Foundation.

Colour effect of façades

The visual perception of colour in coated insulating glazing units depends on a number of factors. Not only the reflectance properties of the glazing itself play a role, but also the lighting conditions, the colour of the surroundings and the viewing angle. In co-operation with the company, TechnoTeam Bildverarbeitung GmbH, we have developed a measurement method and theoretical approaches which allow colour differences for thick, multiple-pane glazing samples to be evaluated quantitatively in the laboratory and at the building location. This represents an important step towards describing the complex colour effect of façades and improving planning capabilities in future.

The work was supported by the German Federal Ministry for Economics and Technology (BMWi) as part of the PRO INNO programme.

Optical Simulation of Solar Collectors with Reflectors

At present, many new types of collectors with reflectors are being developed, mainly because high-temperature heat is often needed for industrial processes or solar cooling. The high temperatures can be achieved by concentrating the solar energy, which is possible with reflectors. With our ray-tracing simulations, we support industrial partners by characterising and optimising both existing collectors and the objects of new development.

Stefan Heß*, Paolo Di Lauro, Matthias Rommel, Hans-Martin Henning

* PSE AG, Freiburg

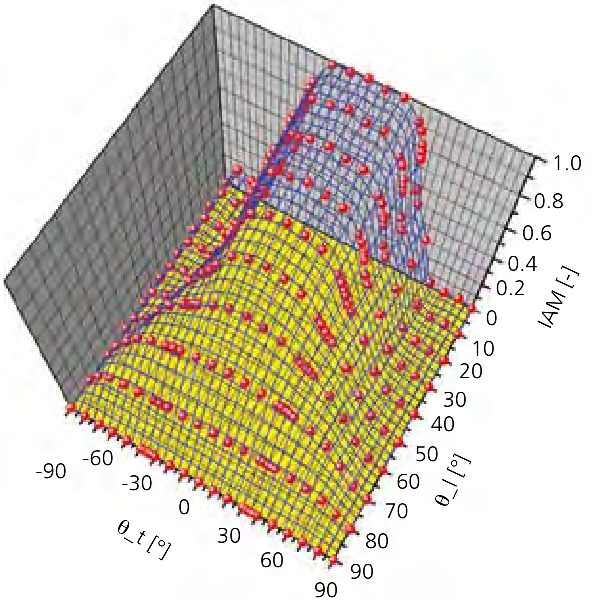


Fig. 1: Three-dimensionally simulated incidence angle modifier for direct radiation of the collector illustrated in Fig. 2 (simulation with real material parameters, acceptance half-angle of 35 °). The direction of incidence was projected onto the longitudinal and transverse optical axes of the collector (θ_l and θ_t respectively) and the simulation result plotted as a red dot. From the simulation results, an IAM of 0.64 was determined for diffuse radiation that was isotropically irradiated from the complete hemisphere.

Results obtained from our ray-tracing calculations with the OptiCAD program include the optical efficiency value of a collector and the incidence angle modifier (IAM) for direct radiation (Fig. 1), from which we determine the IAM for isotropic diffuse radiation. We use these results directly to simulate the annual energy yield for given locations and load profiles. In this way, we can assess the potential of collector types which do not yet exist in reality, and optimise existing or new collector concepts.

When we model focusing or non-focusing (Fig. 2) reflectors in the simulation environment, we are able to take into account not only the scattering of radiation due to diffuse reflection but also the distribution due to macroscopic surface defects ("waviness") or positioning errors. These defects and the characteristic optical parameters of reflectors, collector covers, absorbers and other components can be characterised by measurements at Fraunhofer ISE before simulations are started. This ensures that the model of the collector in the simulation environment is as realistic as possible. The ray-tracing method is also used for sensitivity analyses to determine which defect or material parameter has the greatest influence on collector yield.

We have validated the high quality of our ray-tracing simulations for flat-plate, evacuated tubular and CPC collectors with measurements.

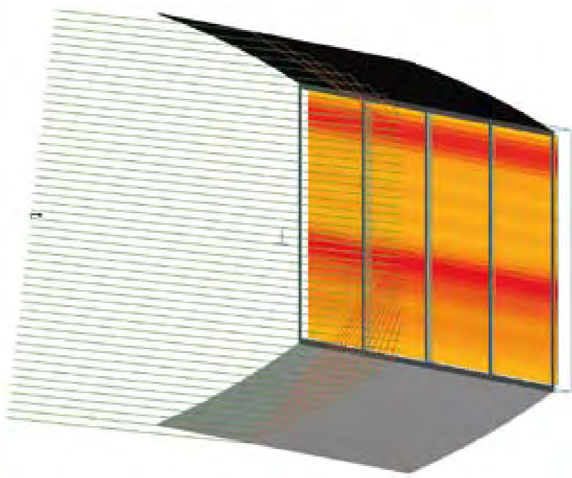


Fig. 2: Ray-tracing simulation of a newly developed, non-focusing collector (simplified representation). A flat-plate collector is equipped above and below with CPC reflectors (compound parabolic concentrator, black and grey). In the figure, an ideally parallel band of rays (green) is incident under a transverse incidence angle of 15 ° on the collector aperture. The resulting intensity distribution on the absorber after interaction with the collector components is illustrated in shades of red.

Our work on ray-tracing is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) as part of a joint project with an industrial partner.

New Concepts for Solar Air Collectors

Solar air collectors are collectors in which the solar heat is transferred by the collector absorber to air rather than to a liquid, as usually occurs. Solar air collectors currently occupy only a very small share of the market but offer a number of advantages compared to "water" collectors. For this reason, we have decided, as the only research institute in Germany, to extend our test equipment to cater for development work on solar air collectors.

Christian Frisch, Jens Richter, **Matthias Rommel**, Christoph Thoma, Hans-Martin Henning

Fig. 1: Air collector test stand, installed for performance measurements on the roof of Fraunhofer ISE. The collector mounted on the solar tracker is visible, as are the individual components of the test circuit in the foreground: two fans (on the inlet and outlet sides), two volume flow meters and the heat exchanger, which defines the operating temperature of the air collector via a controlled thermostat during the efficiency measurement.

Collectors with a liquid heat-transfer medium and air collectors have usually been regarded as competing types of technology up to now. However, solar technology has developed further: The spectrum of applications and materials has become broader, the costs for evacuated tubes have fallen. Simultaneously, new scientific knowledge has been gained and research funding has been increased. It is therefore reasonable and necessary to re-evaluate air collector technology, advance it and exploit its advantages. Air does not freeze or boil, it is non-toxic and is available everywhere. Nevertheless, larger heat exchanger areas and duct diameters are needed due to its thermodynamic properties. On the other hand, cost-effective, simple and innovative systems are possible with air.

We understand air collectors as an extension of existing solar technology. In order to carry out informative development work, we have begun to extend our facilities in this direction. The test stand at Fraunhofer ISE is designed for use both indoors in the laboratory with a solar simulator and outdoors together with a solar tracker (Fig. 1). It is also possible to carry out performance measurements of air collector systems in a field test.

The test stand has already proven itself during the investigations of several solar air collectors:
- solar air collector from a German manufacturer, where the air flows beneath a selective absorber
- flat-plate collector from France, where the air flows over a non-selective absorber
- new evacuated tubular air collector

Figure 2 shows one of the first systems with this collector, which was constructed within a DBU-funded project.

Fig. 2: New evacuated tubular air collector for domestic hot water and solar-assisted heating, installed on a free-standing house. The system was constructed as one of the first of seven systems within a project supported by "Deutsche Bundesstiftung Umwelt (DBU)". Its operation is being investigated and evaluated.

"inHaus2" Research Centre for Non-Residential Buildings in Duisburg

"inHaus2" in Duisburg is an innovation platform for technology, products and applications for non-residential buildings. The aim of the centre is to facilitate higher efficiency in planning, implementing and operating non-residential buildings. A distinguishing feature of the energy concept for the new centre is the application of efficient and innovative technology to cool, heat and ventilate the building. Its implementation and operation are being analysed and evaluated by the Fraunhofer Institute for Solar Energy Systems ISE.

Martin Fischer, **Sebastian Herkel**, Doreen Kalz, Tilmann Kuhn, Jens Pfafferott, Hans-Martin Henning

Fig. 1: Innovative concepts for operation management and optimisation are developed at the "inHaus2" research platform. The "inHaus2" building consists of three building segments, in which innovative systems to transfer heating and cooling energy are applied. These include thermally activated building components such as concrete-core and floor-based systems for heating and cooling (Photo: Fraunhofer inHaus-Zentrum ©Guido Erbring).

In co-operation with more than 50 partners from the commercial sector, "inHaus2" in Duisburg has been taken into operation as a Fraunhofer research platform. Fraunhofer ISE is co-ordinating research on the topics of building operation and facility management.

The energy supply for the building is a major focus. Zones of different usage, such as offices, meeting and seminar rooms, and laboratory and research areas, have been taken into account in the integration of innovative and efficient heating, cooling and ventilation technology. The individual types of technology are adapted to each other in an optimised operation concept and by control strategies. The core of the heating and cooling concept is usage of the ground as a natural source and sink of ambient energy. Ten underground heat exchangers, extending to 120 m below the surface, are tapping this energy from the ground in combination with an electric heat pump. In summer, the ground is used directly for cooling the building. Sorption-assisted air-conditioning to cool and dehumidify the input air is a further component of the building cooling system.

The research and development on building operation and facility management in "inHaus2" is focused on investigating innovative technology for technical building services with regard to operation, energy efficiency and thermal comfort. Beyond this, the energy performance of the complete system – from the energy source through to provision of heating and cooling in the rooms – is to be analysed and evaluated.

The "inHaus2" project is funded by the German Federal Ministry for Education and Research (BMBF), the EU, the State of Nordrhein-Westfalen and the City of Duisburg.

Low-Exergy Concepts to Supply Buildings with Energy Efficiently

Raised expectations by building occupants on the indoor climate and recent warmer summers have led to a rapid increase in the cooled office area in Germany. Thermally activated building components, which can be operated advantageously with ambient energy, provide a large share of the cooling. Although this technology offers the potential for very high energy efficiency, there is a great need for optimisation in practice. To this purpose, we measure and analyse implemented building concepts in operation.

Martin Fischer, Sebastian Herkel, **Doreen Kalz, Jens Pfafferott**, Tobias Zitzmann, Hans-Martin Henning

The desire for comfortable indoor conditions, combined with the demand for the lowest possible energy consumption and widespread scepticism concerning air-conditioning units, has reinforced the trend toward water-based systems for heating and cooling using ambient energy. In 2007, around 845,000 m^2 of thermally active room surfaces were installed in Germany alone. Just on 60 % of new office buildings are cooled via the room surfaces in summer – and some are also heated in this way during winter. Surface cooling systems are also being used increasingly in renovation.

Surface heating and cooling systems can be operated with small temperature differences between the heat-exchanging surface and the room air. The systems are termed low-exergy systems, because heat with low exergy can be used in them. The ground can be used to advantage as a heat sink in summer, and as a heat source in winter if combined with a heat pump. However, the slight temperature differences are also accompanied by the disadvantage that a relatively large flow rate must be maintained in order to transport the necessary amount of heat.

Our measurement projects have demonstrated how important it is to dimension the entire system correctly, install it professionally and then operate it appropriately in order to exploit the potential of this technology. We support our clients with concepts and simulations during the planning phase and then with measurements during operation. We draw on our experience from building practice and research projects to develop low-exergy components further and to optimise them within the complete system.

This work is financed by the German Federal Ministry for Economics and Technology (BMWi) within the "EnOB" and "LowEx:Monitor" projects, and also by the German Federal Office for Building and Regional Planning (BBR) within the "ZukunftBau" research programme.

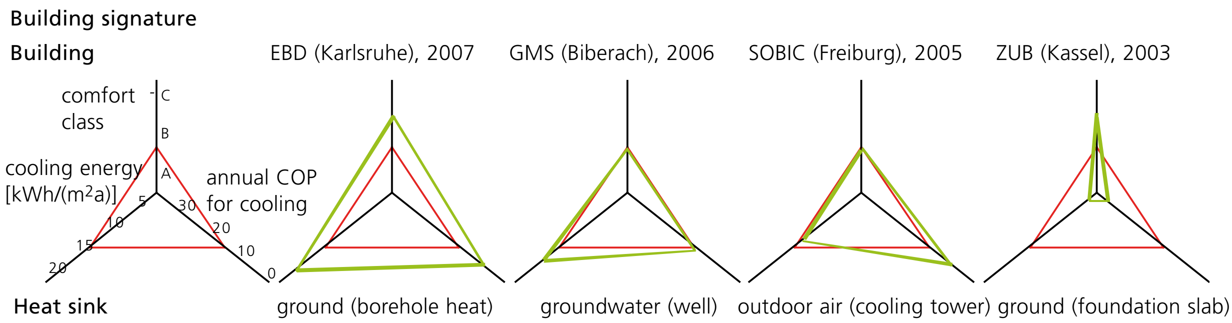


Fig. 1: Good low-exergy buildings (red) maintain a pleasant indoor climate (comfort category A) with as little energy as possible (cooling energy consumption less than 15 kWh/m^2 per year) and high efficiency (annual coefficient of performance for cooling greater than 10). The analysis of four low-exergy buildings (green) identifies the strengths and weaknesses of individual projects.
- Although the EBD building can provide a large amount of cooling energy, the incorrectly dimensioned pipe hydraulics results here in low energy efficiency and – in combination with the inadequate control options – also higher room temperatures.
- Painstaking optimisation of operation led to very good operating behaviour in the GMS building. In the SOBIC project, a cooling tower uses the night air as a heat sink; this is less efficient than using the ground.
- The ZUB building uses only the foundation slab as a heat sink. This is implemented with high efficiency but the cooling energy provided is insufficient to guarantee high thermal comfort.

Quantifying Visual Comfort under Daylight Conditions

With the aim of identifying measurable quantities to characterise the perceived visual comfort at work places, we are investigating the interaction between different parameters for visual comfort at Fraunhofer ISE. In test rooms, we determine the subjective response to different lighting situations under controllable test conditions.

Niloofar Moghbel, **Jan Wienold**, Hans-Martin Henning

In the course of our investigations in the daylighting test rooms at Fraunhofer ISE, we systematically vary the quantity and quality of the view, the lighting colour and the age of the test persons. The subjects complete various tests and fill out a questionnaire about the lighting situation under different boundary conditions. In parallel, the illuminance values on the desk and in the plane of the computer screen, and the spatially resolved luminance in the subject's field of view are measured and recorded.

In the first series of tests, which has already been completed, we investigated four different shading systems. The aim of the investigations is to identify measurable quantities which allow the perceived visual comfort to be assessed reliably. In this first series, we are concentrating our efforts on validating the Daylight Glare Probability (DGP). The Daylight Glare Probability is an index which we developed at Fraunhofer ISE in co-operation with the Danish Building Research Institute SBI within an earlier project.

The results of the investigation show that there is a significant correlation between glare evaluation by the test candidates and the Daylight Glare Probability.

The work is being funded by the German Research Foundation (DFG) within the "Quanta" basic research project.

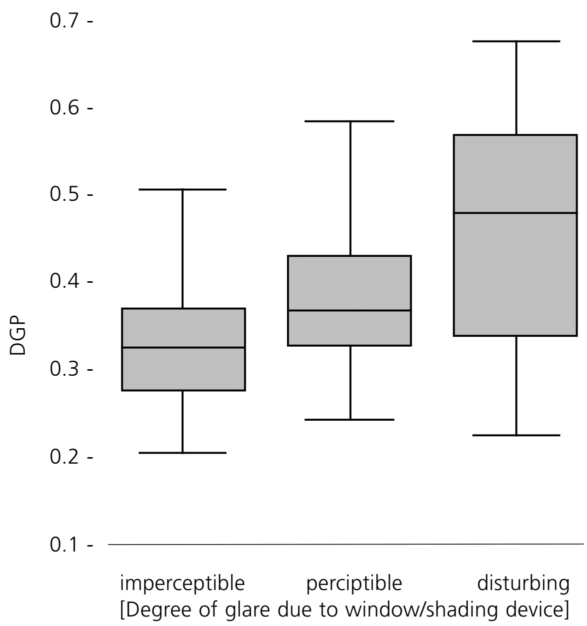


Fig. 1: Glare evaluation versus the Daylight Glare Probability. The boxes represent 50 % of the responses, the horizontal lines above and below the boxes mark the limits for all responses. Analysis of the variance demonstrates a significant correlation between the responses and the DGP value.

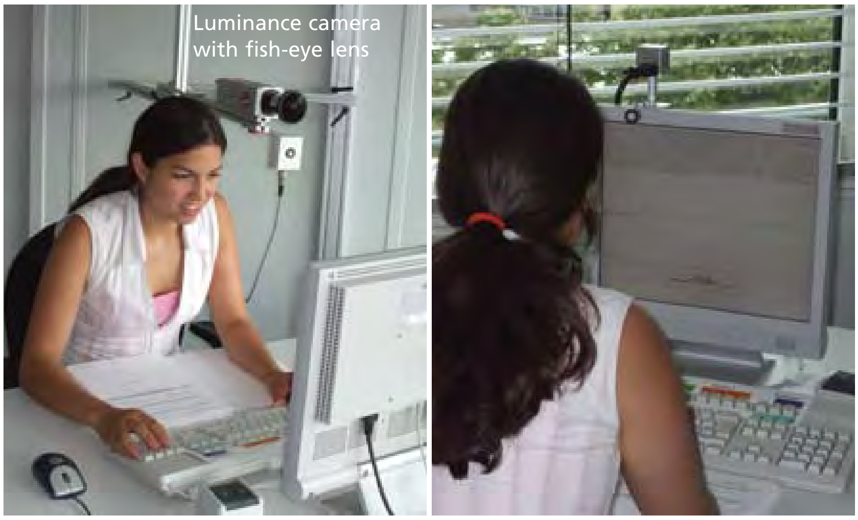


Fig. 2: Measurement configuration for the test room experiments at Fraunhofer ISE: The luminance camera to record the luminance conditions in the candidate's field of view is mounted at a distance of about 15 cm from the candidate's head (see left-hand photo). The candidates must complete various tests involving the computer screen (e.g. retyping text, in right-hand photo) and fill out a questionnaire.

Polymer Materials for Solar Thermal Applications

Solar collectors which consist completely or partly of polymer materials have the potential for considerable cost advantages compared to conventional collectors of metal and glass. However, it is necessary to find materials which meet the optical and mechanical specifications for a high-performance solar collector. In addition, the geometrical configuration must be optimised to compensate for the low thermal conductivity of polymers as far as possible. We have developed suitable simulation tools to this purpose.

Steffen Jack, Thomas Kaltenbach, **Michael Köhl**, Karl-Anders Weiß, Hans-Martin Henning

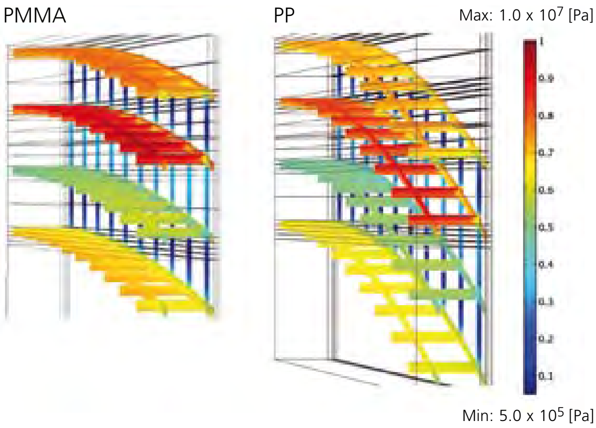


Fig. 1: The image shows the result of a mechanical simulation of absorber channels made of polymer materials. A triple-walled ribbed panel was used for the basic geometric configuration. The heat-transfer medium flows here through the central channel, which supports the overlying absorber layer. The deformation is represented on an expanded scale here, and indicates the effects of the thermal coefficient of expansion for PP (right) being greater than that for PMMA (left). The stress zones are colour-coded.

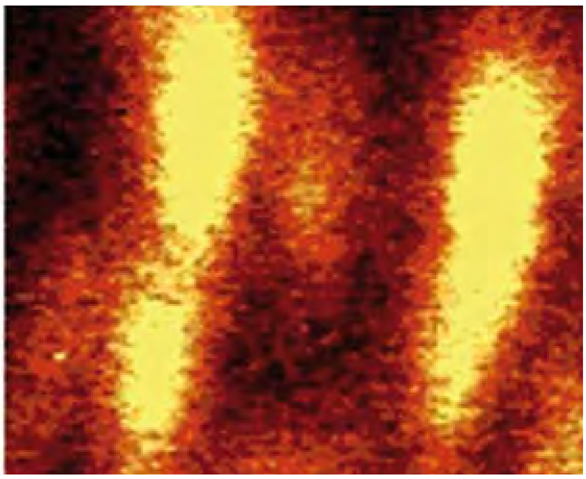


Fig. 2: Evaluation of a depth profile of a PP sample filled with carbon nanotubes, based on Raman microscopy. The scanned zone is 5 µm wide and 5 µm deep, with a resolution of 100 x 100 spectra. The light regions indicate a high intensity for carbon bands and thus represent the distribution of the nanotubes.

Within Task 39 on "Polymeric Materials for Solar Thermal Applications" of the Solar Heating and Cooling Programme of the International Energy Agency (IEA), we are co-operating with companies from the polymer and solar technology branches as well as other research institutes to design a completely new collector for appropriate system concepts. The goal is to achieve optimal system performance. The work is concentrating on the absorption of solar radiation, the thermal conductivity and the heat capacity of the new materials. A simulation tool to optimise the absorber design was developed on the basis of the "COMSOL Multiphysics" finite-element program system. This allows the flow profiles and temperature distributions to be calculated for different geometrical configurations of the channels for the heat-transfer medium, which are then used for parameter sensitivity analysis and optimisation studies. Beyond this, we also investigate the thermo-mechanical stresses which can arise due to temperature gradients in the materials and mechanical stress due to snow loads (Fig. 1).

As part of a joint project with French colleagues from the Institut National de l'Energie Solaire (INES), we succeeded in stabilising polymer materials against UV radiation and significantly increasing their thermal conductivity by the addition of nano-fillers such as carbon nanotubes. These samples are characterised and subjected to comprehensive aging tests at Fraunhofer ISE. Figure 2 shows a Raman microscopic image of a fresh PP sample, in which the spatial distribution of the nanotubes is clearly visible.

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

Measurement and Analysis of a Building Clad with a Composite Vacuum-Insulation Panel (VIP) System

On a demonstration building, we tested a practicable composite thermal insulation system based on vacuum insulation panels that had been developed at Fraunhofer ISE. The system is distinguished by slim dimensions, minimal thermal bridges, protection against damage and good adaptability to building tolerances. Damage-free installation of the insulation, including necessary adaptations at the building site, was accomplished without any problems by local tradespeople. Measurement results have demonstrated the functionality of the system.

Christel Russ, Thomas Schmidt,
Werner Platzer

In order to achieve the thermal insulation values needed to meet modern expectations ($U_W < 0.3$ $Wm^{-2}K^{-1}$), double-layer walls with external insulation are often used. Composite exterior insulation and finish (EIF) systems present an inexpensive option. Insulating panels with a thickness of 200 – 300 mm occupy a large volume and can be architecturally undesirable.

Together with our industrial partners, Porextherm Dämmstoffe GmbH and maxit Deutschland, we have developed a complete composite thermal insulation system based on vacuum insulation panels (VIP) with the same insulating effect as conventional systems, which features a number of advantages:
- only a limited number of standard dimensions necessary for the panels
- protection against damage
- flexible adaptation to required dimensions
- easily planned penetration points
- minimised thermal bridges

As a demonstration object, a free-standing house was clad with the 90 mm thick insulation system (the passive-house variant is 110 mm thick) and equipped with measurement technology for monitoring. The results demonstrated the simple planning process, damage-free and quick installation by local tradespeople and the functionality of the system. A U value of $U_W < 0.13$ $Wm^{-2}K^{-1}$ was achieved for the façade,

Fig. 1: A demonstration building clad with the 90 mm thick, composite VIP insulating system (free-standing house near Giengen/Brenz). The U value for the wall: $U_W = 0.13$ $Wm^{-2}K^{-1}$.

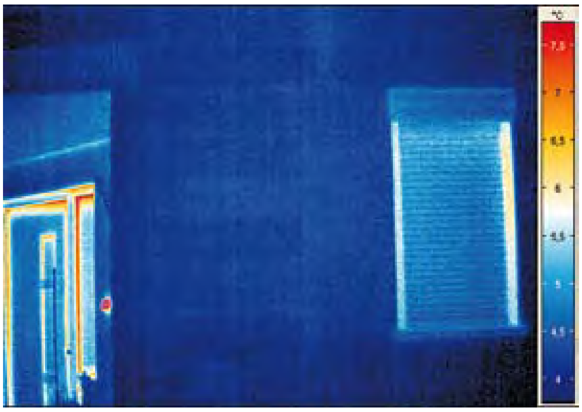


Fig. 2: Thermograph showing a detail of the south-east façade; the somewhat colder (darker) horizontal stripes corresponding to the cover panels can be recognised (temperature difference of about 0.1 K between the regions). There is no evidence of damage to the system.

whereby only three different panel dimensions were used. This indicates that the requirements for cost-effective mass production are fulfilled. The pre-requisites for authorisation as a building product are currently being checked by the "Deutsches Institut für Bautechnik" in Berlin.

The work was financed by the German Federal Ministry for Economics and Technology (BMWi) as part of the "VIBau" project (www.enob.info).

Applied Optics and Functional Surfaces

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 and diverse challenges. To overcome 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, "Applied Optics and Functional Surfaces", is the basis for several market sectors of solar technology: windows and façades, solar thermal collectors, concentrating systems for photovoltaics and solar-thermal power stations, and photovoltaic module technology. 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. Gaso-chromic glazing, in which the absorption can be varied over a wide range, has already been tested successfully in demonstration façades. Glazing units with very good thermally insulating properties show condensation and even frost on the external surface during certain days in winter. In order to reduce these unwanted side-effects, stable low-e coatings are being developed for the outdoor surface.

Microstructured surfaces form the basis for solar-control systems which reflect undesired direct solar radiation but still transmit diffuse daylight. Photonic gratings and light-trapping structures increase the efficiency of organic and silicon solar cells. In photovoltaic concentrator modules, solar radiation is concentrated onto tiny high-performance solar cells. We optimise concentrator optics with regard to its efficiency and cost.

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 and light scattering are central topics 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 (up to 450 °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.

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 by 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 the accuracy of reflector forms with scanning fringe reflectometry. Whenever needed, we extend the palette of services by close co-operation with recognised research institutions within and outside the Fraunhofer-Gesellschaft.

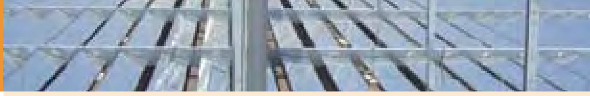
Special facilities:
- vacuum deposition system for quasi-industrial production of complex coating systems over large areas (140 cm x 180 cm)
- interference-lithography equipment for homogeneous production of microstructures and nanostructures over areas of up to 120 cm x 120 cm
- optical measurement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

Applied Optics and Functional Surfaces

FRESDEMO test collector at the Plataforma Solar de Almería in Spain. This collector was used to prove the technical feasibility and practical operation of Fresnel technology with direct evaporation in relevant dimensions for the first time. Fraunhofer ISE optimised the collector design to achieve the target of minimal specific electricity generation costs. A series of freely selectable parameters such as the number of reflector rows and the form of the secondary reflectors were taken into account. The industrial partners, Solar Power/MAN Ferrostaal Power Industry were responsible for the construction. Fraunhofer ISE produced the coatings for the key components, the receiver tube and the secondary reflector.

Contacts

Applied Optics and Functional Surfaces	Dr Werner Platzer	Tel.: +49 (0) 7 61/45 88-59 83 E-mail: Werner.Platzer@ise.fraunhofer.de
Coating – technology and systems	Wolfgang Graf	Tel.: +49 (0) 7 61/45 88-59 46 E-mail: Wolfgang.Graf@ise.fraunhofer.de
Microstructured surfaces	Dr Benedikt Bläsi	Tel.: +49 (0) 7 61/45 88-59 95 E-mail: Benedikt.Blaesi@ise.fraunhofer.de
Lighting technology and solar concentration	Dr Peter Nitz	Tel.: +49 (0) 7 61/45 88-54 10 E-mail: Peter.Nitz@ise.fraunhofer.de
Solar power plants	Gabriel Morin	Tel.: +49 (0) 7 61/45 88-59 94 E-mail: Gabriel.Morin@ise.fraunhofer.de
Lighting technology/ Building applications	Jan Wienold	Tel.: +49 (0) 7 61/45 88-51 33 E-mail: Jan.Wienold@ise.fraunhofer.de
Dye solar cells	Dr Andreas Hinsch	Tel.: +49 (0) 7 61/45 88-54 17 E-mail: Andreas.Hinsch@ise.fraunhofer.de
Organic solar cells	Dr Michael Niggemann	Tel.: +49 (0) 7 61/45 88-54 58 E-mail: Michael.Niggemann@ise.fraunhofer.de
Photovoltaic modules/ PV module pilot laboratory	Dr Harry Wirth	Tel.: +49 (0) 7 61/45 88-51 93 E-mail: Harry.Wirth@ise.fraunhofer.de
Display technology	Dr Benedikt Bläsi	Tel.: +49 (0) 7 61/45 88-59 95 E-mail: Benedikt.Blaesi@ise.fraunhofer.de



High-T-Resistant Absorber Coating for Fresnel Collectors

In contrast to a parabolic trough collector with its evacuated receiver, a Fresnel collector needs a selectively coated absorber pipe, with a coating which is stable in air at high collector temperatures of up to 450 °C. No commercial absorber coating which has been produced to date meets this specification. At Fraunhofer ISE, we have developed a suitable coating, which has been subjected to a field test since 2007 on a 100 m long absorber pipe in the demonstration Fresnel collector at the Plataforma Solar de Almería (see page 35).

Andreas Georg, Wolfgang Graf,
Christina Hildebrandt, Gabriel Morin,
Werner Platzer

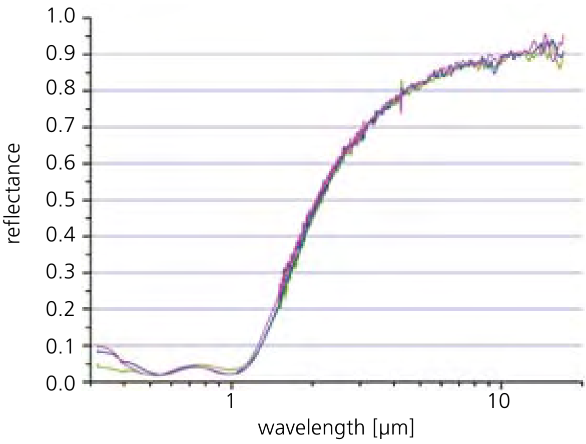


Fig. 1: Unchanged reflectance spectra of the absorber coating on stainless steel after initial tempering of the coating (green), after 300 h (blue) and 925 h (magenta) at 500 °C in air. Practically no change has occurred.

In sputtered, selective cermet absorber coatings, an underlying metal reflector ensures low emission in the IR radiation range and thus low thermal losses from the receiver, whereas the cermet together with an anti-reflective layer is responsible for strong absorption of the solar radiation.

By carrying out optical simulations of these thin-film systems, we investigate the potential of different materials regarding their absorption and emission. However, it is equally important that the individual layers are stable in air at the high operating temperatures of up to 450 °C. In addition to diffusion processes between the substrate material and the absorber coating, oxidation of individual layers or constituent materials can also result in degradation of the selective absorber.

We can trace degradation processes very accurately with durability tests and accompanying optical measurements. More information about the nature of the degradation is provided by surface and material analyses by SEM (scanning electron microscopy) or AES (Auger electron spectroscopy). This information is important in determining the next steps to be taken in the development process and if necessary, to counteract degradation processes with adhesion and barrier layers. The developed coating is stable in air at 500 °C for more than 1000 h and is characterised by an absorptance of 94 % and an emittance of 15 % (relative to a Planck black-body radiator at 380 °C) or 18 % (at 450 °C).

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

Fig. 2: We deposited the selective absorber coating that we had developed onto 100 m of absorber pipe for the demonstration Fresnel collector at the Plataforma Solar de Almería. The photo shows the coated absorber pipes and sputtering equipment which can be used for pilot production series.

Gasochromic Façade Systems

Over the past years, we have developed the foundations for variable solar control based on the gasochromic effect. Together with its industrial partners, Fraunhofer ISE is currently working on the technical implementation. Valuable experience with installation, commissioning, operation and maintenance of the systems can be gained from several new test and demonstration façades. Introduction to the market is in preparation.

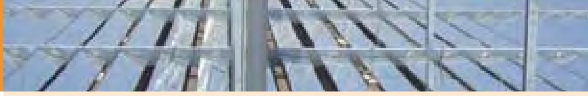
Andreas Georg, **Wolfgang Graf**, Josef Steinhart, Armin Zastrow, Werner Platzer

Fig. 1: Switchable gasochromic façade, installed in a building belonging to the company, Werner Herr GmbH, in Ebringen (September 2008). Aspect of the complete façade in the switched state, viewed from the south-west.

Buildings with good thermal insulation and large glazed areas require some form of solar control to ensure user comfort combined with a low energy consumption for cooling. At Fraunhofer ISE, we are developing solar-control glazing based on the gasochromic effect. This is evident as colouring of the tungsten oxide films which are deposited on the inner surface of the panes, and is caused by reduction of W^{6+} ions to W^{5+}. In contrast to the electrochromic effect, the reversible reduction in gasochromic technology is caused not by electrons injected into the layer but by a minimal concentration of hydrogen that is introduced into the gap between two panes. Gasochromic systems have the advantage that even very large glazed areas with complicated geometric forms can be switched quickly and reliably. They consist of a multiple glazing unit which includes the active, inner coating of WO_3, a gas supply unit (electrolyser) to provide hydrogen and oxygen for each of the façade components (up to 12 m^2) and an electronic controller for the entire system.

Within a project which is funded by the German Federal Ministry for Economics and Technology (BMWi), we are working on detailed improvements for all components and are gaining further experience concerning the systems technology, with the aim of designing a system which is as user-friendly as possible.

Fig. 2: Switchable gasochromic test façade at the Solarhaus Freiburg (January 2008).



Optical Nanostructures for Photovoltaics

New approaches to the optics of solar cells mean that their efficiency can be further increased. Optical nanostructures can be used to select light spectrally or as a function of angle, or to guide the light into a system in a specific direction so that it can be used optimally. These processes are described by the term "photon management". We work on the simulation, production and integration of optical nanostructures in solar systems and characterise their effect.

Benedikt Bläsi, Jan Christoph Goldschmidt, Hubert Hauser, **Marius Peters***, Marcel Pfeifer, Werner Platzer

* Freiburger Materialforschungszentrum FMF, Albert-Ludwigs-Universität Freiburg

The efficiency of solar cells can be increased with optical structures. On the front surface of the cell, they enable light to penetrate better and broaden the angular acceptance range. With the help of nanostructures (e.g. photonic crystals), light can be selected spectrally or as a function of angle, or guided into a system in a specific direction. This lengthens the light path and thus increases absorption within the solar cell. This approach is known as light trapping, and is particularly important for material-conserving thin silicon solar cells. Due to the weak absorptance in the long-wavelength spectral range, the photons would otherwise not be absorbed completely.

Wave optics must be applied to calculate the optical effects correctly. To do so, we use rigorous coupled wave analysis (RCWA). This allows exact determination of the electromagnetic field in almost any arbitrary structure. We use it to simulate and optimise both the optical properties and also their effect on the generation of electricity in the solar cell.

At present we are working on the following applications for structures with dimensions of the same order of magnitude as the wavelength of light:

- back surface gratings for silicon solar cells to increase the absorption efficiency in the low-absorptance spectral range (> 900 nm).
- wavelength-selective filters to increase the light-guiding efficiency in fluorescent concentrators by eliminating the most significant loss mechanism, the loss cone due to total internal reflection
- wavelength-selective filters for spectral separation into light traps. A corresponding system has been patented and is currently being constructed.
- angle-selective filters to suppress photon losses in III-V solar cells

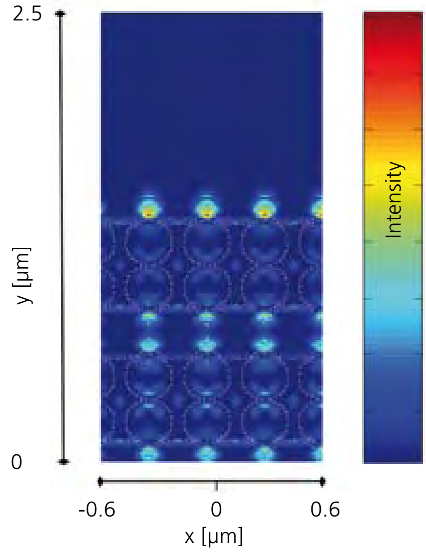


Fig. 1: RCWA simulation of the electromagnetic field within a photonic structure. The image shows the calculated intensity of the z component of the electric field. The photonic structure is indicated by the light dashed line. The structure is three-dimensional; the image shows a cross-section along the z axis.

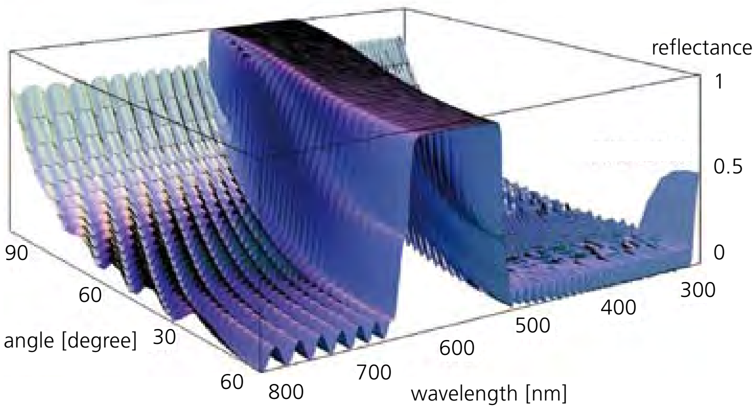


Fig. 2: Angular selectivity of a rugate filter. The zone with high reflectance shifts towards shorter wavelengths as the angle increases. This property can be used to construct a very efficient light trap for the spectral range where the shift occurs.

- angle-selective filters for use in light traps with extreme lengthening of the light path. We were able to demonstrate that in this case, extremely strong light-trapping effects are to be expected.

For the concept of the angle-selective light trap, a filter is needed which transmits light from within a narrow angular range around the sun and reflects light from all other directions. In the system, the light is scattered and reflected by the back surface. A large proportion of the reflected light can no longer pass through the filter, as it is incident under angles for which the filter reflects. As a result, the light remains trapped in the system. In this way, the light path within a system can be lengthened by a factor of maximally 46,200. Initial measurements with corresponding structures demonstrate increased absorption in silicon near the band edge.

Increasing the efficiency of fluorescent concentrators is a further example. In these concentrators, dyes absorb light and subsequently emit it at a longer wavelength. This is guided to solar cells at the edges of the concentrator by total internal reflection. The advantages of this system are the reduction in solar cell area needed and the ability to concentrate diffuse light. An interference filter, a thin-film stack with an optical band edge which selectively reflects only the emitted light, increases the efficiency of a fluorescent concentrator system by a relative value of 20 %. At present, the total efficiency of 3.1 % for an area of 50 cm^2 is still low, but due to the system concentration by a factor of 20, it still supplies 3.7 x more energy than the solar cells without an additional concentrator.

This work was supported by the German Research Foundation (DFG) within the "Nanosun" project (PAK88) and by the German Federal Ministry for Education and Research (BMBF) within the "Nanovolt" project.

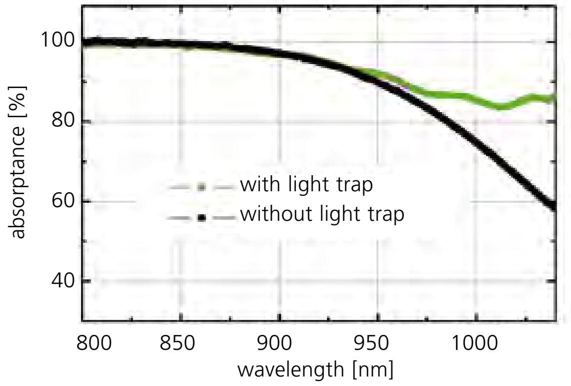


Fig. 3: Measured increase in the absorptance of a thin silicon wafer (40 μm) with and without a light trap. The filter used here has a reflectance edge at 1050 nm. In the spectral range below the reflectance peak, between 900 nm and 1050 nm, the absorption in the silicon has been enhanced by applying the filter.

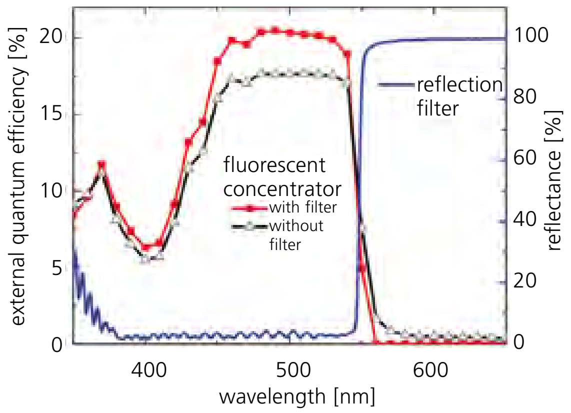
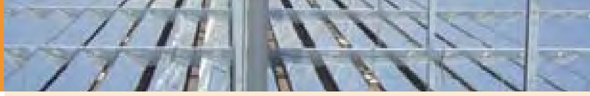


Fig. 4: The measured external quantum efficiency of a fluorescent concentrator system, with and without a photonic structure. The energy-selective filter transmits the light which can be absorbed by the dye almost unhindered. However, it reflects strongly in the emission range of the dye around 600 nm and thus ensures that almost all the light in the concentrator is guided to the edges. This increases the efficiency significantly.

Fig. 5: This sample from the early years of Fraunhofer ISE demonstrates how the light is directed to the edges of the fluorescent concentrator.



Optimisation of Optics for Concentrator Photovoltaics

In large power plants with concentrating photovoltaic modules, not just instantaneous peak values of the module efficiency are decisive but the total annual yield gained in operation. Thus, it is necessary to adapt the system to variable environmental conditions. We have set up measurement stands for spectral and temperature-dependent characterisation of concentrator systems and material properties. The measurement results are input into computer simulations, which are used to optimise the concentrator optics.

Martin Neubauer, **Peter Nitz**, Thomas Schmidt, Thorsten Schult, Werner Platzer

The optical systems used to concentrate light in solar power plants with concentrator photovoltaics (CPV) are subjected to many different environmental effects. In order to achieve the maximum possible electricity yield over the whole year, it is not sufficient to investigate the system only under standard conditions. Instead, the environmental influences on the optical components must be analysed and the system adapted and optimised for variable conditions. Among these influences, the spectral distribution of the incident light and the temperature of the optical components are particularly significant.

In systems which concentrate the sunlight by refraction (refractive optics, e.g. the Fresnel lenses of the FLATCON® system), the refractive index of the lens material is decisive for focusing. Even changes of a few parts per thousand in the refractive index can have noticeable effects on the focal volume of the optics. To optimise the complete system, a very accurate and comprehensive set of refractive index data is needed, which is seldom available for the materials used. At Fraunhofer ISE, we have established a measurement stand with which

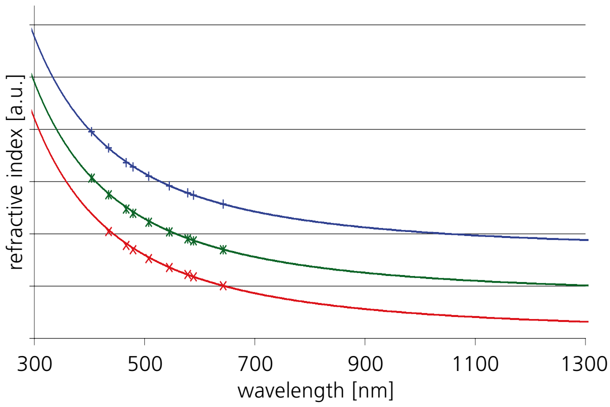


Fig. 1: Spectral dependence of the refractive index of a material which is used to produce concentrator lenses. The spectra are shown for three different temperatures which are relevant to operation. The plotted points are the results of our refractometer measurements.

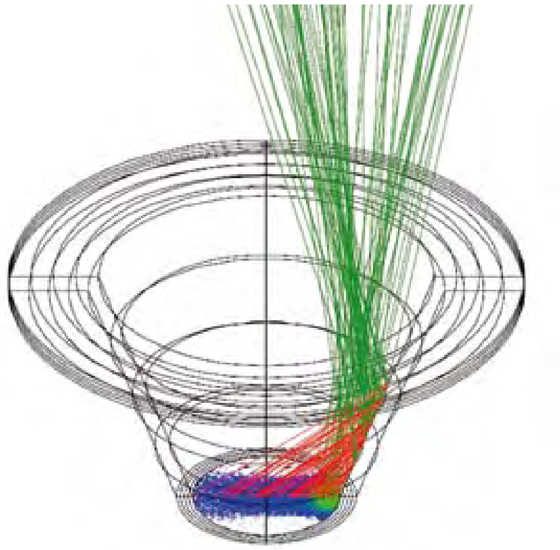


Fig. 2: Visualisation of ray-tracing simulation for a reflecting secondary concentrator under a Fresnel lens, for slight misalignment due to the optics being tilted with respect to the sun’s position. Only a cross-section through the bundle of rays incident on the secondary concentrator is shown. The light intensity on the solar cell is colour-coded from low (blue) to high (green).

the spectral and temperature dependence of the refractive index can be determined with an absolute accuracy of up to 5 x 10^{-5} (Fig. 1).

The results of such refractive index measurements are input into ray-tracing simulations, with which we investigate the effect of the temperature and the solar spectrum on the functionality of individual optical components and the yield of the complete system. We also use computers to model the influence of production tolerances and deviations in the solar tracking. As an example, Fig. 2 shows a fraction of the rays focused by the Fresnel lens. The bundle of rays is shifted sideways if the lens is misaligned and thus is partly incident on a secondary concentrator.

Optical measurement of the concentrator system in our lens measurement stand allows simulations to be validated directly by experiment and enables direct assessment of the production quality under well-defined conditions. We can use light of different wavelengths to this purpose and carry out measurements at different component temperatures. The radiation distribution in the focal volume of the optics is detected, as is shown in Figures 3 and 4. With this measurement facility, we can thus identify and analyse the source of optical losses and then eliminate their cause. This contributes to process control, quality assurance and optimisation of industrial production processes for concentrating optics.

The described instruments allow comprehensive characterisation and optimisation of concentrators for CPV systems, whereby the ambient conditions are not arbitrary or instantaneous combinations, but can be selected and modified deliberately. The results constitute an important input to future predictions of the total annual yield of a system in real operation under specified climatic conditions, which can then be used to optimise the system.

The work was carried out within the "Prokon-PV" project and was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and an industrial partner.

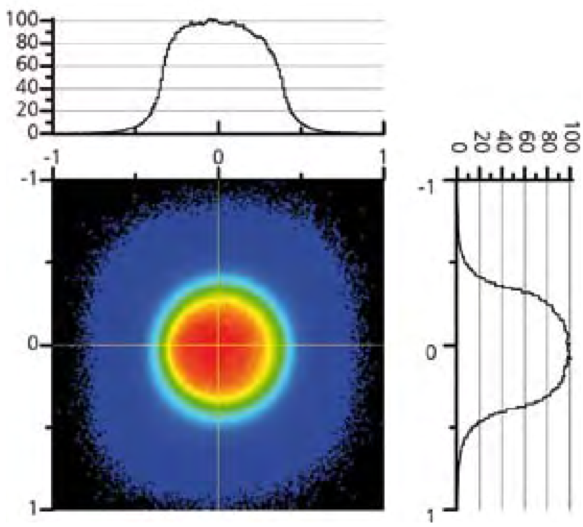


Fig. 3: Radiation distribution in the focal plane of concentrating optics for a defined reference temperature and illumination with monochromatic light. The light intensity is colour-coded in percentage values from low (blue) to high (red). Cross-sections along the indicated lines are plotted in the inserts at the top and the side.

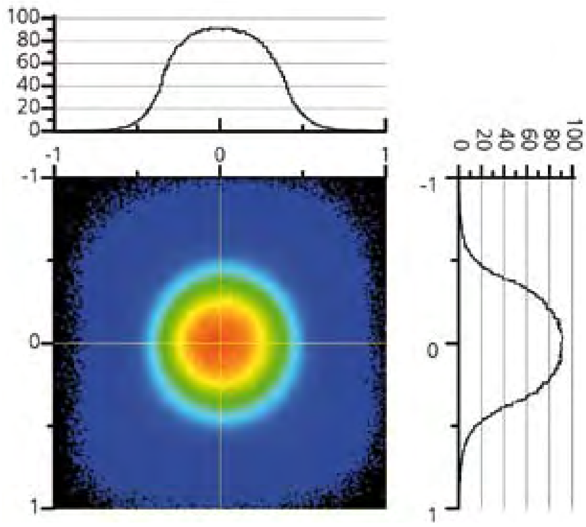
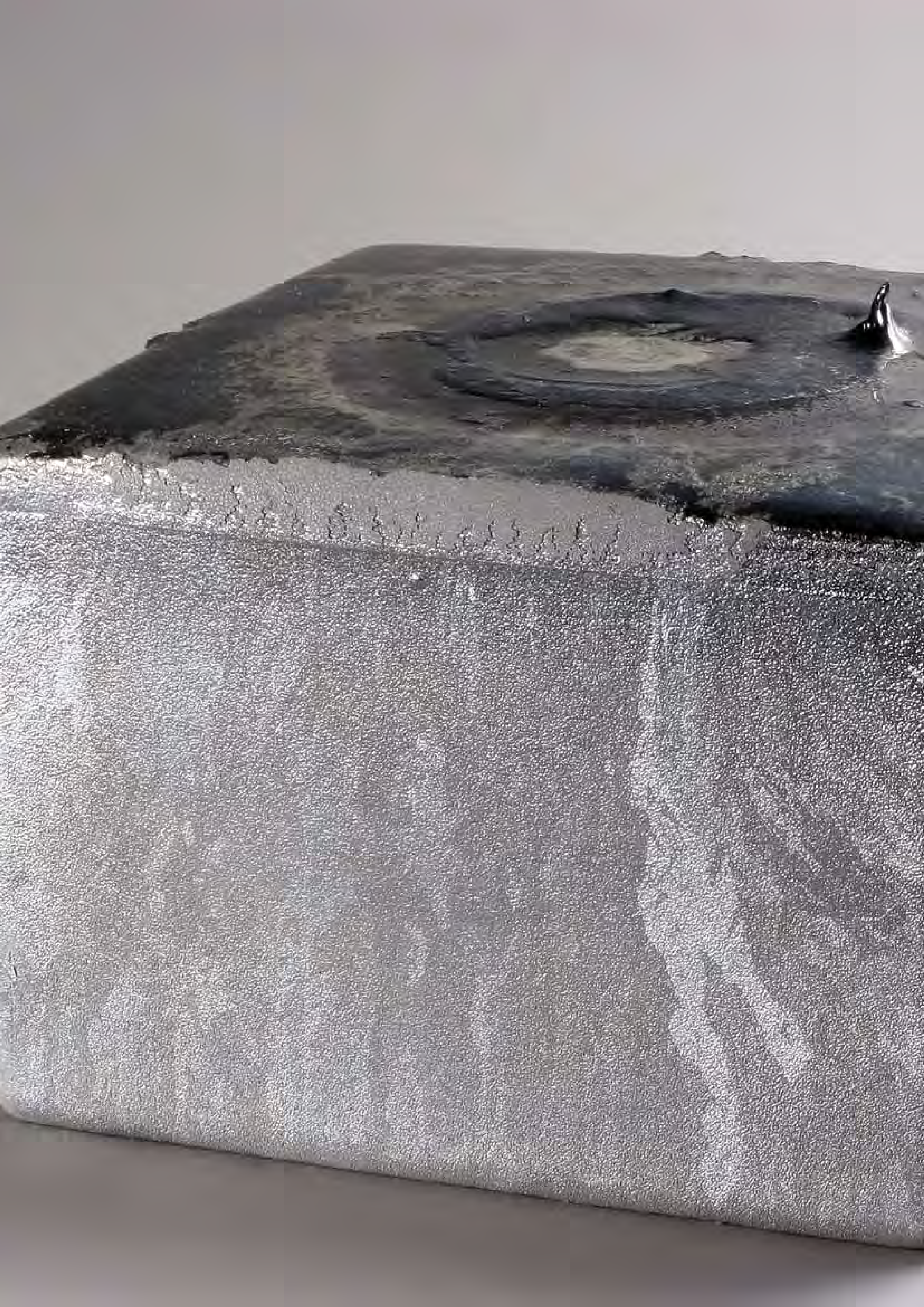


Fig. 4: Radiation distribution in the focal plane of the same concentrating optics as in Fig. 3, but measured at an elevated temperature. Deterioration of the concentration is clearly evident.



Silicon Photovoltaics

Photovoltaics has experienced a boom for more than ten years, which was encouraged particularly by the targeted market introduction programmes in Germany, Spain and other European countries: The globally installed peak power capacity increased during this period from a few hundred MW to more than 10 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 expand our R & D offer over the complete value chain for crystalline silicon photovoltaics, we have significantly intensified our activities on silicon materials development, particularly crystallisation and wafering. In the autumn of 2008, we commissioned the Silicon Material Technology and Evaluation Centre SIMTEC. Our work in this new research centre encompasses epitaxial production of silicon films, the analysis of diverse silicon feedstock materials including novel substances, and materials and processing issues concerning the relevant types of technology. The new laboratories in Freiburg include a crystallisation facility, with which multicrystalline blocks weighing up to 250 kg can be produced. Our scientific work here focuses on adapting the crystallisation processes to each particular type of solar silicon. A new focus in our work is the development of solar cell processes based on the use of purified metallurgical grade silicon PMG.

In our Photovoltaic Technology Evaluation Centre PV-TEC, we can produce both solar cells with screen-printed contacts, as are common in industry, and also solar cells with high-quality surface passivation on a pilot scale, i.e. with a throughput of more than 100 wafers per hour. Furthermore, we have adapted our processes and pilot equipment to the special requirements of very thin solar cells.

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 work at all stages from development to industrial implementation.

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.

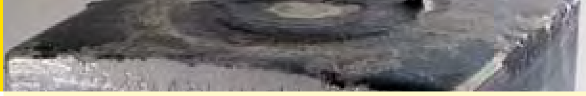
Our activities on silicon solar cells in Freiburg are complemented by the Fraunhofer ISE Laboratory and Service Centre in Gelsenkirchen, Nordrhein-Westfalen, the Technology Centre for Semiconductor Materials THM in Freiberg, Sachsen, which is operated jointly with Fraunhofer IISB, and the Fraunhofer Centre for Silicon Photovoltaics CSP in Halle, which is operated jointly with Fraunhofer IWM. CSP has been supported since 2008 within the German Federal programme for regional clusters of excellence, "Solar Valley Mitteldeutschland" (see page 61).

Silicon Photovoltaics

Multicrystalline block (85 kg silicon) with a base area of 42 x 42 cm^2 and a height of 21 cm, corresponding to 2 x 2 columns, each with a finished vertical edge length of 156 mm. The columnar crystals which grew from the bottom to the top are clearly visible. This structure is a fundamental pre-requisite for high-efficiency solar cells.

Contacts

Silicon photovoltaics	Dr Ralf Preu	Tel.: +49 (0) 7 61/45 88-52 60 E-mail: Ralf.Preu@ise.fraunhofer.de
Silicon photovoltaics	Dr Stefan Glunz	Tel.: +49 (0) 7 61/45 88-51 91 E-mail: Stefan.Glunz@ise.fraunhofer.de
Silicon photovoltaics/ Alternative Photovoltaic Technology	Dr Andreas Bett	Tel.: +49 (0) 7 61/45 88-52 57 E-mail: Andreas.Bett@ise.fraunhofer.de
Silicon material, crystallisation and processing	Dr Stephan Riepe	Tel.: +49 (0) 7 61/45 88-56 36 E-mail: Stephan.Riepe@ise.fraunhofer.de
Crystalline silicon high- efficiency solar cells	Dr Martin Hermle	Tel.: +49 (0) 7 61/45 88-52 65 E-mail: Martin.Hermle@ise.fraunhofer.de
Crystalline silicon thin-film solar cells	Dr Stefan Reber	Tel.: +49 (0) 7 61/45 88-56 34 E-mail: Stefan.Reber@ise.fraunhofer.de
Solar cell processing technology/PV-TEC	Dr Ralf Preu	Tel.: +49 (0) 7 61/45 88-52 60 E-mail: Ralf.Preu@ise.fraunhofer.de
Concentrator technology	Dr Andreas Bett	Tel.: +49 (0) 7 61/45 88-52 57 E-mail: Andreas.Bett@ise.fraunhofer.de
Characterisation of solar cells and materials	Dr Wilhelm Warta	Tel.: +49 (0) 7 61/45 88-51 92 E-mail: Wilhelm.Warta@ise.fraunhofer.de
Photovoltaic modules/ Module pilot laboratory	Dr Harry Wirth	Tel.: +49 (0) 7 61/45 88-51 93 E-mail: Harry.Wirth@ise.fraunhofer.de
Laboratory and Service Centre, Gelsenkirchen	Dr Dietmar Borchert	Tel.: +49 (0) 2 09/1 55 39-13 E-mail: Dietmar.Borchert@ise.fraunhofer.de
Technology Centre for Semiconductor Materials THM, Freiberg	Prof. Roland Schindler	Tel.: +49 (0) 1 617 253 0142 E-mail: rschindler@fraunhofer.org
Fraunhofer Centre for Silicon Photovoltaics CSP, Halle/Saale	Prof. Gerhard Willeke	Tel.: +49 (0) 3 45/55 89-168 E-mail: Gerhard.Willeke@csp.fraunhofer.de



SIMTEC – Silicon Material Technology and Evaluation Centre

We have established the Silicon Material Technology and Evaluation Centre SIMTEC in order to intensify our work on the early processing steps in the value chain of silicon wafer technology. This new research and development platform at Fraunhofer ISE has more than 1000 m^2 of laboratory area at its disposal. We conduct investigations there on silicon feedstock material, block crystallisation and crucible coating. Block processing, wafering and high-throughput silicon epitaxy are also included among our research services.

Martin Arnold, Yaniss Bdioui, Fridolin Haas, Teresa Orellana, David Pocza, Stefan Reber, **Stephan Riepe**, Norbert Schilllinger, Mark Schumann, Matthias Singh, Andreas Bett

At present, several new processes are being developed and established around the world to purify metallurgical-grade silicon cost-effectively for solar cells. Independent evaluation of the produced materials, from crystallisation through to the solar cell, is essential to facilitate rapid growth of photovoltaics far beyond the current production capacity. By establishing SIMTEC, we have filled a gap and can now reproduce all processing steps at Fraunhofer ISE, so that we can offer qualified and comprehensive analysis under one roof of the various intermediate steps up to the finished solar cell.

Complementing the existing laboratories, SIMTEC is our research centre for silicon materials evaluation and technological development. Our work encompasses not only the analysis of diverse and new feedstock materials, but also the materials and processing aspects of the technological steps used to prepare them:

Fig. 1: Crystallisation from silicon feedstock covering a wide quality range is our first research focus within the silicon value chain. The photo shows feedstock in a quartz crucible for a block weighing 85 kg. The crystallised block is illustrated in the introduction to the chapter on silicon photovoltaics. (see page 42).

Fig. 2: We can study different approaches to directional solidification with individual process control in our crystallisation unit, where blocks with variable dimensions from 20 kg to 250 kg can be solidified. In the photo, the open furnace can be seen with a graphite support crucible for a Si block weighing 85 kg.

- directional solidification of multicrystalline blocks
- block processing by sawing and grinding columns
- wafer cutting by multi-wire saws
- silicon deposition/epitaxy in high-throughput processes

We accompany all of the listed technological steps by numerous analytical methods and simulation which are available either on site at SIMTEC or in other laboratories of Fraunhofer ISE.

For the chemical analysis of the feedstock, we are developing a standardised procedure with various analytical methods which allow an initial estimate of the material's potential for solar cell processing. In order to minimise the introduction of additional impurities to the material, we are investigating crucible systems and coatings with enhanced purity that also cost less. The crystallisation itself occurs as directional solidification according to the vertical gradient freeze (VGF) process with active cooling in an industrial but still very flexible crystallisation facility. By controlled influence of the crystallisation procedure, we aim to achieve faster solidification parallel to improved crystal quality, and thus increase the quality of the process. As the first step, we developed a crystallisation programme for a medium crucible size of 85 kg. This allows our work to be more effective and focused than when dealing with the process for 250 kg which has also been established. For fundamental investigations concerning material properties and crystallisation, we can also offer a block mass of 20 kg. The block is processed with a band saw which can be used very flexibly to prepare arbitrary columnar forms and smaller samples for characterisation purposes. In addition, the columns can be ground and chamfered in SIMTEC before wafering. We optimise the wafering process – the interface to solar cell processing – by investigating various mixtures of cutting agents and the subsequent wafer cleaning. One particularly successful result of work at SIMTEC has been the cutting of wafers that are only 70 µm thin.

Another technological focus of our work is the deposition and epitaxy of extremely pure silicon films by the chemical vapour deposition process. We develop deposition units which allow continuous operation and a high throughput. With these units, we can implement e.g. the EpiCell concept (see page 48).

The establishment of SIMTEC was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Fraunhofer-Gesellschaft.

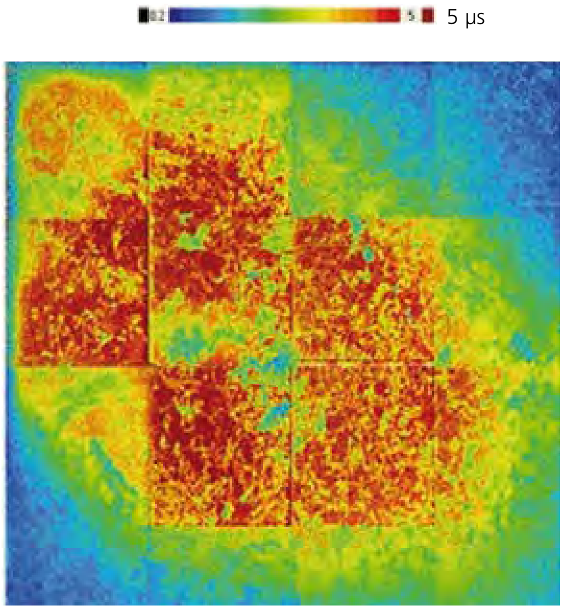


Fig. 3: In our characterisation laboratory, we can already make an initial quality estimate for the cut columns of the block. The image shows the spatial distribution of the charge carrier lifetime over a horizontal cross-section through the cap of a Si block with a base area of app. 62 cm x 62 cm. The pronounced inhomogeneity is attributed to uneven solidification, among other causes.

Work towards Cost-Effective Epitaxial Thin-Film Solar Cells

Our strategy to develop cost-effective thin-film solar cells is following the approach of preparing a high-quality silicon film on inexpensive silicon substrates. We aim to save costs and simultaneously achieve a high solar cell efficiency value. After very successful steps demonstrating the "proof of concept", further development up to production maturity is on the agenda. We are applying ourselves to this complex task in the new SIMTEC laboratory (see pages 46–47), where we are developing both the necessary equipment and processes.

Martin Arnold, Marion Drießen, Elke Gust, Fridolin Haas, Fabian Kiefer, Miroslawa Kwiatkowska, Harald Lautenschlager, Stefan Lindekugel, David Pocza, **Stefan Reber**, Stephan Riepe, Norbert Schillinger, Evelyn Schmich, Mark Schumann, Matthias Singh, Andreas Bett

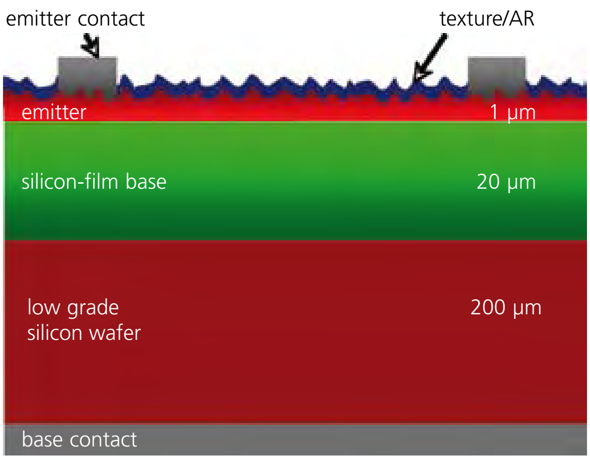
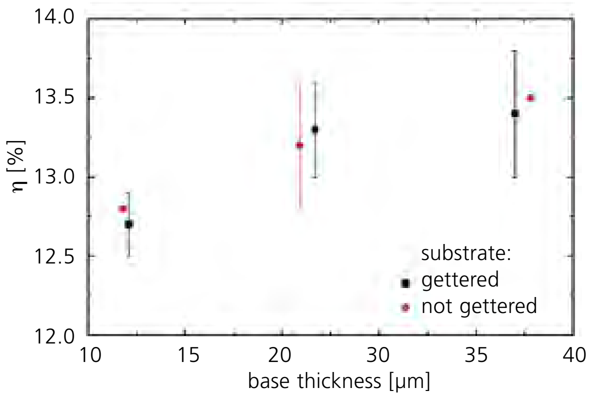


Fig. 1: Schematic cross-section through the EpiCell. A thin silicon film is grown epitaxially on a multicrystalline or monocrystalline substrate, i.e. the film has the same crystal structure as the substrate. The film is of very high quality and thus offers the potential for an efficient solar cell. The combined film and substrate can be further processed with conventional technology to produce a solar cell and then be included in a module.



An epitaxial wafer equivalent is based on the idea of applying a thin film of extremely pure silicon onto a wafer of impure silicon material and then further processing it into a high-efficiency solar cell. We produce the epitaxial film by chemical vapour deposition. The resulting structure – the epitaxial wafer equivalent – can be processed with conventional solar cell technological procedures to create a so-called "EpiCell" (see Fig. 1). Two issues must be addressed to transfer this concept to production maturity: On the one hand, high-throughput epitaxial equipment had to be designed, on the other hand, a suitable, cost-effective substrate had to be developed. We are working on both aspects in the new SIMTEC research laboratory. There, we are designing and constructing two continuously operating silicon-deposition facilities, the ConCVD as a prototype system with a throughput of 1 m^2/h, and the ProConCVD production system with a planned throughput of 15 m^2/h.

Previously, we had little influence on substrate production for the EpiCell, as it was carried out by external partners. With SIMTEC, we have now succeeded for the first time in implementing all of the processing steps ourselves from the feedstock silicon up to the EpiCell. Up to now, the crystallisation of four silicon blocks weighing 250 kg or 85 kg for EpiCell substrates has already achieved good quality: the EpiCell efficiency values obtained by use of these substrates reached 13.9 %. This is only slightly lower than our record value of 14.3 % using externally produced substrates with otherwise identical conditions.

The project was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Fraunhofer-Gesellschaft.

Fig. 2: Efficiency values of EpiCells that were completely produced at Fraunhofer ISE: It is evident that the efficiency value increases with the thickness of the base. However, a saturation limit is reached, indicating that the film quality can still be improved. One approach is gettering, a procedure in which metals such as iron are removed from the substrate. The fact that the difference in efficiency value between gettered and untreated substrates is only small indicates that the crystallisation has already provided a very pure substrate.

Screen-Printed Solar Cells with Thermally Stable Back-Surface Passivation

Solar cells with passivated and locally contacted back surfaces are becoming increasingly important also for industrial production. When the metallisation technology based on screen printing continues to be used, not only the passivation quality itself will be important for the back-surface passivation but also high thermal stability. We have already achieved significant improvement in the efficiency for thin Cz-Si wafers with thin-film stacks of SiO_xN_y *and* SiN_x*, which were deposited using the PECVD process developed at Fraunhofer ISE.*

Dietmar Borchert, Luca Gautero, Marc Hofmann, Sinje Keipert, **Jochen Rentsch**, Markus Rinio, Pierre Saint-Cast, Johannes Seiffe, Ralf Preu

Cell concepts with passivated and locally contacted back surfaces have already been introduced into the industrial production of crystalline silicon solar cells. In combination with the laser-fired contact (LFC) technology patented at Fraunhofer ISE for local, back-surface contacts, we have produced industrially screen-printed solar cells with passivation coatings applied by plasma-enhanced chemical vapour deposition (PECVD) and screen-printed aluminium films on the back surface. These have higher efficiency values than comparable solar cells with an aluminium contact over the entire surface. The PECVD coating stack consists of a hydrogen-rich SiO_xN_y:H layer on the interface to the silicon and a SiN_x:H layer as a barrier to the aluminium metal contact. This type of passivation stack results in surface recombination speeds of $S_{eff} < 20$ cm s^{-1}, accompanied by thermal stability to exposure to a conventional contact-firing step. When applied to thin Cz-Si wafers (< 200 µm), cell efficiency values of up to 18.3 % were achieved with this approach, with a significant increase in the open circuit voltage V_{OC} and the short circuit current I_{SC} compared to reference solar cells with a metal contact over the whole back surface. Measurements of the internal quantum efficiency confirmed the improvement, particularly for the long-wavelength spectral range that is relevant for the back surface of the solar cell.

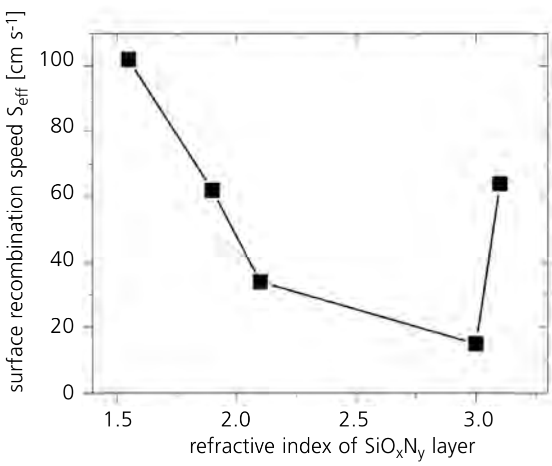


Fig. 1: Surface recombination speeds S_{eff} for fired stacks of SiO_xN_y/SiN_x produced by PECVD on symmetrical FZ-Si test wafers, plotted versus the refractive index of the SiO_xN_y layer. The excellent passivation quality of these stack systems is demonstrated by surface recombination speeds of less than 20 cm s^{-1} that were achieved.

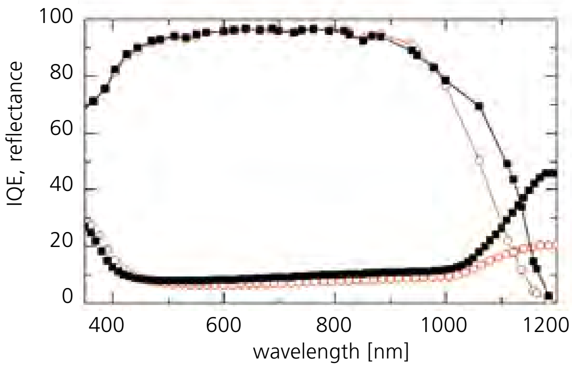
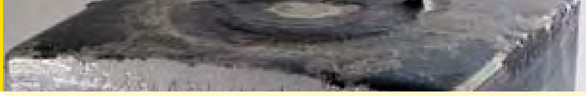


Fig. 2: Internal quantum efficiency (IQE) and reflectance of the screen-printed, passivated and locally LF-contacted Cz-Si solar cell (black) compared to a standard solar cell with an aluminium contact over the entire surface (red). The superiority of the passivated solar cell is particularly evident in its better performance in the long-wavelength spectral range.

The work was funded within the "Crystal Clear" integrated project by the EU and within the SLIM project by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).



Laser Ablation Processes for Industrial Solar Cell Production

We are developing numerous different processes for solar cell production, applying the laser systems that are available at Fraunhofer ISE. Selective laser ablation processes occupy a key position. They can be used for rapid and local structuring of etching and diffusion barriers, for direct processing of the silicon itself, to penetrate thin films before subsequent metallisation or for electrical isolation of metal layers.

Andreas Grohe, Christian Harmel, Ulrich Jäger, Annerose Knorz, Jan Nekarda, Ralf Preu

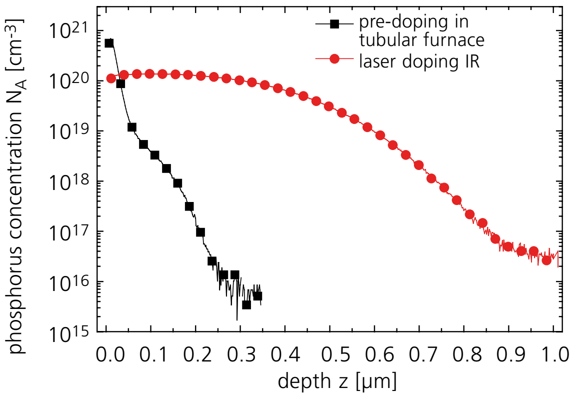


Fig. 1: Example of doping profile before (black squares) and after (red circles) laser doping a planar silicon surface. By alloying in additional phosphorus from phosphor-silicate glass remaining on the surface, the surface resistance drops from the initial value of 126 Ω/sq to 17 Ω/sq.

Selective structuring methods represent an important approach to increase the efficiency of solar cells. The structuring steps serve various purposes. In many novel metallisation procedures, local penetration of passivation layers ensures that electric contact is made between the metal contact and the semiconductor. To produce selective emitters or to define the emitter and base in back-surface contact solar cells, either diffusion barriers must be structured or a dopant must be locally alloyed into silicon to allow local diffusion. Finally, the metal layer that has been deposited over the entire surface can be selectively removed by laser to electrically isolate the two poles of the back-surface contact solar cells. Direct ablation of silicon is required both for the industrially applied laser edge insulation process and also to create via holes to transport charge carriers from the front surface to the contacts on the back surface.

Our investigations have revealed that individual laser parameters must be identified for each process due to the diversity of requirements. To do so, we can draw on our years of experience and also our selection of lasers with a wide range of wavelengths and pulse durations. The laser beams are guided by different means in industrially relevant equipment and experimental facilities.

This work is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the State of Baden-Württemberg and by industrial partners within various projects.

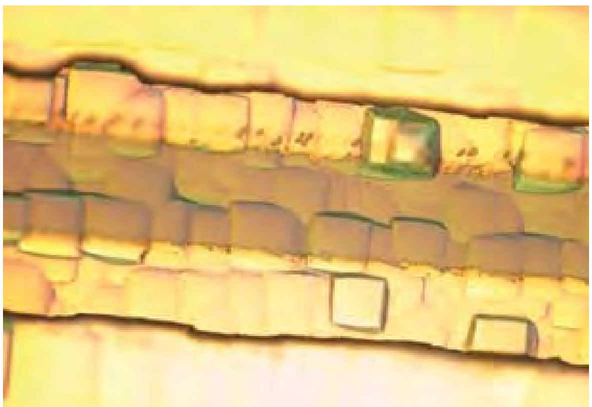


Fig. 2: Surface of a silicon wafer. The microscopic image shows a broad strip which was made by ablation of a silicon layer close to the surface. The subsequently deposited layer combination of 200 nm silicon dioxide covers the entire surface, whereas the 50 nm thick coating of amorphous silicon which was deposited on top of it has been ablated along a line within the first strip.

Inkjet Technology to Structure Highly Efficient Industrial Solar Cells

The inkjet technology applied at Fraunhofer ISE was subjected to significant further development. In addition to the previously existing procedures to open masked dielectric layers, we are now able to structure emitters for back-contact solar cells and metal layers deposited over large areas for interdigitated contacts. This means that all the structuring steps that are needed for highly efficient solar cells can be carried out with inkjet technology.

Daniel Biro, Dietmar Borchert, Marcus Bui, Raphael Efinger, Denis Erath, Arne Fallisch, Roman Keding, Nicola Mingirulli, Rainer Neubauer, Jochen Rentsch, Jan Specht, David Stüwe, Ralf Preu

In the middle of 2007, we established inkjet technology for solar cell structuring at Fraunhofer ISE. The first developments focused on fine structures for the front surface. Here, we were able to achieve seed layer widths of app. 20 µm in silicon nitride even on textured surfaces.

After that, we successively investigated the suitability of the technology to structure oxides, emitter diffusion zones and metallised areas. All types of layers can be coated with inkjet masks that allow subsequent structuring. As the equipment used allows very precise alignment, these processes can be combined with each other, so that inkjet technology can be applied for all structuring processes needed for a complete back-surface contact solar cell. For example, initially the emitter can be structured and then a passivating oxide layer can be produced and opened at pre-defined positions. Finally, a metal layer can be deposited and structured.

As the layers are composed of tiny droplets, there is no limit to the structures which can be created, apart from the droplet size. Production facilities with a high throughput are available today. Industrial dissemination of the technology can thus be anticipated.

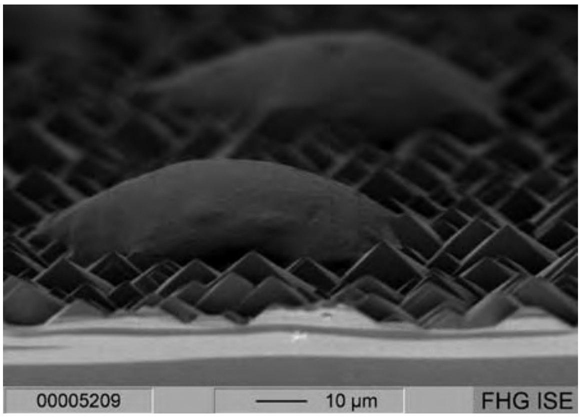


Fig. 1: Scanning electron micrograph of a hot-melt wax drop that was printed with inkjet technology. The very large aspect ratio enables films to be printed which can be applied in lift-off processes but also act as barrier layers. We expect that yet smaller droplets can be formed with different printing heads, if higher resolution is desired.

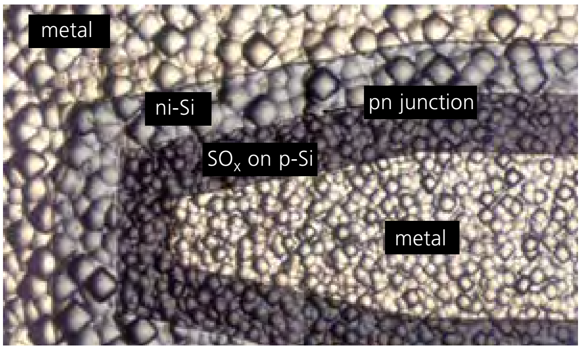
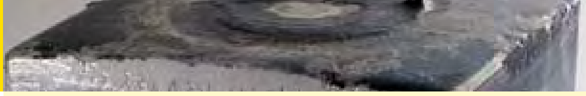


Fig. 2: Back surface (microscopic image) of an EWT (emitter wrap through) back-contact solar cell, which was produced in a Fraunhofer WISA project. All the structuring processes applied were based on inkjet technology. Both the pn-junction and the metal layer were structured by applying an inkjet masking process with a subsequent etching step. The highly precise and rapid process allows the production of complex, geometrically aligned structures.

The work was supported within the "Solar Chain" project as part of the Fraunhofer WISA Programme, and by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the "MASSE" project.



Wet-Chemical Processing Technology

In addition to process optimisation, quality control is becoming a more important issue for wet-chemical etching within solar cell production. On-line analytical techniques are of particular interest here. At Fraunhofer ISE, we have developed a suitable method, namely near-infrared spectroscopy (NIR), which is now applied on a broad scale for process evaluation. Further developments in the field of alkaline texturing allow the usual industrial processing times to be halved.

Katrin Birmann, Stefanie Eigner, Heike Furtwängler, David Kakhiani, Gero Kästner, Rainer Neubauer, Antje Oltersdorf, **Jochen Rentsch**, Anika Schütte, Martin Seitz, Martin Zimmer, Ralf Preu

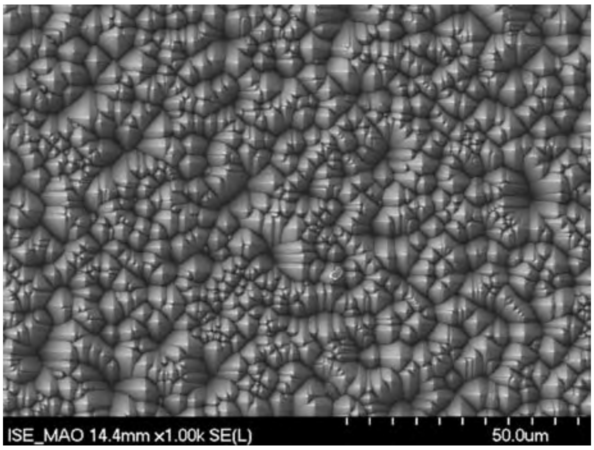
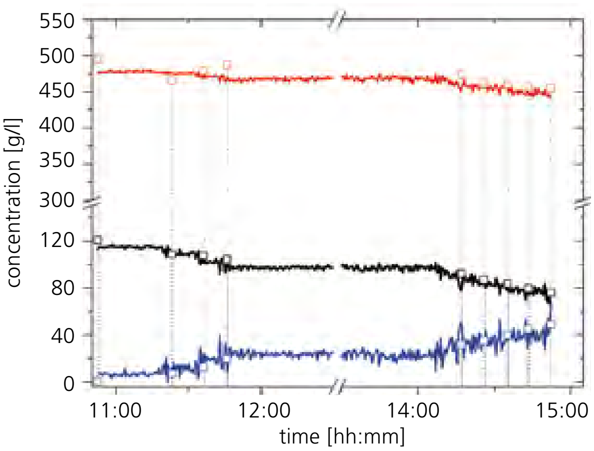


Fig. 1: Scanning electron micrograph of a Cz-Si wafer surface that has been subjected to alkaline texturing with KOH and cyclohexane diol. Due to the higher boiling point of the additive, clearly reduced processing times of less than 10 minutes at higher processing temperatures can be achieved, so that the throughput of conventional industrial texturing systems can be almost doubled.



Process management and control for wet-chemical texturing and cleaning are becoming increasingly important in the industrial production chain to manufacture silicon solar cells. In addition to the cost reduction potential offered by optimising the duration between replacements of a bath mixture or shortening processing times, the aspect of continuous quality control is becoming more and more significant. To reach the former goal, we at Fraunhofer ISE have developed a rapid alkaline texturing technique for monocrystalline silicon wafers, in which complete surface coverage with random pyramids and weighted reflectance values of around 11 % are achieved within 10 minutes. In the field of quality control, we developed both reference analytical methods in the off-line mode (ionic chromatography, titration) and also rapid, on-line analytical methods to trace all of the essential bath components in the etching and cleaning baths. In particular, by applying near-infrared spectroscopy (NIR), a complete analytical method was developed for acidic etching mixtures based on $HF/HNO_3/H_2O$ which allowed not only the concentration of the main bath components to be followed, but also the enrichment with silicon in the form of hexafluorosilicic acid. In particular, more efficient recharging with unused chemicals meant that the duration between replacements of a bath mixture could be lengthened and the stability of the bath composition improved.

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

Fig. 2: Near-infrared (NIR) spectroscopic analysis of an acidic texturing bath with on-line control of the concentration of HF (black), HNO_3 (red) and hexafluorosilicic acid (blue). To validate the new method, reference analyses were made with ionic chromatography (coloured squares).

Single-Wafer Tracking in Solar Cell Production

Due to the rapidly growing production capacities and the rising efficiency values, process control for solar cell production is gaining significance increasingly. In order to acquire quality-control data wafer for wafer, we have developed a procedure for wafer marking and automatic wafer identification, and studied its reliability throughout the entire solar cell process.

Gernot Emanuel, Markus Glatthaar*, Andreas Grohe, Alexander Krieg, **Stefan Rein**, Albrecht Weil*, Ralf Preu

* PSE AG, Freiburg

Increasingly, the industry is demanding single-wafer tracking for process control, as deeper insight into the technological processes can be gained by correlation of the measured data for each individual wafer. As a purely logistic material-tracking method is not robust enough for industrial application, we have developed a wafer identification procedure at Fraunhofer ISE. This procedure is based on a standard bar code which is engraved onto the front surface of the solar cell (Fig. 1a) and can be read out by a special reading device that was developed together with the Manz company. We have developed a laser process which generates structures that are retained throughout the complete production process but do not affect the performance of the solar cell. Although the bar codes are hardly visible, they become clearly evident under special illumination and can be decoded with an image-processing algorithm (Fig. 1b). We have investigated the reliability of the automatic code identification on all surfaces which are relevant to PV. When a suitable coding form is selected, average detection rates exceeding 94 % are already achieved over the entire processing chain of industrially relevant solar cell processes with surface texturing. In some individual processing steps, detection rates of 100 % have been reached. Due to the existing potential for improvement, it appears possible to upscale the procedure to a robust tracking system in the near future.

The work was supported by the Fraunhofer-Gesellschaft and the State of Baden-Württemberg within the "LASERFAKT" project.

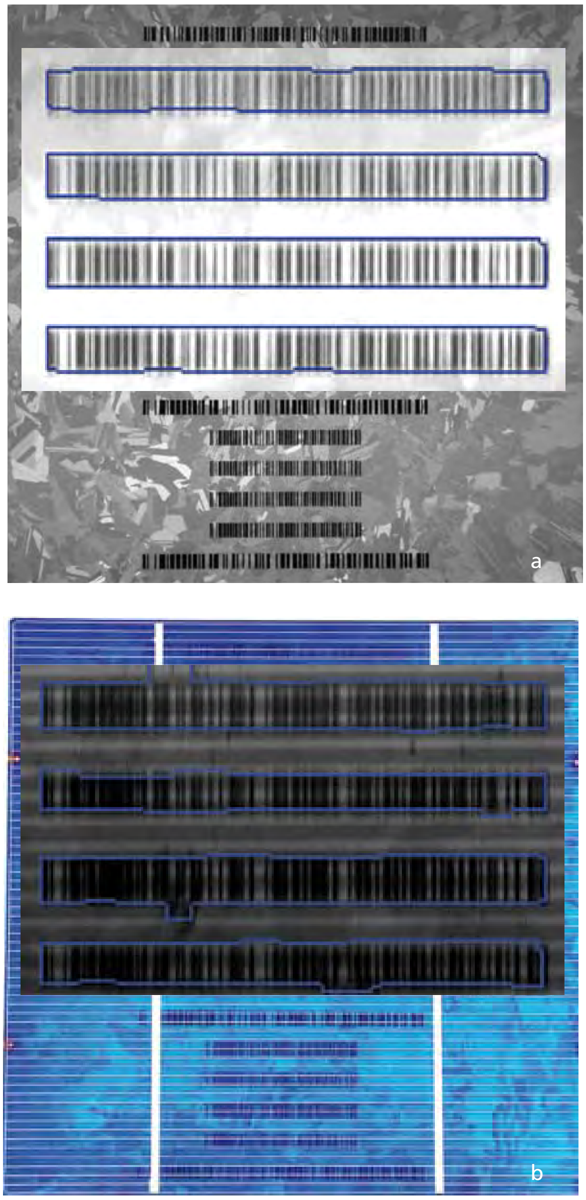


Fig. 1a and b: Optical appearance of different bar code test structures under diffuse illumination on a multicrystalline silicon wafer (a) immediately after laser marking and (b) after the complete solar cell production process (with acidic texturing, anti-reflective coating and metallisation). In the inserts are images from the code reader, which are recorded automatically under direct illumination with optimal camera settings, subjected to image processing and then evaluated.

Microscopic Analysis of Silicon Materials

We have significantly extended our characterisation methods for solar cells by integrating a modern analytical scanning electron microscope into the measurement methods. Microscopic analysis for material characterisation of e.g. multicrystalline silicon includes determining the distribution of elements to identify precipitates, measuring the crystal orientation and measuring the recombination activity on the microscopic scale. Cathodoluminescence measurements complement the defect characterisation.

Wolfram Kwapil, **Martin Schubert**, Wilhelm Warta, Stefan Glunz

Silicon with high concentrations of impurities often contains precipitates of foreign atoms at grain boundaries and displacements. Whereas small metal precipitates can only be detected with suitable synchrotron measurements, we are now in a position to identify large precipitates by applying EDX (electron-dispersive X-ray spectroscopy). Foreign atoms agglomerate preferentially along the grain boundaries between certain defect orientations.

With the electron back-scatter diffraction (EBSD) technique, we determine the orientation of crystallites in spatially resolved images, allowing us to characterise the crystallite dimensions and orientations. Within crystallites, displacements which are enriched with foreign atoms can be responsible for reduced material quality. Measurement of the defect luminescence with high spatial resolution allows us to analyse regions with a high concentration of displacements, which we can now detect with the cathodoluminescence measurement instrument that is integrated into the microscope.

Fig. 1: Measurement of crystal orientation by electron back-scatter diffraction (EBSD) in the scanning electron microscope. We can determine the crystal orientations in multicrystalline silicon with high spatial resolution, based on automatic evaluation of interferences between the electrons that are diffracted by the crystal lattice.

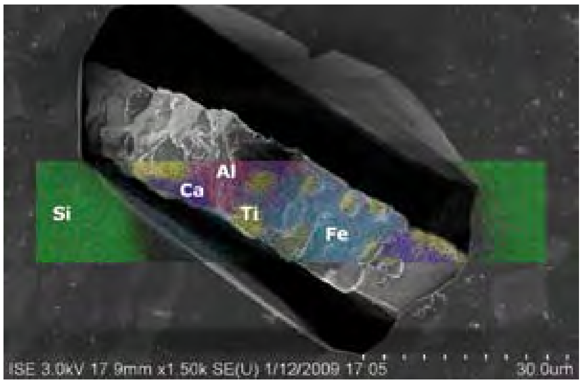
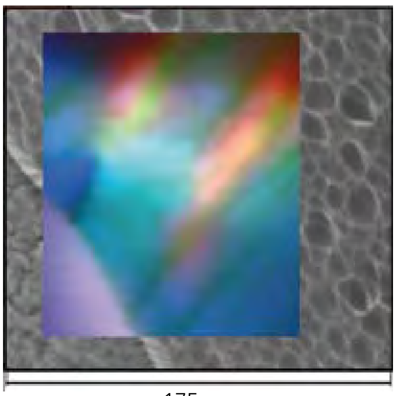


Fig. 2: Analysis of the distribution of elements by electron-dispersive X-ray spectroscopy (EDX). Analysis of the X-ray spectrum that is emitted after electron bombardment provides information about the distribution of elements within the sample with high spatial resolution. Larger metal precipitates near the surface can be analysed in this way.



175 µm

Fig. 3: Scanning electron micrograph (grey) with a superimposed cathodoluminescence spectroscopy measurement (coloured). The colour coding gives a compressed representation of the defect luminescence spectra. Blue represents a shift of the average photon energy to higher values, red indicates a shift to lower values. Defect-rich regions of low material quality (to the right of the grain boundary in the scanning electron micrograph) are characterised by strongly varying luminescence spectra over a small area. The illustrated measurement was made in co-operation with NREL, USA.

Hot Spots at Reverse Breakdown Points in Defect-Rich Silicon Solar Cells

In partly shaded modules, individual cells can be subjected to reverse voltages between 12 and 14 V. With our imaging measurement methods at Fraunhofer ISE, we have demonstrated that local breakdowns of the pn junction can already occur at these comparatively low reverse voltages. We succeeded in correlating one category of particularly early breakdowns with certain defect zones which display a characteristic fingerprint in defect luminescence.

Martin Kasemann*, Wolfram Kwapil, **Wilhelm Warta**, Stefan Glunz

* Freiburger Materialforschungszentrum FMF, Albert-Ludwigs-Universität Freiburg

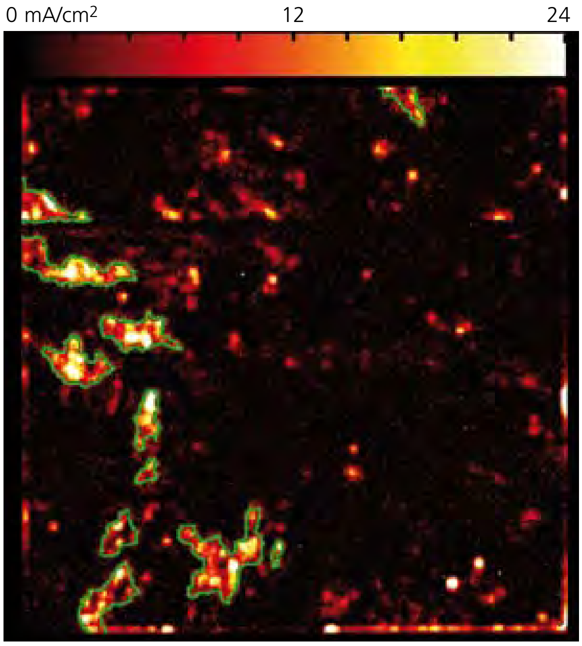


Fig. 1: Local breakdown current in a multicrystalline solar cell (156 mm x 156 mm), measured with an applied reverse voltage of 12.8 V. The most important breakdown zones, which correlate with recombination-active defects, are outlined in green in the image.

If the pn junction in a solar cell becomes locally conductive when a reverse voltage is applied, high local current densities and thus high power dissipation can occur (Fig. 1). Under certain operating conditions, this can lead to destruction of the solar cell and the module. Up to now, shunts were regarded as the most likely candidates for hot spots. We have now demonstrated that hot spots due to local junction breakdown can be particularly dangerous due to their steep current-voltage characteristic, even at low reverse voltages around 12 V.

By applying modern imaging measurement procedures, we have succeeded in identifying different breakdown categories in defect-rich multicrystalline material and showing that an important category of early breakdowns correlates with certain material defects (Fig. 2). Furthermore, we also found that the defect zones in breakdown regions could be distinguished from other defect zones by a characteristic fingerprint in the defect luminescence. Detailed characterisation is now following, with which we aim to understand the underlying breakdown mechanisms, in order to prevent the occurrence of hot spots in solar cells made of defect-rich material by adapting the production process.

The hot-spot problem will become more pronounced as increasing numbers of defect-rich silicon wafers are used for solar cell production. Therefore, we have also developed an in-line method for ultra-fast, spatially resolved hot-spot detection and classification.

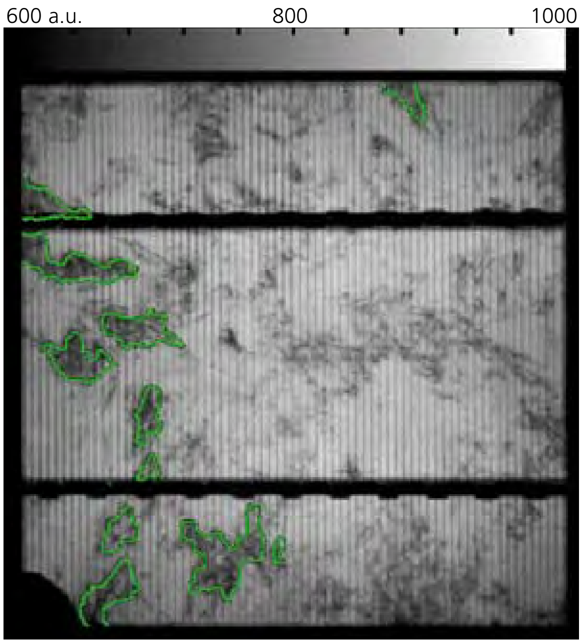
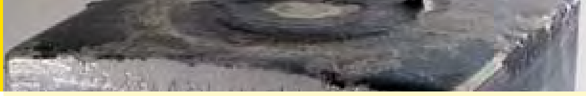


Fig. 2: Electroluminescence image of the cell at a forward voltage of 540 mV. The dark areas show regions of high recombination/defect density. Breakdown zones correlate with certain defect regions, whereas other defect regions do not display any breakdown. Further spatially resolved measurements of the sub-bandgap luminescence have indicated a characteristic difference in the defect regions, which is now being investigated in more detail.

This work was funded within the "SolarFocus" joint project by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).



High-Efficiency Solar Cells of n-type Silicon

Various physical advantages are offered by n-type silicon, compared to the p-type silicon that has been used up to now. We have overcome the greatest challenge to implementing highly efficient solar cell structures on this material, namely the passivation of the boron emitter on the front surface, by applying Al_2O_3 for front-surface passivation. This has enabled the production of solar cells on n-type silicon with an efficiency value exceeding 23 % for the first time.

Jan Benick*, Antonio Leimenstoll, Oliver Schultz-Wittmann, Sonja Seitz, Stefan Glunz

* Freiburger Materialforschungszentrum FMF, Albert-Ludwigs-Universität Freiburg

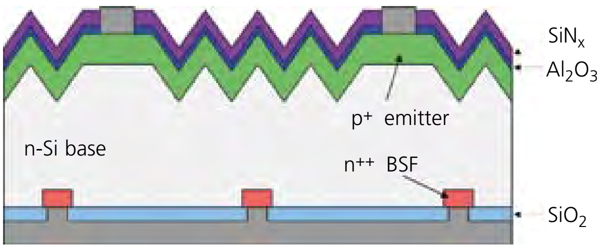


Fig. 1: High-efficiency (PERL) solar cell structure (PERL = passivated emitter rear locally diffused). The boron emitter on the front surface of the solar cell was passivated with Al_2O_3. To reduce reflection losses, we have reinforced the 30 nm thin, passivating Al_2O_3 film with an anti-reflective coating (40 nm SiN_x).

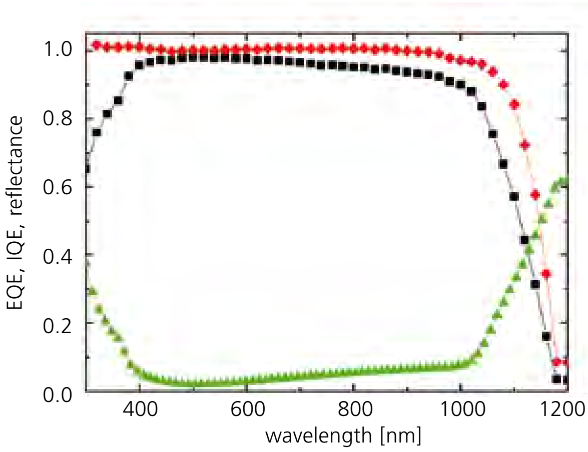


Fig. 2: External quantum efficiency (EQE – black), internal quantum efficiency (IQE – red) and reflectance (green) of the high-efficiency solar cells on n-type silicon. The efficiency of the Al_2O_3 passivation of the front surface is evident particularly in the optimal conversion of the short-wavelength spectral range.

To achieve high solar cell efficiency values, effective surface passivation is needed in addition to long diffusion paths in the raw material. The use of n-type silicon offers advantages with regard to the diffusion pathlengths: On the one hand, it displays greater tolerance to well-known impurities (e.g. iron), on the other hand, light-induced degradation such as is known particularly for p-type Cz silicon does not occur.

The main problem to date in implementing high-efficiency solar cell structures on n-type silicon has always been the boron emitter on the front surface of the solar cell. At Fraunhofer ISE, we have now optimised the boron emitter profile in extensive test series with regard to minimal recombination losses. However, it became evident that the surface could not be optimally passivated with the conventional layers such as SiO_2 or SiN_x. By using Al_2O_3 for the front-surface passivation, we have now solved this problem in co-operation with the Technical University of Eindhoven. A high density of negative charges passivates strongly boron-doped surfaces effectively. With a value of approximately 10^{13} cm^{-2}, Al_2O_3 is one of the few dielectric materials to offer such a high density of negative charges. In addition to its excellent passivation of the strongly boron-doped front surface of the solar cell, Al_2O_3 also features almost ideal optical properties for use as a front-surface film (n = 1.65, no absorption). With Al_2O_3 to passivate the boron emitter, an efficiency value of > 23 % (V_{OC} = 703 mV, I_{SC} = 41.2 mA cm^{-2}) was achieved at Fraunhofer ISE for the first time for high-efficiency solar cells made of n-type silicon.

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

High-Efficiency Solar Cells with Printed Contacts

The metallisation of solar cells is playing an increasingly important role when the efficiency is to be raised or silicon solar cells are to be produced more cost-effectively. By applying new printing techniques such as aerosol printing and simultaneously developing special contact inks, we have succeeded in increasing the efficiency of silicon solar cells that were produced under near-industrial conditions to above 20 %.

Sebastian Binder, Aleksander Filipovic, **Matthias Hörteis**, Daniel Schmidt, Robert Woehl, Stefan Glunz

The efficiency of silicon solar cells can be increased if the front-surface metallisation occupies a smaller area by employing slimmer contacts and also if the metal-semiconductor interface is improved. With the goal of reducing the line width of front-surface contacts from currently app. 120 µm to less than 30 µm, we have optimised the aerosol printing technique for application in solar cell processing.

At present, we can achieve line widths of less than 30 µm on textured solar cells. Reducing the contact area indeed means that more current can be generated in the solar cell, but this advantage can only be exploited if the contact resistance from silicon to metal is also decreased. The task was thus to develop an ink with which solar cells could be contacted with lower electrical resistance, despite the reduced contact area.

With the front-surface metallic ink that was recently developed at Fraunhofer ISE and its application in an aerosol-printing process, we have increased the efficiency value of a printed silicon solar cell with a passivated back surface to more than 20 %. It is particularly noteworthy that we have succeeded in contacting a SiN_x passivated emitter with a sheet resistance of more than 100 Ω/sq, which is not possible with conventional pastes and inks. These weakly doped emitters allow very high voltages exceeding 660 mV and internal quantum efficiency values approaching 100 %.

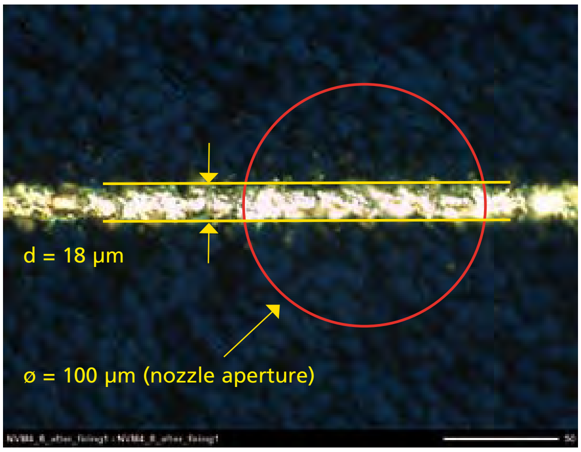


Fig. 1: Microscopic image of an aerosol-printed line. The resulting line width is more than five times narrower than the diameter of the nozzle opening (indicated by the red circle).

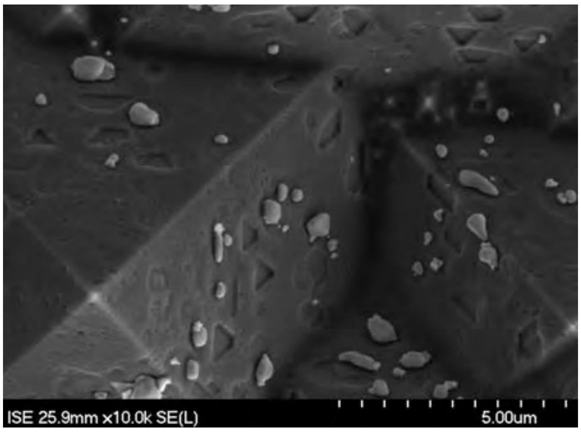


Fig. 2: Scanning electron micrograph of the position of a contact finger after removal by etching. The silver crystallites and their geometric imprints in the silicon are characteristic for a good electric contact. Here, the crystallite density is shown on a solar cell with an emitter sheet resistance of more than 100 Ω/sq.

Application of Laser Chemical Processing (LCP) for p-type Laser Doping

Silicon solar cells with efficiency values exceeding 20 % can be achieved with n-type laser doping by applying the proprietary LCP technology at Fraunhofer ISE. Now we have also succeeded in demonstrating p-type doping with LCP. This means that local high dopant concentrations can be applied rapidly and efficiently by LCP to both the front and the back surfaces of high-efficiency solar cells.

Christopher Baldus-Jeursen, Andreas Fell*, Christoph Fleischmann, Cornelia Ghadami, **Filip Granek**, Sybille Hopman, **Daniel Kray**, Kuno Mayer, Matthias Mesec, Ralf Müller, Andreas Rodofili, Arpad Mihai Rostas, Maria Isabel Sierra-Trillo, Stefan Glunz

* Freiburger Materialforschungszentrum FMF, Albert-Ludwigs-Universität Freiburg

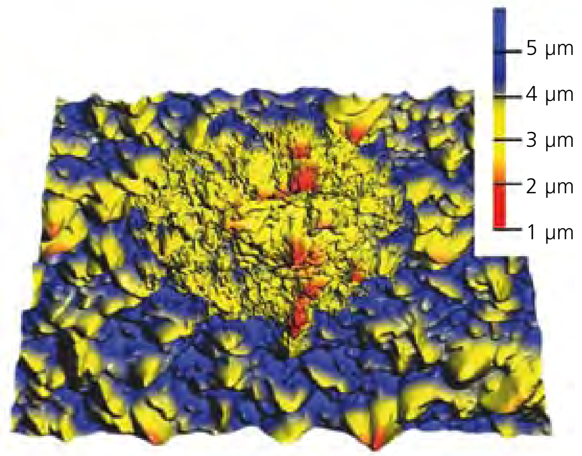


Fig. 1: Confocal microscope image of an opening point formed by LCP in a thermally grown oxide passivation layer. The very gentle process allows local doping with a shallow crater depth and contributes to the formation of ohmic contacts with low recombination activity.

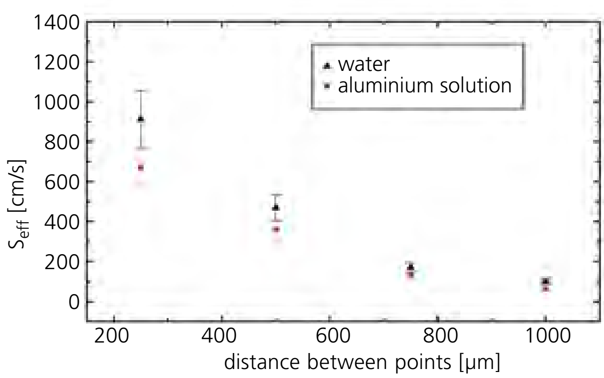


Fig. 2: Measured surface recombination speeds S_{eff} of local point contacts, which were produced by applying LCP with water or a solution containing aluminium. The lower values for LCP with an aluminium-containing solution indicate the creation of an Al LBSF (local back-surface field) which can reduce recombination at the back surface.

Highest-efficiency solar cells include highly doped zones under both contacts. These serve to reduce the specific contact resistance and recombination losses, among other effects. As the necessary diffusion is usually associated with complex high-temperature processes – e.g. in a tube furnace – it is not applied on a standard basis for the industrial production of solar cells.

Laser diffusion by the laser chemical processing (LCP) technique offers a very simple and elegant option to achieve local high diffusion without heating up the entire wafer. The dopant (e.g. phosphorus for n-type doping and aluminium or boron for p-type doping) in a suitable solution is used as the light-guiding liquid. This is formed in a nozzle into a laminar jet, into which short laser pulses are coupled. The laser melts the surface layer, which is doped by the simultaneously incident liquid jet. This has already been demonstrated for n-doping with phosphorus. Now we have succeeded with p-type doping for the first time, using a solution containing aluminium. This makes it feasible to create local back-surface fields (LBSF) in p-type solar cells or selective emitters in n-type solar cells. Experiments on LCP diffusion with boron instead of aluminium are currently in progress.

This work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) as well as our industrial partners, Deutsche Cell, Manz Automation, REC Solar and Synova.

Precise Connection Technology for Solar Cells

In our prototype laboratory for modules, we are refining processes for the electrical connection of solar cells. The driving forces are the decreasing wafer thicknesses, the trend toward lead-free materials and the cost pressure in module production. The increasing demands in production and quality assurance require more precise control of the processes. One of our main activities is thus on dynamically controllable, selective soldering processes.

Carsten Malchow, Michael Meißner, **Harry Wirth**, Werner Platzer

Dynamic soldering processes based on lasers or induction allow the input energy to be regulated particularly accurately. The pre-requisites are high speeds in temperature determination, signal processing and power control.

The laser beam heats up the surface of the cell connector by absorption. In order to make better use of the laser's radiated energy, we have investigated various measures to reduce the reflectance.

The most successful treatment reduces the reflectance by app. 25 percentage points (Fig. 1), which almost doubles the energy input efficiency. When solar cells are connected with pre-tinned copper strips, one challenge is to transfer a pressing force between the strip and the cell. We have developed a pressing device which ensures an appropriate contact for the materials, without disturbing the laser beam.

By combining several different measures, we were able to achieve high quality and reproducibility of the point-soldered connections, together with lead-free solder and short processing times. Figure 2 shows the distribution of peel forces that were measured between connectors and cells. We also significantly reduced the thermo-mechanical stresses which remain between the cell and cell connector after the connection process.

Some of the work was carried out within the EU-funded "Crystal Clear" project.

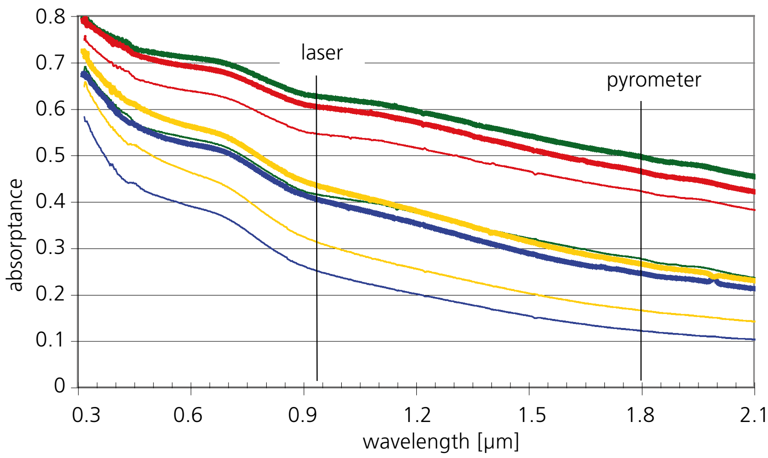


Fig. 1: Spectral absorptance of the surface of a cell connector after different types of treatment. The wavelengths of the laser and the pyrometer are marked.

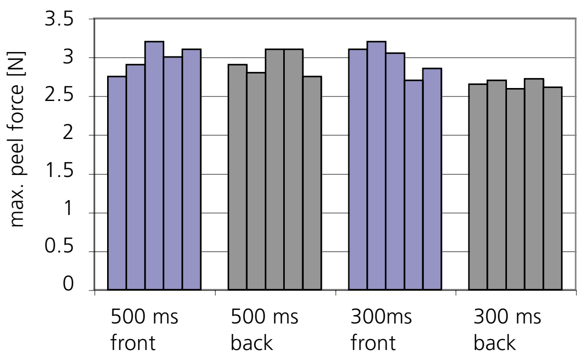
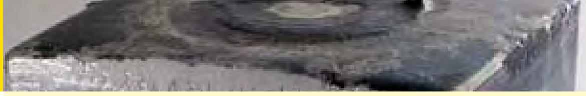


Fig. 2: Peel forces for cell connectors which were point-soldered with a laser, with five soldering points per bus bar, lead-free solder, processing times of 500 and 300 ms, values for the front and back surfaces of the cell.



The "Solar Valley Mitteldeutschland" project in the Federal Cluster of Excellence Programme

With members from Central Germany, one of the internationally leading regions in the PV branch, the "Solar Valley Mitteldeutschland" Cluster of Excellence aims to unite industrial partners and research facilities along the entire value chain for silicon photovoltaics. With the planned investments and research efforts, grid parity can be achieved in Germany within the next five to seven years and photovoltaics can become established as the most significant energy technology of this century.

Jörg Bagdahn*, Gerhard Willeke*

* Fraunhofer Centre for Silicon Photovoltaics CSP, Halle (Saale)

The "Solar Valley Mitteldeutschland" Cluster of Excellence is one of five prize-winners in the first round of the Cluster of Excellence competition organised by the German Federal Ministry for Education and Research (BMBF). The association unites 27 companies and 12 research facilities from Thuringia, Saxony-Anhalt and Saxony as well as further strategic partners such as Fraunhofer ISE in Freiburg. By including these strategic partners, the cluster can cover the complete value chain for silicon photovoltaics (Fig. 1). The project, which will run from 2009 to 2013 with a volume of 80 million euros, is scientifically co-ordinated by Fraunhofer CSP, a joint centre belonging to Fraunhofer IWM and Fraunhofer ISE.

In the first three large projects on xµ Materials (project management: CiS, Erfurt), xµ Cells (project management: ersol, Erfurt) and xµ modules (project management: Fraunhofer CSP, Halle), the basis will be established for industrially producing materials, highly efficient solar cells and modules on ultra-thin silicon wafers. In these projects, one goal is to identify the optimal wafer thickness (first target: 130 µm) with which the euro/watt price for industrial production can be minimised by using inexpensive solar silicon and lengthening the service lifetime of modules.

Further projects on crystallisation, wafering (project management: Fraunhofer CSP), processing technology, thin-film technology and building and system integration (project management: Fraunhofer ISE) are currently being prepared.

Silicon Production	Crystallisation	Wafer Production	Cells	Modules / Thin-Film	System Integration
Extremely pure silicon is obtained by thermal decomposition of extremely pure silicon compounds.	The silicon which is suitable for photovoltaics is processed in furnaces into cylindrical single crystals or multi-crystalline blocks.	The crystallised silicon is cut with band and wire saws into ~ 150 µm thick wafers.	After purification, solar cells are produced from the wafers by doping and coating processes.	A number of cells are connected electrically with each other to form a module, then embedded in a polymer layer and covered with a glass pane.	The modules are integrated electrically and structurally into a building, e.g. as a façade or roof system.
Photovoltaic companies					
PV Silicon, City Solar	ersol, Q-Cells, Wacker Schott	Q-Cells, ersol, PV Silicon, Wacker Schott, Sawate	Q-Cells, ersol, Sunways, EverQ, Solar	SOLARWATT, CSG Solar, Solarion, Signet Solar, Sontor, Sunfilm, ersol thin films	SunStrom
System manufacturers, suppliers					
	CGS/PVA Tepla, Heraeus	Jenoptik, SiC Processing	Jonas & Redmann, Roth & Rau, FHR, AIS Automation Dresden, ALOtec, von Ardenne, Jenoptik	Fresnel Optics, P-D Industries, von Ardenne, AIS Automation, FHR, Roth & Rau	SMA
Universities and research institutes					
	CSP, THM, FZD	CSP, TUBA, THM, CiS, BAM, CiS	ISE, CSP, CiS, IWS, FEP, FZD	CSP, ISE, CiS	ISE, CSP, TUD

Fig. 1: Value chain for crystalline silicon solar technology and the distribution of roles among the members of the "Solar Valley Mitteldeutschland" Cluster of Excellence (Status: 05/2008).

The Fraunhofer Centre for Silicon Photovoltaics CSP

The Fraunhofer Centre for Silicon Photovoltaics CSP in Halle (Saale), located at the heart of the Central German Solar Valley, is a joint establishment of the Fraunhofer Institutes for Solar Energy Systems ISE and Mechanics of Materials IWM. Founded in 2007 and equipped with infrastructural funding of 60 million euros, Fraunhofer CSP is currently working with a staff of 29 on various topics of the value chain for silicon photovoltaics under the motto of "More PV electricity from less silicon".

Jörg Bagdahn*, Gerhard Willeke*

* Fraunhofer Centre for Silicon Photovoltaics CSP, Halle (Saale)

Fraunhofer CSP is concentrating on the following topics:

- Crystallisation:
  Further development of the vertical gradient freeze (VGF) (Fig. 1), Czochralski (Cz) and float zone (FZ) processes on an industrial scale
- Microstructure/Analytics:
  The diagnostic centre at Fraunhofer CSP analyses microstructure (Fig. 2) and material composition down to the ppb range.
- Wafer/cell mechanics:
  Analysis of structural stability and durability of individual components based on models for material mechanics
- PV packaging:
  Novel, low-stress contacting processes to connect Si solar cells
- Modules:
  Analysis of the reliability and lifetime of PV modules by application of thermo-mechanical simulation accompanied by mechanical load tests and other tests
- Photon management:
  Increasing solar cell efficiency values by modification of the radiation spectrum with optically active materials (e.g. glass ceramics)

The units for thin-film technology and electrical materials analysis/solar cell characterisation are still being planned.

Fraunhofer CSP is currently located in the premises of Fraunhofer IWM in Halle but will move to its own buildings at Schkopau (PV packaging) and Halle in 2009 and 2011 respectively.

Fig. 1: Industrial crystallisation facility (VGF) to produce multicrystalline silicon ingots.

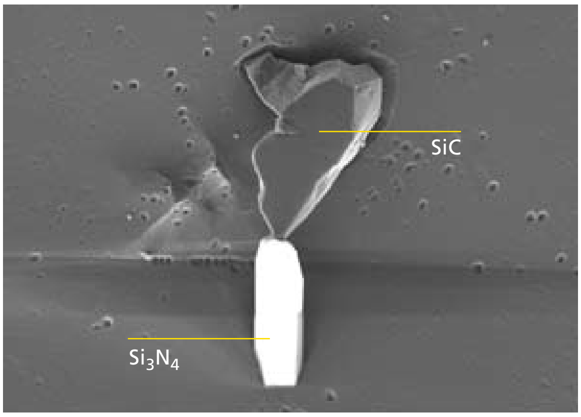
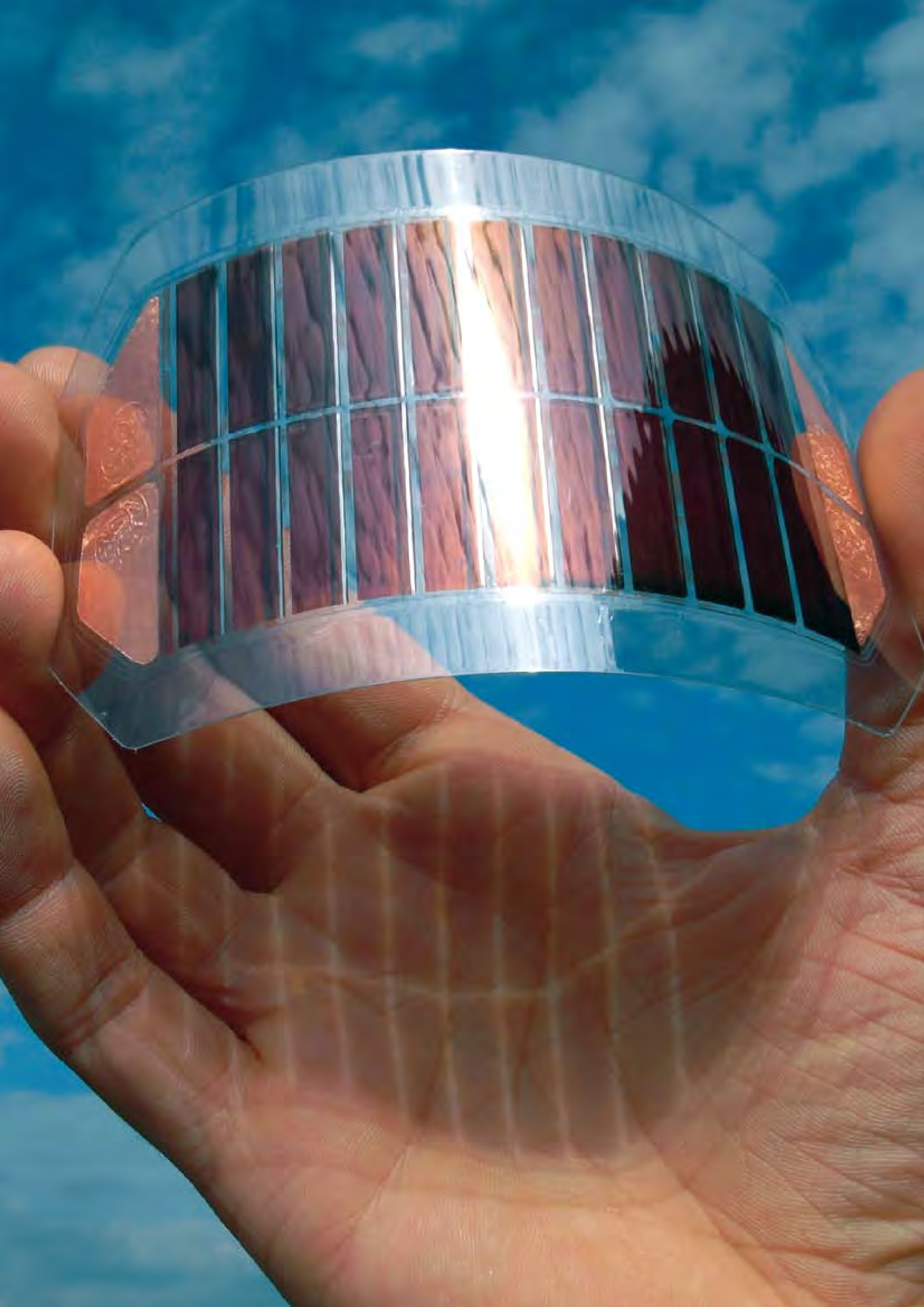


Fig. 2: Scanning electron micrographs (SEM) of impurities in multicrystalline silicon. Clusters of SiC and rods of Si_3N_4 which formed during the crystallisation process have been exposed by etching away the silicon material. The micro-crystallites are distinguished by their characteristic forms and the material contrast.



Alternative Photovoltaic Technology

Complementing the work on silicon photovoltaics (see page 42), our research and development on solar cells also extends to other types of photovoltaic technology: III-V semiconductors, dye solar cells and organic solar cells.

III-V semiconductors and their application fields

Multi-junction solar cells, based on III-V semiconductors such as gallium indium phosphide, aluminium gallium arsenide or gallium arsenide, achieve the highest efficiency values of all types of solar cells. In 2008 we achieved the world record value of 41.1 % at a concentration of 454 suns for a triple-junction solar cell. Triple-junction solar cells of GaInP/GaInAs/Ge have already been applied successfully for years in space. In recent years, we have contributed to the successful market introduction of these extremely efficient solar cells, combined with optical concentration of sunlight, for terrestrial applications. In addition to these two PV market segments, we supply III-V solar cells to niche markets such as laser power beaming, thermophotovoltaics and other specialised applications.

For extra-terrestrial applications, we are working on radiation-resistant, multi-junction cells (triple to sextuple) and in addition, we adapt these cells for special applications such the environments of Mars and Jupiter. For terrestrial use, we are developing concentrator cells for the highest optical concentration factors of up to 2000 and efficiency values of around 40 percent. In addition to developing cell processes for industry, we also adapt concentrator solar cells to the specific requirements of our clients.

A further focus within our work on concentrator solar cells is the development of appropriate characterisation techniques and instruments for application in industrial production. In co-operation with our CalLab calibration laboratory, we offer calibrated measurements of multi-junction solar cells. Furthermore, we develop complete concentrator module and system packages. The FLATCON® technology, which was developed at Fraunhofer ISE, is one example. Following a pilot production phase in our Concentrator Technology and Evaluation Centre ConTEC, these concentrator modules have been successfully manufactured since the autumn of 2008 by our spin-off company, Concentrix Solar GmbH, in its own 25 MW production line.

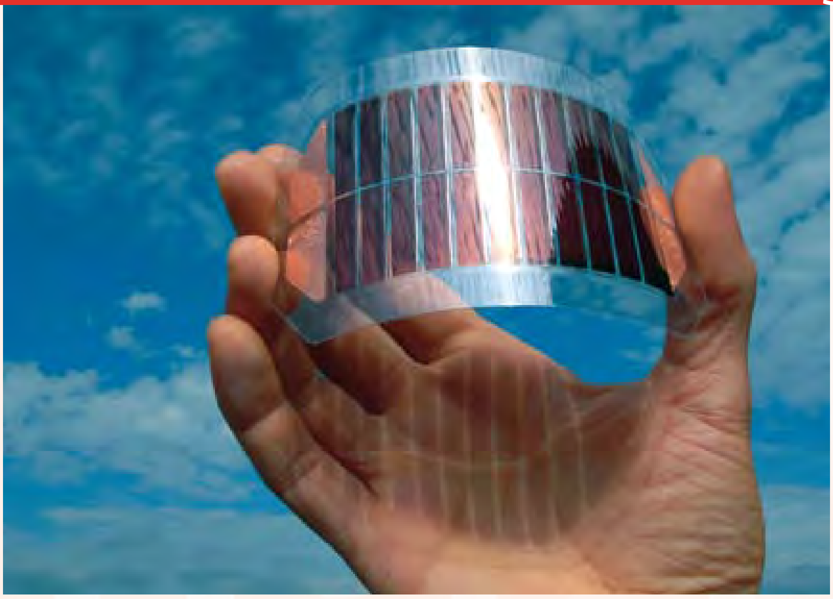
Dye solar cells

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 implementing design aspects was demonstrated in prototypes. The module durability is being tested in the laboratory and outdoors. In addition to the development of cell and production concepts, work is concentrating on scaling up dye solar modules for applications in the architectural sector.

Organic solar cells

Organic solar cells are particularly attractive due to the anticipated low production costs. High mechanical flexibility will open up new application fields for photovoltaics in future. We are developing new cell structures which can be produced from cost-effective materials with efficient processes. The goal of these developments is production in a roll-to-roll process. We were able to produce the first solar cell modules with technology that can be transferred to continuous production. Aiming for higher efficiency and longer lifetimes, we are investigating new organic semiconductors and electrodes, and the durability of encapsulated solar cells in accelerated aging tests. Our investigations have shown that by now, lifetimes of several years are realistic.

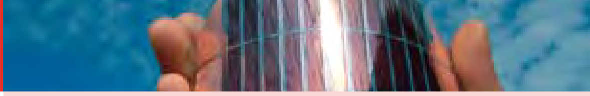
Alternative Photovoltaic Technology



Organic solar cells are a promising type of solar cells for the future. The low material consumption and the application of efficient production technology hold great potential for cost-effective production. Further advantages – particularly with a view towards applications – include mechanical flexibility and low weight. The efficiency value of organic solar cells is currently between 3 % and 5 %. At Fraunhofer ISE, intensive research is now being conducted to establish the basis for commercialising organic solar cells. (see article on page 68).

Contacts

Silicon Photovoltaics/ Alternative Photovoltaic Technology	Dr Andreas Bett	Tel.: +49 (0) 7 61/45 88-52 57 E-mail: Andreas.Bett@ise.fraunhofer.de
Applied Optics and Functional Surfaces	Dr Werner Platzer	Tel.: +49 (0) 7 61/45 88-59 83 E-mail: Werner.Platzer@ise.fraunhofer.de
Concentrator technology	Dr Andreas Bett	Tel.: +49 (0) 7 61/45 88-52 57 E-mail: Andreas.Bett@ise.fraunhofer.de
III-V epitaxy and cells	Dr Frank Dimroth	Tel.: +49 (0) 7 61/45 88-52 58 E-mail: Frank.Dimroth@ise.fraunhofer.de
Dye solar cells	Dr Andreas Hinsch	Tel.: +49 (0) 7 61/45 88-54 17 E-mail: Andreas.Hinsch@ise.fraunhofer.de
Organic solar cells	Dr Michael Niggemann	Tel.: +49 (0) 7 61/45 88-54 58 E-mail: Michael.Niggemann@ise.fraunhofer.de
Characterisation of III-V solar cells	Dr Gerald Siefer	Tel.: +49 (0) 7 61/45 88-54 33 E-mail: Gerald.Siefer@ise.fraunhofer.de



III-V Multi-Junction Solar Cells with Efficiency Values > 41 %

The highest efficiency values for converting sunlight into electricity are obtained with III-V multi-junction solar cells. To produce such cells, a multi-layer stack with three to five pn junctions in compound semiconductors such as GaInP or GaInAs is grown epitaxially. The resulting complex structure can contain up to 40 individual layers, which must be characterised by the highest crystalline purity and quality. This technology is standard for satellite power supplies and is currently occupying an increasing share of the market for high-concentration photovoltaics.

Frank Dimroth, Jara Fernandez, Benjamin George, Wolfgang Guter, Ranka Koch, Eduard Oliva, Simon Philipps, Manuela Scheer, Jan Schöne, Gerald Siefer, Marc Steiner, Alexander Wekkeli, Elke Welser, Andreas Bett

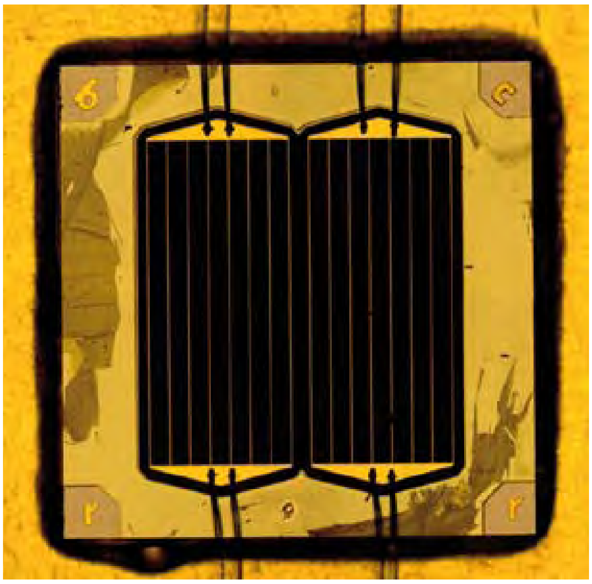


Fig. 1: The new world-record solar cell from Fraunhofer ISE, made of $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ with a cell area of 5.09 mm^2.

Monolithic multi-junction solar cells have been developed at Fraunhofer ISE for more than ten years. To produce the solar cell structures, we use a production reactor for metal organic vapour phase epitaxy (MOVPE) of the same type as is used by our industrial partners. With this special equipment, III-V compound semiconductors can be grown epitaxially with the greatest purity and crystalline quality. The most successful solar cell structure at present consists of three pn junctions in $Ga_{0.35}In_{0.65}P$, $Ga_{0.83}In_{0.17}As$ and Ge. These three materials absorb sunlight in different spectral ranges from 300 to 780 nm, up to 1020 nm and up to 1880 nm respectively. We know from theoretical simulations that this bandgap combination is particularly advantageous for converting radiation with the terrestrial solar spectrum into electricity. In addition to the materials named above, the actual solar cell structure includes many further layers which serve as barriers for charge carriers or as electrical connections between the sub-cells. In order to achieve the highest efficiency values, we have optimised not only the quality of the materials and the interfaces but also the contact structure and the production processes for the solar cell. Thus, in 2008 we achieved an efficiency value of 41.1 % for a concentration of 454 suns – a new world record! Even with a yet higher concentration factor of C = 1700, the cells still operate with an efficiency value of 37.6 %. In this way, expensive semiconductor areas can be saved in highly concentrating PV systems – an approach to reduce electricity generation costs further in future.

The work was supported by the EU, the "Deutsche Bundesstiftung Umwelt (DBU)", the German Federal Ministries for the Environment, Nature Conservation and Reactor Safety (BMU) and for Education and Research (BMBF), and an industrial partner.

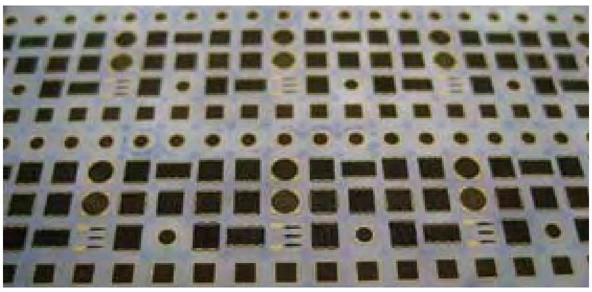


Fig. 2: Development of different cell dimensions and forms – optimised for applications in specific PV concentrator modules.

ConTEC – Concentrator Technology and Evaluation Centre

As part of our work on concentrator photovoltaics, we have established the Concentrator Technology and Evaluation Centre ConTEC at Fraunhofer ISE. With it, we offer our clients an industrial platform to develop, produce and characterise concentrator modules. Together with our spin-off company, Concentrix Solar, we have processed more than 1 million components there, applying processes that were previously developed at Fraunhofer ISE. We also use the Centre for new developments. The most recent example is a concentrator module with a second optical stage, which features an efficiency value exceeding 28 %.

Armin Bösch, Frank Dimroth, Fabian Eltermann, Tobias Gandy, Joachim Jaus, Michael Passig, Gerhard Peharz, Gerald Siefer, Stefan Thaller, Maike Wiesenfarth, Oliver Wolf, **Andreas Bett**

A central goal of our development work at Fraunhofer ISE is to reduce the costs for photovoltaically generated electricity. Concentrator technology, in which the sunlight is focused optically onto a small solar cell, is one technological option to reach this goal. For years we have dedicated ourselves particularly to high-concentration photovoltaics based on multi-junction solar cells made of III-V semiconductors. These cells achieve efficiency values of around 40 % and thus guarantee high system efficiency values. Our industrial partner, Concentrix Solar, has published AC system efficiency values exceeding 23 %. There is currently great interest in concentrator technology due to this high efficiency. We have responded over the last few years at Fraunhofer ISE by establishing the Concentrator Technology and Evaluation Centre. It is equipped with industrial production facilities from the microelectronic sector: a die bonder, an in-line soldering furnace, a thin-wire bonder, a thick-wire bonder and characterisation instruments developed especially for concentrator technology. These include the MAPCON analyser, a device which controls the quality of thousands of cells on a wafer, an automated pulsed solar simulator for solar cell assemblies with subsequent classification into quality classes, and a module measurement stand which allows us to measure modules under reproducible conditions in the laboratory. In co-operation with Concentrix Solar, we have already processed more than 1,000,000 components for FLATCON® modules on this pilot production line.

At the same time, we continue to develop new, industrially relevant processes, e.g. the integration of a second optical concentrator stage into modules. The first modules produced on our line have already achieved a record efficiency value of 28.2 % on our outdoor measurement stand.

The scientific work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the Fraunhofer-Gesellschaft and Concentrix Solar.

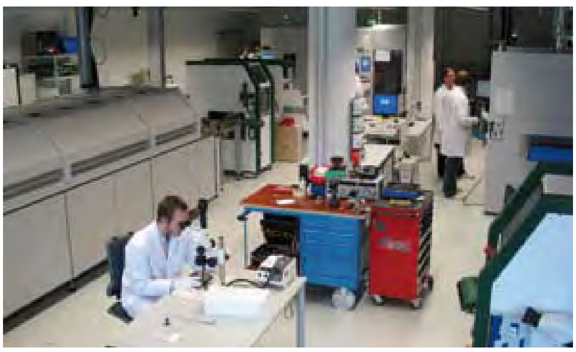
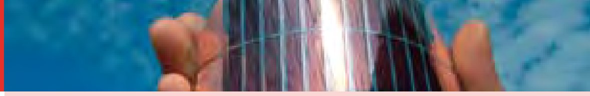


Fig. 1: Equipment in the ConTEC hall (from left to right):
- reflow furnace for soldering processes
- thin-wire bonder to contact the front surface of the solar cell with 50 µm thin gold wires
- tester for component assemblies: light and dark measurement of solar cell assemblies
- pick & place facility: extremely precise component mounting over a large area

Fig. 2: FLATCON® modules with reflective elements on the solar cells. Our pilot line was used for the assembly. The module achieved a record efficiency value of 28.2 %.



Investigation of the Long-Term Stability of Organic Solar Cells

Apart from efficiency and cost-effective producibility, another important criterion for positioning novel organic cell technology on the market is the cell stability. With the help of accelerated aging experiments, we are investigating the degradation mechanisms in organic solar cells and identifying suitable encapsulation materials. Our investigations show that lifetimes of several years are now realistic.

Michael Niggemann,
Hans-Frieder Schleiermacher, Martin Schubert, Felix Stelzl*, Uli Würfel, Birger Zimmermann, Werner Platzer

* Freiburger Materialforschungszentrum FMF, Albert-Ludwigs-Universität Freiburg

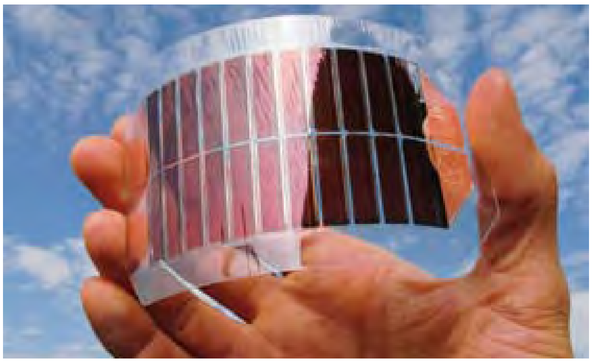
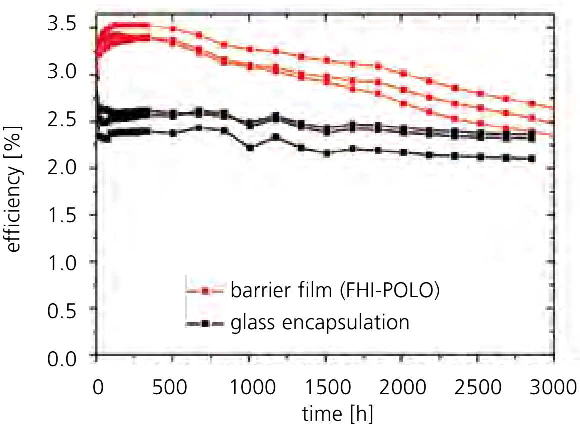


Fig. 1: Flexible organic solar cell module. The first application areas for the future are energy-autonomous systems and mobile power supplies for small devices.



Long-term stability, efficiency and production costs will determine the future application areas for organic solar cells. Other important aspects, particularly for the first applications in small systems, include mechanical flexibility, mass and design (Fig. 1). When investigating the stability, our goals are both to identify degradation processes as a basis for cell optimisation and to predict the expected lifetime under realistic application conditions.

We investigate the degradation mechanisms in unsealed solar cells under defined stress conditions, e.g. different gas atmospheres. By applying different measurement methods such as impedance spectroscopy, we can monitor the degradation of contacts and identify the more stable contacts. The investigation of transparent sealing/cover materials and adhesives is carried out under continuous illumination of the solar cells. Solar cells that are covered with glass show a decrease in the efficiency of about 10 % after 3000 hours of continuous illumination (Fig. 2). The construction of flexible solar cells that are stable for long periods poses a major challenge. A decrease of only 20 % after 2000 hours was already achieved with a transparent barrier film from the POLO Fraunhofer-Verbund for polymer surfaces. In the first approximation, a radiation dose of 1000 hours corresponds to a year of solar radiation in Central Europe. This stability is promising for the use of organic solar cells in the first mobile applications.

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

Fig. 2: Measurement of the long-term stability of organic solar cells with different transparent barrier materials under continuous illumination with a sulphur lamp. The spectrum of the sulphur lamp used has a lower UV intensity than the standard AM 1.5 solar spectrum. The cell temperature is about 55 °C.

Dye Solar Cells Progressing towards Market Introduction

Dye solar cells are produced at Fraunhofer ISE with a screen-printing process. A durable seal is achieved by glass-frit soldering. Unlike conventional solar cells, a metal-organic dye is responsible for converting light into electricity in dye solar cells. Parallel to the development of cell and production concepts, our work is concentrating on quality control and the up-scaling of dye solar modules.

Jörg Bernhard, Katarzyna Bialecka, Yacine Boulfrad, Henning Brandt, **Andreas Hinsch**, Katrine Jensen, Piotr Putyra*, Krzysztof Skupien*, Welmoed Veurman, Gregor Zieke, Werner Platzer

* Freiburger Materialforschungszentrum FMF, Albert-Ludwigs-Universität Freiburg

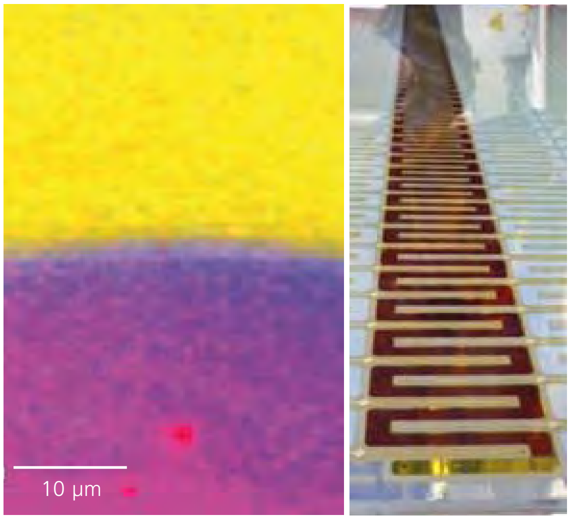


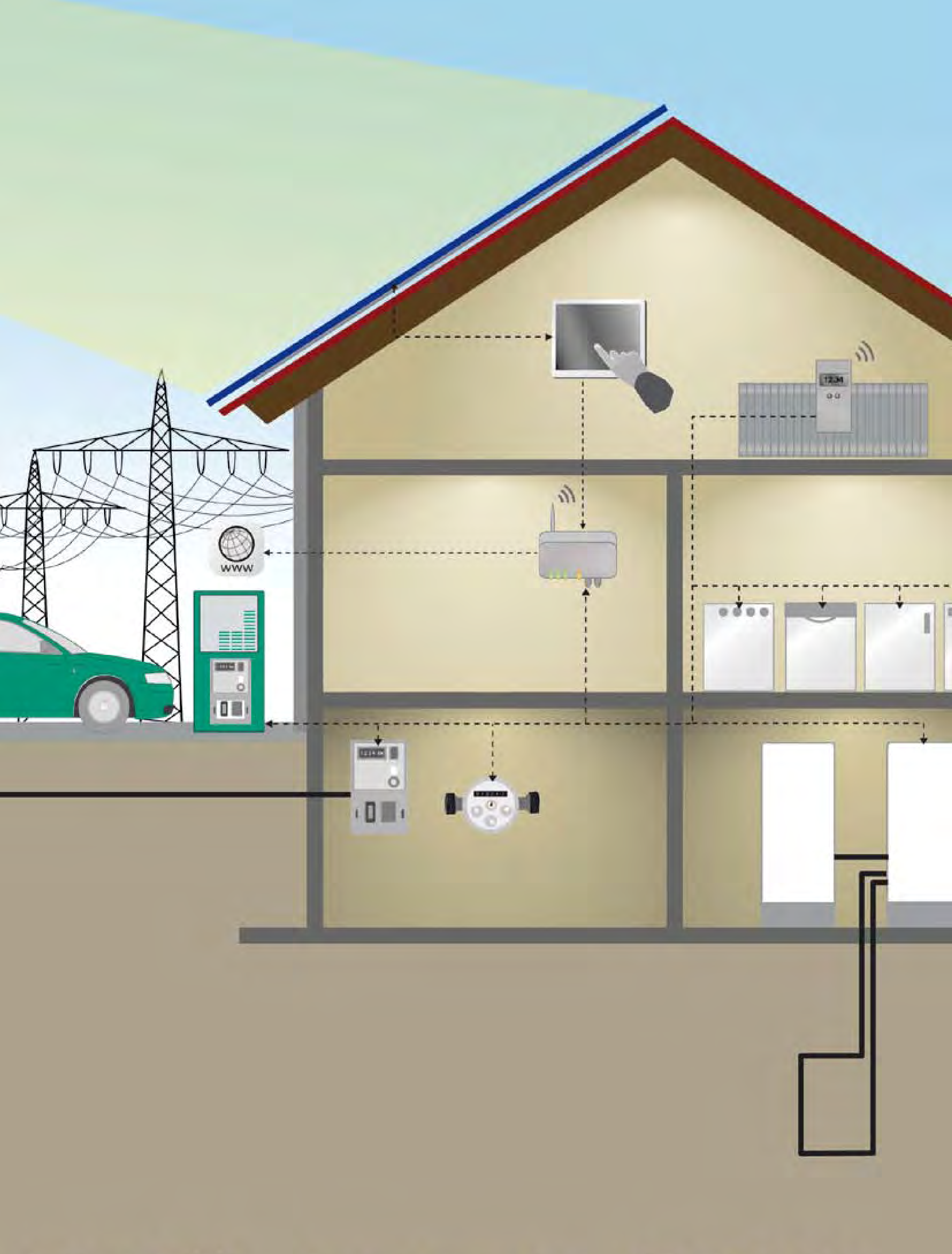
Fig. 1: Surface scan (left) based on Raman spectroscopy of the edge zone of a dye solar cell (right). The electrolyte (yellow), the titanium dioxide electrode material (blue) and the dye (red) can all be detected and distinguished spectroscopically.

Fig. 2: The filling process for a dye solar module with dimensions of 60 cm x 100 cm. Together with Fraunhofer IAO, we have developed and constructed an industrially relevant production unit for this process.

In recent years, the technology for producing dye solar cells has approached industrial implementation more closely. This makes the development of quality-control methods for materials and the production process increasingly important. We have tested possible quality-control tools which could be integrated later into an ongoing production process. Measurements of the transient photovoltage and charge extraction, spatially resolved Raman spectroscopy (Fig. 1), and photocurrent and impedance spectroscopy were identified as particularly suitable, non-destructive characterisation methods. Furthermore, we have developed a measurement stand for electrochemical characterisation of the long-term behaviour of the electrolyte and sealant materials. In an outdoor test stand, we have acquired data for internally series-connected module prototypes under realistic conditions as a function of incident intensity and angle.

The screen-printing and sealing of larger-area dye solar modules was optimised in several workshops which were conducted on the premises of our industrial partners. For the first time, we were able to successfully demonstrate the procedure developed at Fraunhofer ISE to introduce the dye over a module area of 60 cm x 100 cm (Fig. 2). At present, a filling and sealing unit is being constructed for this process which is based on components from industrial production technology. Together with Fraunhofer IAO, we prepared a study on the energy amortisation time of dye solar cells in the building façade.

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



Smart Grids Smart Metering Smart Homes

Renewable Power Generation

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. A good 10 % of the photovoltaic modules sold world-wide are used in these markets, some of which are already economically viable without external subsidies.
In addition, there is an enormous market for decentralised water desalination and purification technology based on renewable energy sources. For this broad spectrum of applications, we develop concepts, components and systems for off-grid power supplies based on photovoltaics, fuel cells, wind energy and hydroelectricity. We are working intensively on optimising operation management strategies and control systems for all common types of technology in order to reduce battery aging and operating costs.

Construction of grid-connected systems is the largest global market of the photovoltaic branch today. To maintain the strong market growth stimulated by market introduction programmes now that subsidies are decreasing, the costs for the systems technology must be reduced continually. Inverters to feed photovoltaic electricity into the grid are already of high quality today. Nevertheless, there is still considerable potential for increasing efficiency and reducing costs, 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 for the entire power spectrum up to the MW range in the fields of circuit design, as well as dimensioning and implementing analog and digital controllers.

We offer a wide range of services for quality assurance and operation monitoring of PV systems and characterisation of PV modules, which encompasses yield predictions, plant authorisation and monitoring of large systems and precision measurements of modules. Our photovoltaic calibration laboratory, ISE CalLab, is one of the internationally leading laboratories in this field.

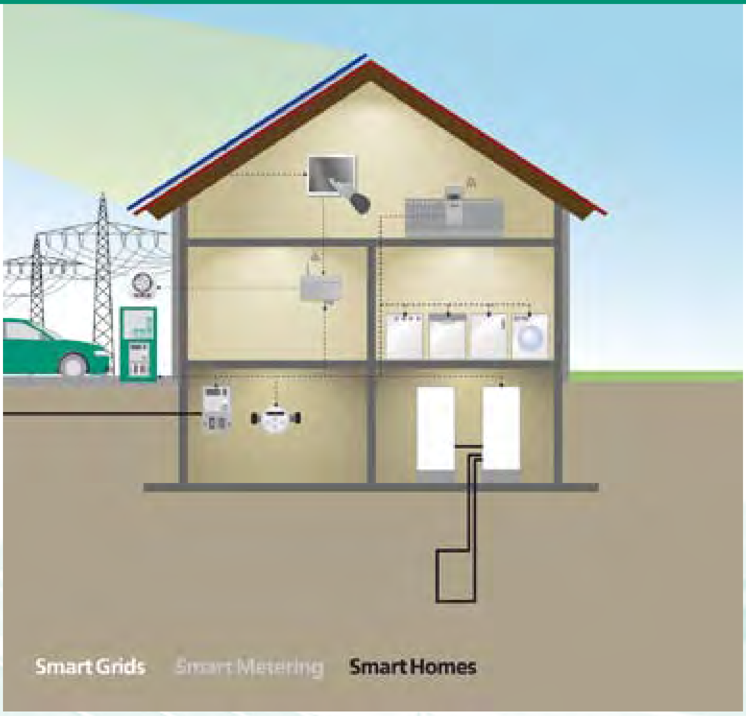
Regardless of whether photovoltaic, wind-energy, hydroelectric or combined heat and power plants are involved: In Germany alone already ten thousands of distributed generators feed their electricity into the distribution grids. In order to cope with the anticipated enormous penetration rates and the associated technical, ecological and economic demands, we are developing new concepts and components based on modern communications technology for energy management of distributed generators and loads in the distribution grid. Involvement of the electricity customers with regard to usage behaviour, consumption visualisation and efficient billing methods (smart metering) is playing an increasingly important role in this process.

In their plans to achieve the announced environmental goals, the Federal government, industry and science attribute great significance to electro-mobility, based on vehicles that run partly or completely on electricity and draw their energy from the grid (plug-in vehicles). Fraunhofer ISE is working at the interface between the vehicles and the grid on concepts for an environmentally acceptable power supply and optimal integration of the vehicles into the electricity grid. Together with partners from the car and power industry, the Institute is developing components for energy management and energy transmission.

For solar power generation on a large scale, predominantly for application in southern countries, Fraunhofer ISE is working on technology for solar-thermal power stations.

The facilities for our work on renewable power generation include:

- power electronics laboratory with modern equipment and software for power up to more than 500 kW
- development environments for micro-controllers, digital signal processors (DSP) and embedded systems
- measurement laboratory for electromagnetic compatibility (EMC)
- laboratory for information and communications technology
- smart metering laboratory
- measurement and calibration laboratory for solar modules
- outdoor test field for solar components
- battery laboratory for development and testing over a wide range of current, voltage and temperature values
- lighting measurement laboratory
- test stands for fuel cells operating with hydrogen and methanol
- spatially resolved characterisation of fuel cells
- testing and development laboratory for drinking water treatment systems



Structure of the smart metering system. The EWE box functions as a central energy gateway to process the meter data. In future, further value-added services such as distributed load management are foreseen for the box.

Contacts

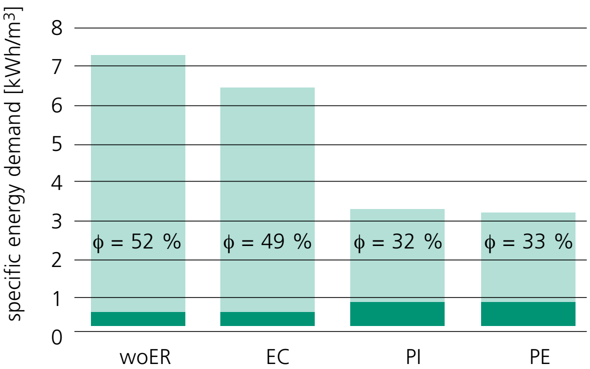
Renewable Power Generation	Dr Günther Ebert	Tel.: +49 (0) 7 61/45 88-52 29 E-mail: Guenther.Ebert@ise.fraunhofer.de
Distributed generation	Dr Thomas Erge	Tel.: +49 (0) 7 61/45 88-53 37 E-mail: Thomas.Erge@ise.fraunhofer.de
Smart grids, smart metering and operation management	Dr Christof Wittwer	Tel.: +49 (0) 7 61/45 88-51 15 E-mail: Christof.Wittwer@ise.fraunhofer.de
Power electronics and controls technology	Dr Bruno Burger	Tel.: +49 (0) 7 61/45 88-52 37 E-mail: Bruno.Burger@ise.fraunhofer.de
Electric storage systems	Dr Matthias Vetter	Tel.: +49 (0) 7 61/45 88-56 00 E-mail: Matthias.Vetter@ise.fraunhofer.de
Grid-connected photovoltaic systems	Klaus Kiefer	Tel.: +49 (0) 7 61/45 88-52 18 E-mail: Klaus.Kiefer@ise.fraunhofer.de
Solar power stations	Dr Werner Platzer	Tel.: +49 (0) 7 61/45 88-59 83 E-mail: Werner.Platzer@ise.fraunhofer.de
Stand-alone power supplies and isolated grids	Dr Matthias Vetter	Tel.: +49 (0) 7 61/45 88-56 00 E-mail: Matthias.Vetter@ise.fraunhofer.de
Fuel cell systems	Dr Christopher Hebling	Tel.: +49 (0) 7 61/45 88-51 95 E-mail: Christopher.Hebling@ise.fraunhofer.de
Hydrogen generation and storage	Dr Thomas Aicher	Tel.: +49 (0) 7 61/45 88-51 94 E-mail: Thomas.Aicher@ise.fraunhofer.de
Systems and electric procedures for water desalination and purification	Dr Matthias Vetter	Tel.: +49 (0) 7 61/45 88-56 00 E-mail: Matthias.Vetter@ise.fraunhofer.de
Thermal solar systems and procedures for water desalination and purification	Matthias Rommel	Tel.: +49 (0) 7 61/45 88-51 41 E-mail: Matthias.Rommel@ise.fraunhofer.de
Photovoltaic modules/ PV module pilot laboratory	Dr Harry Wirth	Tel.: +49 (0) 7 61/45 88-51 93 E-mail: Harry.Wirth@ise.fraunhofer.de

New Generation of Photovoltaically Powered Reverse-Osmosis Desalination Plants

For an efficient and economic supply of desalinated water to nearby houses, villages and commercial enterprises, we are developing photovoltaically powered reverse-osmosis desalination plants with energy recovery but no batteries. Our work has concentrated on technically and economically optimised dimensioning of the systems and the design of optimised operation management strategies on the basis of specially developed analytical and simulation tools.

Manuela Eisele, Caroline Heidtmann, Fabian Krömke, Alexander Schies, Hannes Schmoch, Matthias Vetter, **Joachim Went**, Günther Ebert

Fig. 1: View of the ocean along one of the driest but also sunniest coasts of Europe (Jandia, Fuerteventura, Spain). On the Canary Islands and in southern Spain, the drinking water supply is already provided by desalination plants on a large technological scale. Water is supplied to some villages (Cabo de Gata, Almería, Andalusia) by tank trucks in summer.



The increasing scarcity of drinking water in many countries has resulted in a rising demand for desalination plants for seawater and brackish water. In this context, an enormous market potential also for small, autonomous desalination plants can be anticipated (Fig. 1).

The next generation of autonomous, photovoltaically powered reverse-osmosis plants for seawater desalination should not include electric storage units for economic reasons. Direct connection of the PV generator to the hydraulic plant presents a series of new challenges to research and development. Initially, suitable components must be selected which allow the plant to be operated in accordance with the power supply offered by the sun.

To this purpose, we have developed an analytical tool at Fraunhofer ISE with which we can evaluate the energy demand and economic viability of widely differing system concepts for reverse osmosis. This allows innovative approaches and components to be classified and evaluated reliably with respect to their suitability (Fig. 2). We can model the dynamic performance of the plant with a detailed simulation program that was developed at Fraunhofer ISE. We use this tool to develop new algorithms for operation management and control of a reverse-osmosis plant. This is controlled in accordance with the power supplied by the sun.

The load profile for the desalination processes, which is determined in this way as a function of the solar power supply and the operation management concept, then forms the basis for dimensioning the PV generator.

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

Fig. 2: Example of a system comparison based on the specific energy demand of four reverse-osmosis concepts: without energy recovery (woER), with a hydraulic motor (EC), with a pressure intensifier (PI) and with a pressure exchanger (PE) as energy recovery units. The corresponding share of the specific energy demand is shown for water pre-treatment (dark) and the reverse osmosis process for the best yield ϕ in each case.

Lithium Batteries for Plug-In Hybrid Vehicles and Stationary Applications

To enable lithium batteries for plug-in hybrid vehicles and stationary applications to be simulated, we have developed a system model for various technological types of lithium ion batteries. In addition to sufficient accuracy for system simulation, important criteria included comparatively simple and fast parametrisation, high computing speeds and good adaptability to various types and models of lithium battery technology.

Andreas Rudolph, Simon Schwunk, Robert Thomas, **Matthias Vetter**, Günther Ebert

In the context of sustainable energy supply scenarios, electric vehicles are playing an increasingly important role in combination with renewable sources of energy. At Fraunhofer ISE, we are investigating the lithium battery for this application. To do so, we have developed a model which allows the lithium battery to be simulated at a high computing speed. We chose Shepherd's approach as a basis, which describes the open circuit voltage behaviour of batteries and has frequently been used for the simulation of lead-acid batteries in photovoltaic systems. Although this model does not include dynamic features, it can reproduce stationary states with sufficient accuracy. This approach is adequate for system considerations, e.g. concerning energy-related issues over long periods of time. With the modifications that we have made, this model is now also suitable for describing lithium batteries. The model was implemented in the Dymola simulation environment.

The work was based on measurements of various charging and discharging currents and the accompanying voltages in our battery laboratory. We developed our own program to extract and optimise the parameters which we use to model new types and models of battery technology quickly and simply. We have validated the model using different profiles from our laboratory.

The work is supported by the German Federal Ministry for Education and Research (BMBF) within the framework of the German-French Fraunhofer-Carnot co-operation programme.

Fig. 1: The photo shows two of the lithium batteries that were modelled within the German-French co-operation project, EMSIS. The negative electrode consists of carbon for both batteries; the positive electrode is made of $LiCoO_2$ for the left-hand cell and of $LiFePO_4$ for the right-hand cell. The developed model can be used for batteries of different capacities and technological types.

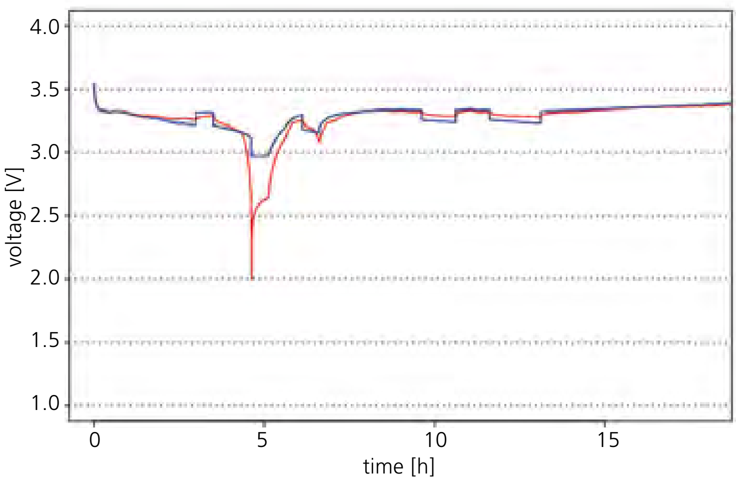


Fig. 2: The graph shows a validation sequence of the model for the battery based on $LiFePO_4$. The red line represents the measured cell voltage, the blue line shows the cell voltage as calculated using the model. The state of charge was varied between 0 and 100 % during the period illustrated. The model simulates the behaviour of the lithium battery very well for the states of charge higher than 10 % which are relevant to system simulation.

Modelling and Development of Control Strategies for Redox-Flow Batteries

The storage unit plays a key role in electricity systems with a high proportion of fluctuating regenerative sources. Among the various types of storage technology which are currently being investigated, the so-called redox-flow battery presents an interesting option due to its specific characteristics. In order to optimise the application and operation of these batteries, we are developing system models which are suitable both for designing simulation-based control strategies and for evaluation with respect to energy-relevant and economic criteria.

Martin Dennenmoser, Simon Schwunk,
Tom Smolinka, **Matthias Vetter**, Günther Ebert

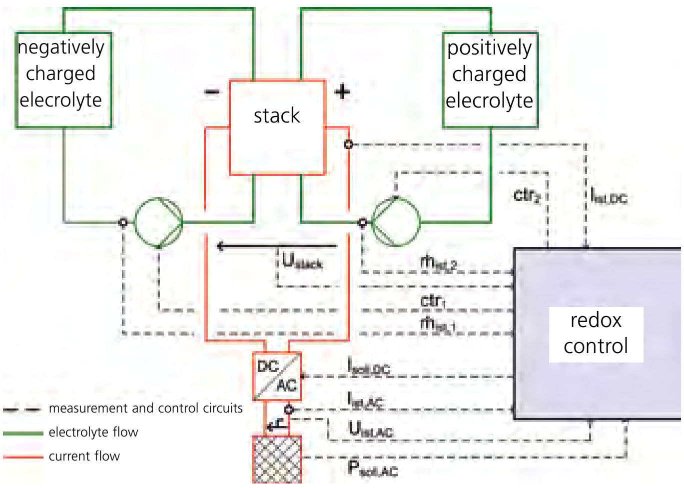
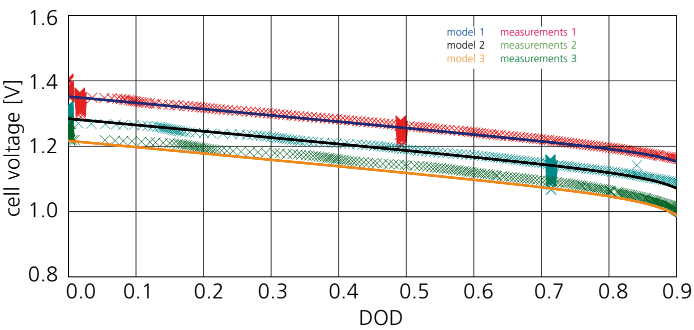


Fig. 1: Control concept for a vanadium redox-flow battery. The "RedoxControl" controller ensures optimised operation of the redox-flow battery as a function of the operating mode (charging and discharging), the operating point and the state of charge of the battery system.



Using the vanadium redox-flow battery which is currently being developed at Fraunhofer ISE (see page 97) as an example, we are preparing a system model in the Dymola simulation environment, using the Modelica programming language to define the model. The system model consists of sub-models for the stack, the tanks, the piping, the pumps, the valves and the inverter for grid connection.

With these models, it is feasible to design simulation-based control strategies from the first drafts up to implementation. The presently implemented control concept is illustrated in Figure 1.

In addition to their application in simulation-based control strategies, the developed models are designed to allow technical and economic analyses and optimised integration into an energy system. This encompasses both applications in stand-alone systems (single buildings, autonomous mini-grids) and in grid-connected systems (large storage systems, distributed small storage units). The sub-model for the stack calculates the reaction mass flows in the electrochemical cell from the power demand. The state of charge of the vanadium redox-flow battery can be determined from the resulting changes in concentration. We have applied Shepherd's approach to describe the voltage and current characteristics as a function of the state of charge (Fig. 2).

The work is being carried out within a Fraunhofer joint project.

Fig. 2: Measured and simulated cell voltage of a vanadium redox-flow battery during discharge as a function of current and state of charge. For this comparison, constant currents of I1 = 20 A, I2 = 30 A and I3 = 40 A were maintained during discharge.

Characterisation of Photovoltaic LED Lamps

We have developed a three-stage testing procedure to assess the quality of photovoltaically powered lamps with white LED's (light-emitting diodes). It was applied for cost-effective testing of more than ten LED lamps to determine their potential to replace candles or petroleum lamps in rural areas. It became evident that predominantly lamps with high-power LED's achieved operating lifetimes of more than 10 000 h. There are very few lamps based on multiple low-power LED's which maintain stable illumination over this operating period.

Georg Bopp, Stephan Lux, Norbert Pfanner, Michael Strasser, Günther Ebert

Altogether 1.6 thousand million people do not have access to a public electricity grid. Petroleum lamps are often used for lighting in rural areas of developing and threshold countries. These pollute the environment, provide poor-quality light and impose a heavy financial load on the users, with an annual petroleum consumption of about 35 l.

An alternative is offered by small, photovoltaically powered lamps. These provide significantly better lighting and are environmentally friendly. In addition, some of the systems can also supply power for mobile phones, radio and television.

During the last two years, compact fluorescent lamps and lead-acid batteries in photovoltaically powered lamps were largely replaced by white LED's and nickel-metal hydride (NiMh) batteries. If the rural population is to purchase such lamps and use them effectively, the LED lamps must be inexpensive and function reliably for many years under difficult conditions.

As the long-term stability and thus the quality of very cheap LED lamps are often poor, we have developed a three-stage testing procedure to accelerate quality control. Lamps which have inadequate mechanical or electrical quality are disqualified already in the first testing stage. This reduces testing time and testing costs when defects are clearly evident. In the second testing stage, electric properties such as the power generated by the photovoltaic module and the LED efficiency value are tested. In the third testing stage, the long-term stability of the LED illumination is evaluated.

The work is supported by the German "Gesellschaft für Technische Zusammenarbeit GTZ" and the World Bank.

Fig. 1: Different types of photovoltaically powered LED lamps. The models on the left and the right are each equipped with a single high-power white LED; the centre model contains many low-power LED's. During the day, the integrated NiMh rechargeable battery is charged by a small photovoltaic module with app. 5 W power. Depending on the dimensions, illumination times of 3 to 8 h during the night are achieved. The quality of the photovoltaic modules and the rechargeable batteries is relatively good, the average deviation from the rated value is minus 10 %.

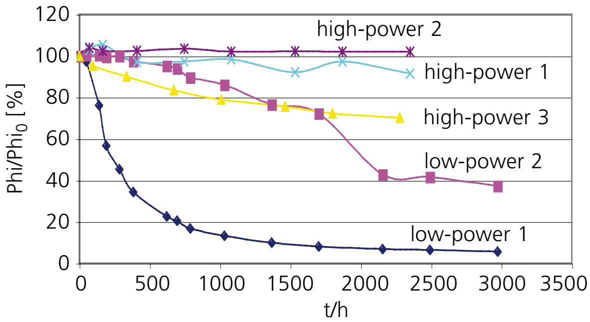


Fig. 2: Stability of luminous flux versus operation time. The illumination from most of the low-power LED's already degrades after 200 – 1500 h to 70 % of the initial value, marking the end of the lamp's lifetime. This lifetime is much too short for room illumination purposes. By contrast, the luminous flux from most of the high-power LED's is stable over many thousands of hours and lifetimes of 10,000 – 50,000 h are achieved.

Smart Metering System with Feedback on Consumption, Costs and CO_2 Emission

On commission to the Oldenburg utility, EWE AG, Fraunhofer ISE has developed a smart metering system which provides real-time feedback to electricity and gas customers about their energy consumption, the resulting costs and associated emission of CO_2. Our development encompassed both the technology for communications and feedback, and an innovative tariff system. The conservation and redistribution effects of this system are now being investigated in a field test involving 400 households.

Markus Büttner, **Stefan Feuerhahn**, Dominik Noeren, Harald Schäffler, Thies Stillahn, Christof Wittwer, Michael Zillgith, Günter Ebert

Fig. 1: The display receives energy data via ZigBee radio and shows daily values, quarter-hourly values and real-time power values.

The application of so-called smart meters is an important component in the introduction of resource-conserving energy management systems. Fraunhofer ISE, supported by the Fraunhofer Applications Centre for Systems Engineering AST, has developed a system that is based on such meters.

The central component of this system is the EWE box, an energy gateway in the customer's household which reads out electronic electricity and gas meters via an M-bus network. The measured data are transmitted via ZigBee radio from there to a portable display and transferred via the customer's DSL connection to a call-up server of the energy utility. In this way, the data are available for further processing such as billing and visualisation in the Internet portal. To this purpose, we have developed hardware prototypes for the energy gateway and the feedback display. The contents of the feedback systems (display, Internet portal and monthly consumption analysis) were also designed and implemented by us. In addition, time-zoned and load-dependent tariff models that are based on simulations can be offered to the clients. The systems will now be tested for a year and their effectiveness evaluated in a field test with 400 households.

The project was supported by the utility, EWE AG.

Fig. 2: Structure of the smart metering system. The EWE box serves as the central energy gateway and processes the meter data. In future, further value-added services such as distributed load management are planned for the box.

VIRTPLANT – Optimisation of Distributed Power Plants in Freiburg

With the goal of using the decentralised power generation potential efficiently, we developed and implemented a new integrated optimisation approach for system operation management in a distribution grid. We prepare operating schedules for distributed generators on the basis of load and generation predictions. The schedules are optimised according to the requirements of grid operation, the energy market situation or expectations on a sustainable energy supply.

Thomas Erge, Bernhard Wille-Haussmann, Christof Wittwer, Alexander von Zastrow, Günter Ebert

The efficient integration of distributed electricity generators directly at the feed-in level into distribution grids will play a key role in power supply in the future. We have developed a concept and tools for the operation management of distributed systems, which aim to achieve improved technical integration and greater energy-economic benefit from decentrally generated electricity. We have adapted this approach to the situation of the Freiburg utility, badenova AG & Co. KG and developed it further. There is a large proportion of distributed generation in the badenova grid, consisting of combined heat and power (CHP) plants, wind turbines, photovoltaics and other aggregates. With the help of scientific prognosis systems and the analysis of historic data, we have succeeded in predicting load and generation profiles, including the fluctuating input from renewable energy sources. Starting from a model of the complete system, we can now optimise the operation management of controllable generators and alterable loads according to criteria from grid operation or electricity trading. The resulting "day-ahead" operating schedules are transmitted to badenova's central control unit and form the basis for operating decisions by the staff there. Directly automated control of the distributed generators is foreseen as a future option.

In practical test operation, we demonstrated that advantages result both for the plant owners and for the operator of the distribution grid from appropriate operation management of the CHP plants.

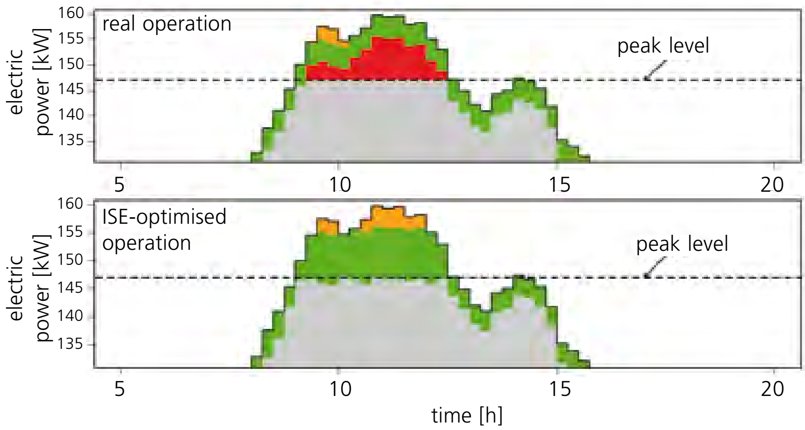


Fig. 1: The purchase of peak power from large-scale electricity transmission grids creates a financial load which is passed on to all customers. With our energy management system for distributed generators, we have succeeded in predicting peak power. By applying optimised thermal-electric operation management to local CHP plants and other generators, sufficient electricity can be generated locally at the right time, significantly reducing the consumption of external peak power.

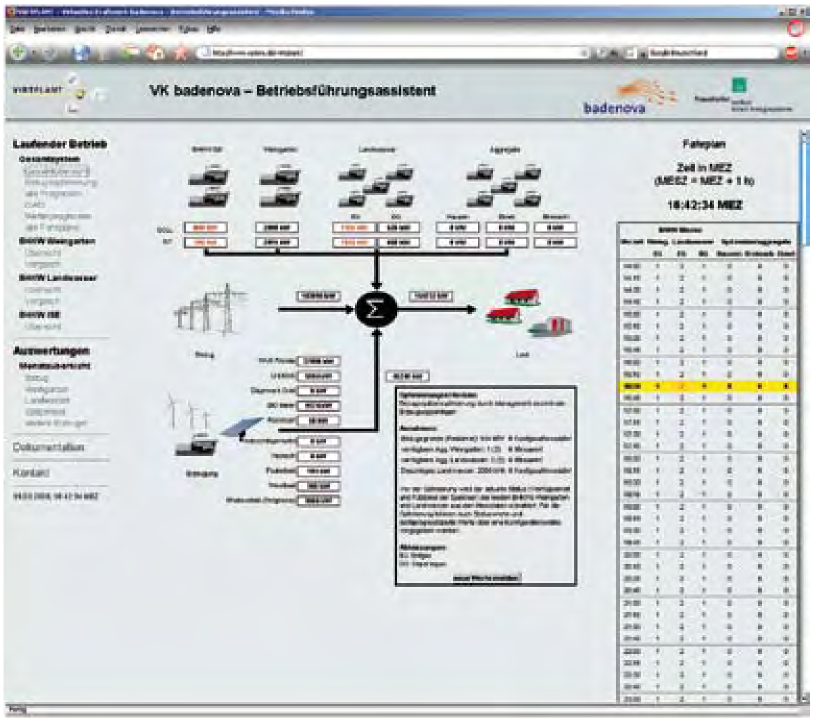


Fig. 2: A web-based operation management assistant is used to transmit the operation schedules for controllable generators and loads to the central control unit of the Freiburg utility, badenova, and to quickly indicate deviations between the planned goals and the real situation. In addition, we provide further comprehensive information such as load and generation predictions, operation analyses and energy balances.

The project was supported by the Innovation Foundation of badenova AG & Co. KG.

New Simulation Models for Optimised Yield Forecasts

Yield forecasts represent an essential tool for the preparation of financing concepts for larger photovoltaic plants. We have developed a new simulation model for PV modules to improve the quality of our predictions. This model can accept input data directly from the manufacturer's data sheet or from measurements made in the module calibration laboratory (CalLab) at Fraunhofer ISE.

Wolfgang Heydenreich, Klaus Kiefer, Björn Müller, **Christian Reise**, Günther Ebert

Fig. 1: How many MWh of electricity will this plant generate in a typical year? In order to answer this question, the properties of the installed module type as documented in its data sheet must be modelled as exactly as possible. Each percentage point error in the prediction corresponds to a financial value of about € 35,000 per year for a system with 10 MW installed power (as illustrated here in the photo).

The main information provided by a yield forecast is the anticipated annual energy yield, specified as an absolute value in kWh or related to the system dimensions in kWh per kWp. The simulation models which are used to calculate this predicted value should reproduce the behaviour of the system components as accurately as possible. Uncertainties in these models, just like uncertainties in the meteorological data used, affect the total uncertainty of the prediction.

We have developed a new model for the module efficiency as a basis for calculating the PV generator power. In contrast to previously used models, which drew on semiconductor physics, this procedure is based on only three elementary model assumptions. It is thus only just as complex as necessary, but as simple as possible, in order to reproduce the module properties specified in a data sheet with a small number of parameters.

Investigations showed that the accuracy which can be achieved even with our simple model is still limited by the uncertainty in the available specifications from data sheets. However, this uncertainty can be largely avoided by the use of data from commissioned measurements by our module calibration laboratory to parametrise the model. Typical errors in the reproduction of measured efficiency profiles are then significantly lower than 0.5 %.

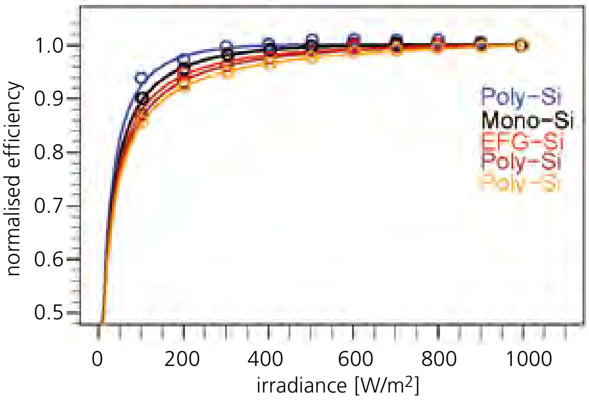


Fig. 2: Each different type of module shows different behaviour for the efficiency value. The dependence on the irradiance is shown here. All curves, which were measured in our calibration laboratory, are normalised to the same efficiency value for standard test conditions (1000 Wm^{-2}). At 200 Wm^{-2}, the efficiency value is between 2.1 % and 7.8 % lower.

Mutual Shading in Tracking Photovoltaic Plants

As the available ground area is limited, mutual shading due to the trackers is unavoidable in tracking photovoltaic plants. The extent of shading losses is important for predicting the system yield and optimising the geometrical configuration of the installation. We have thus developed a procedure at Fraunhofer ISE which determines these losses by the application of RADIANCE ray-tracing software.

Klaus Kiefer, **Björn Müller**, Christian Reise, Günther Ebert

Tracking systems have become established on the market for free-standing photovoltaic plants due to the higher yields which can be gained in comparison to fixed systems. In planning such systems, it is essential to find a good compromise between the area occupied and unavoidable losses due to mutual shading.

The simulation program that we have developed calculates mutual shading with the help of the RADIANCE ray-tracing software. A section of the complete system is modelled in the software (Fig. 1). The software sensors located on the central tracker in Fig. 1 then "measure" the irradiance for each time step of the simulation. High temporal resolution of the simulation is needed in order to take account of all radiation conditions, solar positions and tracker positions. Our software thus uses about 45,000 time steps to simulate the yield of a tracking system for one year (Fig. 2).

The results include information on the additional yield due to the tracking and the shading losses for a given distance between modules. Optimal configurations can be found by varying the distances between modules. Furthermore, the simulated irradiance values can be used to optimise the layout of the individual module strings on the trackers. This optimisation alone makes it possible to avoid shading losses in the percentage range.

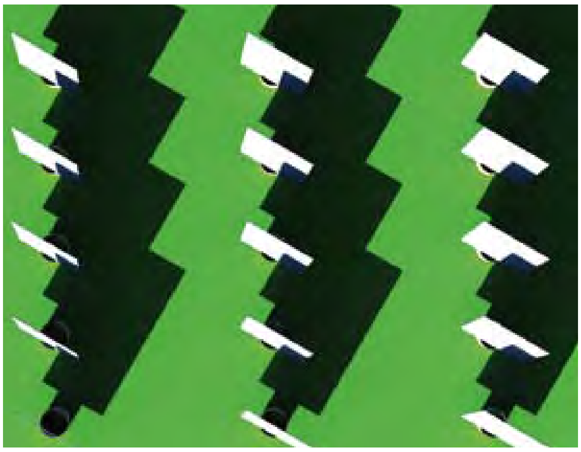


Fig. 1: Modelling a photovoltaic system with double-axis tracking in RADIANCE. As an example, the image shows an overhead view of the trackers and their shadows on 21st December at 2 p.m. at a location in Southern Europe.

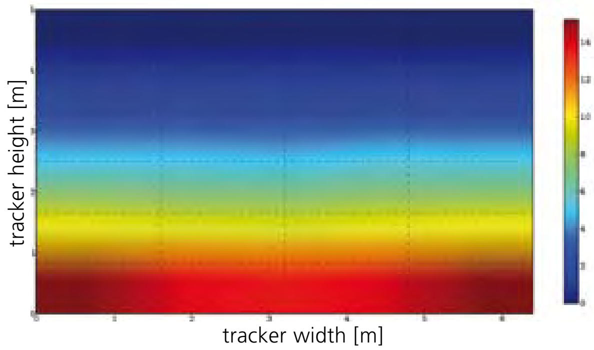


Fig. 2: Shading losses (in % over a year) for a system with double-axis solar tracking. The graph shows the area that is equipped with modules for the tracker at the centre of Fig. 1. The dashed lines indicate the edges of the individual modules. The largest losses occur at the two lower corners of the tracker surface (app. 15 % of the radiation incident on the module plane). The upper row of modules is hardly shaded at all.

Power Quality Functions of PV Inverters

The rapidly growing sector of distributed electricity generation is changing the properties of distribution grids. We are developing photovoltaic (PV) inverters which actively participate in controlling the grid to ensure its stability. They provide reactive power and can continue to feed in power if short circuits occur in the grid. Furthermore, we are extending the digital controllers of PV inverters to become active filters which can compensate for the voltage distortions caused by electronic loads.

Stefan Reichert, **Christoph Siedle**, Günther Ebert

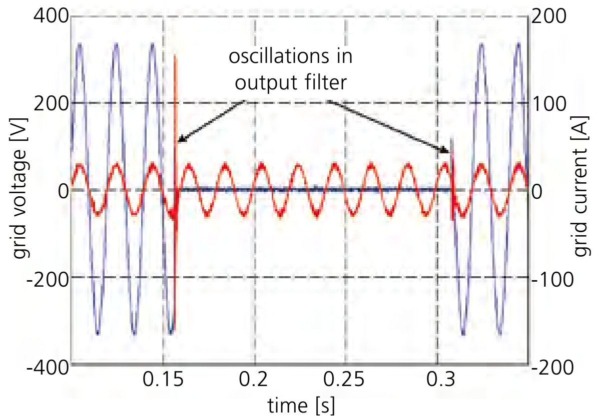
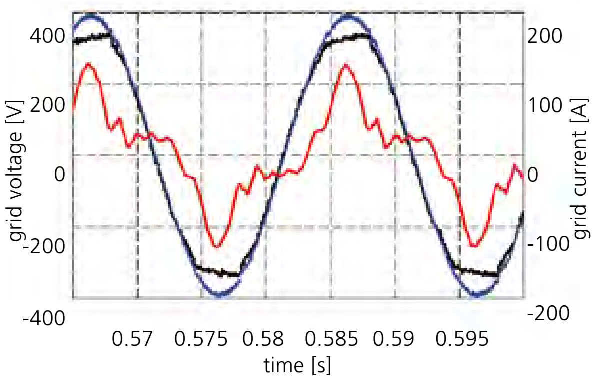


Fig. 1: Grid short circuit: The current from the inverter (red) is fed into the grid with a controlled sinusoidal profile of the correct frequency and amplitude for the duration of the short circuit, and thus supports the grid. The rapid changes in the voltage (blue) at the beginning and end of the short-circuit phase cause strong fluctuations in the output filter of the inverter, which are attenuated within 2 ms by the highly optimised control algorithm.



The increasing penetration of electricity distribution grids with distributed generators changes the dynamic properties of the grids. The grid operators are reacting with new specifications for generators in medium-voltage and low-voltage grids to ensure grid stability.

Apart from providing reactive power, in future feed-in inverters must be able to support the grid during short-term voltage breakdowns and short circuits. We are developing inverters with these features. Figure 1 shows the simulation of current that is fed into the grid by an inverter for the duration of a grid short circuit. The simulation model processes real grid voltage values.

Non-linear loads such as computers, televisions or energy-saving lamps distort the sinusoidal grid voltage by the harmonic components of their currents. This causes increased losses in other loads. In this case, PV inverters can be effective as active filters and feed in compensating currents into the grid. We are designing and implementing suitable procedures for this. The distorted grid voltage in Fig. 2 is modified back to a sinusoidal profile by a 50 Hz active current with a superimposed compensation current that is rich in harmonics.

If grid faults continue for longer periods, directly connected loads can be powered with an emergency power supply from our inverter after it has been disconnected from the grid. When the grid becomes available again, it is switched back in without interruption.

Fig. 2: Compensation of distortion: The grid voltage with its flattened peak (black) is transformed back into a sinusoidal form (blue) by fed-in current with strong harmonic components. The inverter makes upper-harmonic currents available to compensate loads which distort the grid voltage with their harmonic-rich spectrum.

Reliability and Durability of Photovoltaic Modules

Manufacturers of solar modules currently give performance guarantees for 20 years and more. This is possible only because relevant experience on service lifetime is available for the materials used. Anyone who wishes to apply alternative, less expensive materials has difficulty in assessing their reliability. In order to create new possibilities in this field, we are developing an accelerated aging test for solar modules and are setting up outdoor exposure sites at locations with extreme climatic conditions.

Claudio Ferrara, Markus Heck, **Michael Köhl**, Daniel Philipp, Karl-Anders Weiß, Hans-Martin Henning

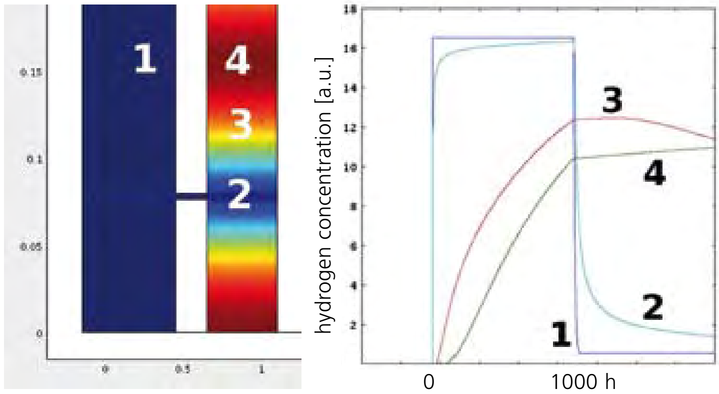


Fig. 2: Modelling the distribution of the water concentration in the encapsulation material of photovoltaic modules with crystalline silicon cells (white). The left-hand graph shows the moisture distribution after 1000 h of the damp heat test (85 % r. h. / 85 °C) in a colour-coded representation (high humidity is blue). The change in water concentration with time is shown in the right-hand graph for four selected positions in the module. Saturation is reached quickly at the back surface (No. 1, blue line).

Aging processes in a photovoltaic (PV) module are primarily influenced by the following factors: ultraviolet radiation, mechanical loads e.g. due to snow and wind, internal stresses resulting from different coefficients of thermal expansion and diffusion of water and oxygen.

Simulation programs based on finite elements help us to understand energy and mass transport in PV modules. An important result is that even with the damp heat test (85 % r.h., 85 °C) specified by the IEC 61215 standard, the encapsulating materials are not homogeneously humidified after a test duration of 1000 h, but that at least 3000 h are needed (Fig. 1). To validate the simulation results and the accelerated tests of service lifetime, we have exposed commercial modules and test modules with innovative material combinations to arid, tropical, alpine and urban environmental conditions. Analysis of the loads, based on continuous monitoring over a complete year, revealed that the moisture load in the tropics is four times higher than in the Alps, for instance. One result of these investigations is that, depending on the location, exposure periods of 3000 to 13,000 h are needed for realistic prediction of the response to moisture of PV modules with the common EVA encapsulation material over a lifetime of 25 years (EVA – ethylene vinyl acetate).

The cluster project on "Reliability of PV Modules" is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

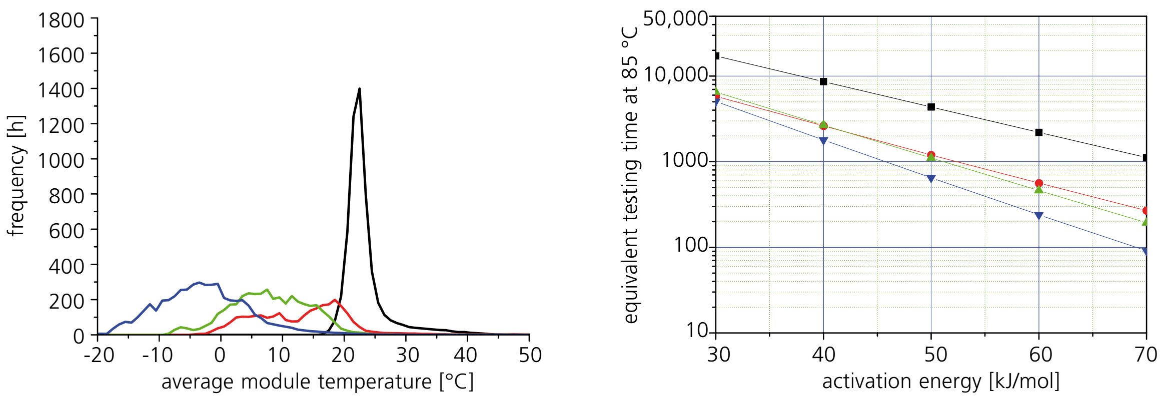


Fig. 1: Frequency of periods with high humidity (> 80 % rel. humidity) as a function of the average module temperature at four outdoor exposure locations, Schneefernerhaus (alpine – blue), Cologne (urban – green), Sede Boqer in Israel (arid – red) and Serpong in Indonesia (tropical – black). The frequency distributions show the clear differences in the humidity and temperature loads (left), which naturally lead to very different damp heat testing times ranging from 3000 to 13,000 hours (right) to simulate a service lifetime of 25 years for EVA with an activation energy of 34 kJ/mol (right).

Comparison of Concepts for Solar-Thermal Power Plants

Our simulation models for the techno-economic optimisation and evaluation of large solar-thermal power plants and smaller systems for cogeneration of electricity, heat and cooling power are continuously being extended. Technologically, we have focused on component development and experimental quality assurance in the relatively new field of linear Fresnel concentration. In view of the progress achieved, we are convinced that this will make a substantial contribution to solar-thermal generation of electricity on the medium term.

Torsten Gutjahr, **Anna Heimsath**,
Helena Hülsey, **Gabriel Morin**, Sanmati Naik,
Anton Neuhäuser, Peter Nitz,
Andreas Sauerborn, **Werner Platzer**

Solar-thermal power plants with concentrating collector fields can achieve electricity generation costs between 15 and 20 ct/kWh or even less in areas with a large proportion of direct radiation (e.g. Mediterranean region, North Africa, South-West of the USA). Apart from the climatic prerequisites, it is important that a power plant has a consistent concept regarding the quality and dimensioning of the solar array, storage and operation design, and that these factors are adapted to the project-specific parameters. The production processes and selection of components influence both the costs and the yield and must therefore be optimised.

This task is complex due to the large number of mutually interacting parameters and cannot be undertaken effectively with simple methods. We have therefore continuously expanded our models for techno-economic optimisation as a central aspect. Applying them, we can:

- support technical decisions and dimensioning
- identify and quantify potential for (further) development of products
- evaluate and optimise commercial power plant projects and concepts

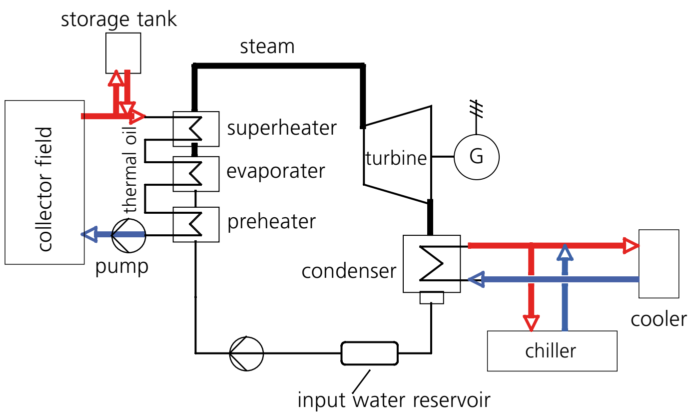


Fig. 1: Example of integration of a thermal absorption chiller and a thermal storage unit into a cyclic process for electricity generation (power and cooling combination, schematic).

In addition to electricity generation alone (thermal turbines based on steam and organic Rankine processes), we have extended our simulation tools so that we can evaluate heat and power (and cooling) cogeneration e.g. with outputs of process steam or absorption cooling power (Fig. 1).

Realistic simulation models must be validated experimentally. Equally, specifications of components such as receivers, primary reflector arrays or circulation systems must be checked with regard to their optical and thermodynamic behaviour. Quality assurance in the factory and on site is necessary to ensure economic viability (Fig. 2).

Experimental characterisation methods and test stands are thus continuously further developed at Fraunhofer ISE. Measurements of reflectors and receivers, particularly for the more recent Fresnel collectors, have been the main focus up to now. The collector efficiency values which we predicted with our simulations are currently being confirmed by measurements which we are making together with DLR at the FRESDEMO test facility (Fig. 3), which was constructed by MAN at the solar research platform at Almería in southern Spain.

One main difficulty confronting the economic evaluation of Fresnel collectors is the lack of a commercial data base on the investment and operating costs of this type of collector. We have thus calculated the so-called break-even costs, for which the Fresnel collector is economically competitive with the commercial parabolic trough.

Assuming reference costs for parabolic troughs of € 275 per m^2, the Fresnel collector may cost between 100 and 220 €/m^2 (relative to the aperture area), depending on the technological variant. Fundamentally lower optical efficiency values are offset by cost advantages due to the use of flat primary reflectors, less stringent demands on the construction due to lower wind loads, and higher concentration factors.

In view of recent developments in the technology, we are convinced that the cost goals will be reached with the Fresnel concept and that the technology will make a decisive contribution to solar-thermal electricity generation on the medium term.

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

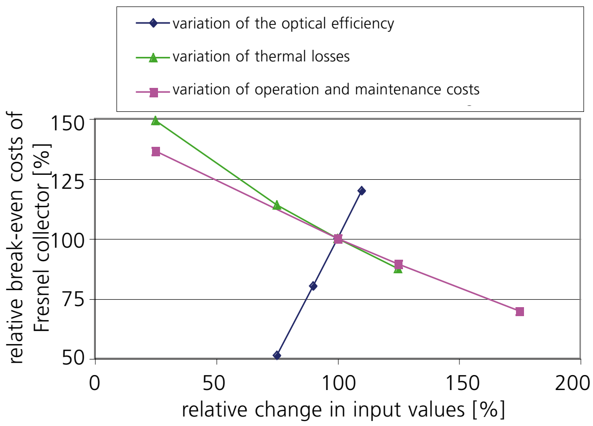


Fig. 2: Influences on the relative break-even investment costs for the linear Fresnel collector compared to the parabolic trough. The quality of the optical components is very critical for the economic viability: If the average optical efficiency is reduced by inaccuracy, soiling or degradation by 10 %, the allowable investment costs for the Fresnel collector decrease by 20 %.

Fig. 3: FRESDEMO test collector at the Plataforma Solar de Almería, Spain. Measurement of this collector serves as the basis for techno-economic evaluation of Fresnel technology (base case).

Electricity from hydrogen

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, hydrogen is produced by means of renewably generated electricity using electrolyser systems. 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 will be used to store intermittently generated 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 the power for on-board electrical systems independently of the drive-train. Finally, miniature fuel cells are excellent alternatives or supplements to rechargeable batteries in off-grid power supplies or small electronic appliances, due to the high energy density of hydrogen or alcohol. 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.

Research on innovative technology to obtain hydrogen and convert it efficiently to electricity and heat forms the core of the “Hydrogen Technology“ business unit at Fraunhofer ISE. 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 into hydrogen-rich reformate gas. 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-damaging carbon monoxide in the reformate gas. Such systems can be used in applications that include stationary combined heat and power plants (CHP), auxiliary power units (APU) and off-grid power supplies.

As our contribution to a sustainable energy supply, we are extending our portfolio to include the conversion and usage of biomass. A technical prototype for gasification of wood is being developed, with which we intend to demonstrate the feasibility of a new process which was developed by Fraunhofer ISE in co-operation with other partners. Furthermore, we are developing a reactor to use energy from biomass consisting of green algae.

To obtain hydrogen from water, we develop 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 such as environmental scanning electron microscopy (ESEM), cyclovoltammetry (CV) and inductive coupled plasma spectroscopy (ICP).

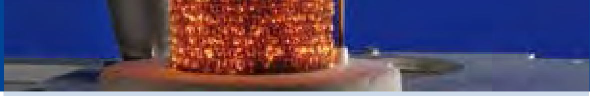
The membrane fuel cell, operated with hydrogen or methanol, is our favoured energy converter in the power range from milliwatts to several hundred watts, being efficient, environmentally friendly, quiet and requiring little maintenance. In addition to the well-known system configuration based on fuel cell stacks, we have focussed on flat, series-connected miniature 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 the development of 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 on-board electrical systems for cars, trucks, ships or aeroplanes (APUs), as well as stand-alone power supplies for off-grid applications and small portable electronic systems.

A newly developed catalytic oil evaporator (in the background) is able to convert heating oil completely into vapour, without forming residues. The heating oil vapour is then used as the fuel for a gas burner (in the foreground). This development makes it feasible to burn heating oil (or diesel as an alternative) in a modulating mode over a wide load range in a gas burner. Up to now, this has not been technically possible in oil burners.

Contacts

Hydrogen technology	Dr Christopher Hebling	Tel.: +49 (0) 7 61/45 88-51 95 E-mail: Christopher.Hebling@ise.fraunhofer.de
Fuel cell systems	Ulf Groos	Tel.: +49 (0) 7 61/45 88-52 02 E-mail: Ulf.Groos@ise.fraunhofer.de
Hydrogen production	Dr Thomas Aicher	Tel.: +49 (0) 7 61/45 88-51 94 E-mail: Thomas.Aicher@ise.fraunhofer.de
Chemical energy storage	Dr Tom Smolinka	Tel.: +49 (0) 7 61/45 88-52 12 E-mail: Tom.Smolinka@ise.fraunhofer.de
Integration of fuel cells into stand-alone power supplies	Dr Matthias Vetter	Tel.: +49 (0) 7 61/45 88-56 00 E-mail: Matthias.Vetter@ise.fraunhofer.de
Power and control electronics for fuel cells	Dr Bruno Burger	Tel.: +49 (0) 7 61/45 88-52 37 E-mail: Bruno.Burger@ise.fraunhofer.de
Control strategies for fuel-cell CHP plants in buildings	Dr Christof Wittwer	Tel.: +49 (0) 7 61/45 88-51 15 E-mail: Christof.Wittwer@ise.fraunhofer.de



Fully Automated, Portable 300 W_{el} Reformer/Fuel Cell System

For off-grid power supply, we have developed a fully automated, portable 300 W_{el} reformer/fuel cell system. Denatured ethanol is used as the fuel for it. The system is suitable for numerous applications such as a power supply for caravans, yachts, small traction engines, telecommunications or emergency back-up power.

Thomas Aicher, **Johannes Full**, Christoph Ketterer, Christian Lintner, Lisbeth Rochlitz, Christopher Hebling

Fuel cell systems (FCS) for off-grid power supply in the range of several hundred watts are ideally combined directly with a hydrogen-generating reformer, if they are to achieve long periods of autonomous operation. The main advantage of such reformer/fuel cell systems (RFCS) is that the high energy storage density of the fuel is united with the high power density of fuel cells.

Numerous systems of this type are currently being developed for applications such as power supplies for caravans, yachts, telecommunications, emergency back-up power and small traction engines. In order to make these power supply systems accessible also to consumers, the fuel must be commercially available, inexpensive, safe and non-toxic. Ethanol meets all of these requirements.

At Fraunhofer ISE, we are currently developing an ethanol RFCS with a net electric power of 250 W. The system should be suitable for outdoor use, i.e. for operation at outdoor temperatures between -10 °C and +40 °C. The electric power should be available as soon as the system is switched on. This means that the starting phase of the reformer, during which hydrogen does not yet flow to the fuel cell, has to be

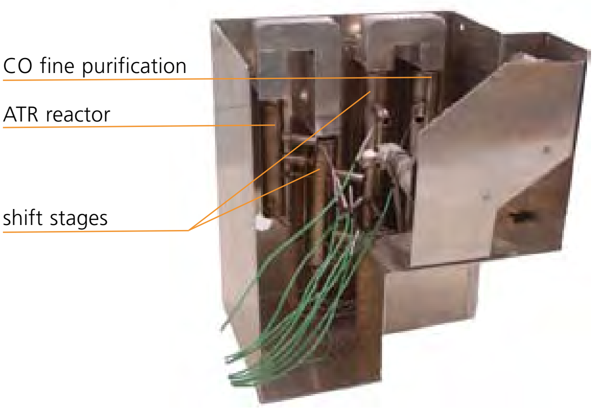


Fig. 1: "Hot box" of the 300 W_{el} ethanol reformer system. The individual reactor stages (autothermal reformer – ATR, 2-stage shift and CO fine purification) can be seen. The green cables are connected to thermocouples, which measure the temperatures in the individual reactor stages.

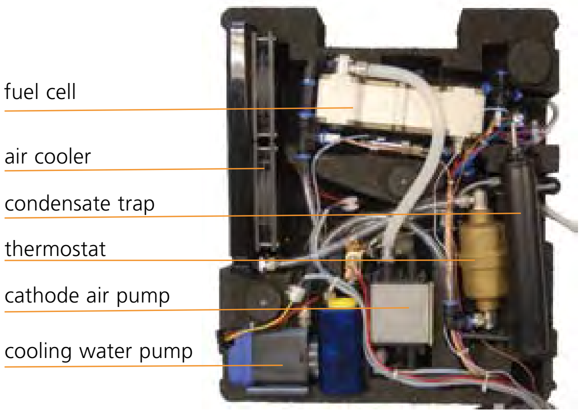


Fig. 2: View of the fuel cell module with all associated peripheral components.

bridged with a buffer battery. The total system volume and mass will amount to about 95 l and 30 kg. The partners in this joint project are the companies, DMT, EGO, Elbau, Intratec, Lifebridge, Magnum and Umicore, and the HSG-IMIT research institute.

In the final year of the three-year project, we transferred the system, which had previously been operated in a test stand, to a modularly constructed, fully automated functional model. Work concentrated on the optimisation of the starting and stopping processes. By applying a well-adapted starting process and a regeneration phase during the stopping phase, we succeeded in improving the long-term stability of the catalysts such that even after 50 starts and stops, more than 150 h of operation and longer idle periods, the gas concentration achieved was still suitable for FC operation.

The fuel cell generates power of app. 300 W with reformate at the anode and ambient air at the cathode. After comprehensive tests, in which the air supply, the inlet temperature, the FC purging interval and the temperature of the cooling water were varied, we were able to achieve stable operating conditions (Fig. 3).

The gas conversion efficiency is about 80 % at maximum power. The air number on the cathode side is between 2.5 and 3. The air bleed amounts to app. 2 % of the hydrogen contained in the reformer. The air bleed is needed to oxidise carbon monoxide which has remained in the reformate, and thus raise the CO tolerance of the fuel cell. The anode is purged periodically, i.e. gas is released to the surroundings for a short time and thus causes a pulse which removes water droplets from the anode. In long-term tests, we will test whether the fuel cell can be operated on a continuous basis with these parameters. Together with the DMT company, we are preparing a housing design which divides the RFC module into several functional modules (Fig. 4). The individual modules (fuel cell, reformer, electronics and tank) are constructed separately and thus can also be optimised separately. All modules will be mounted on top of each other in a transport cart. Individual modules can be removed as needed for transport or maintenance.

The work was supported by the German Federal Ministry for Economics and Technology (BMWi) within the "RBZ-Modul" project.

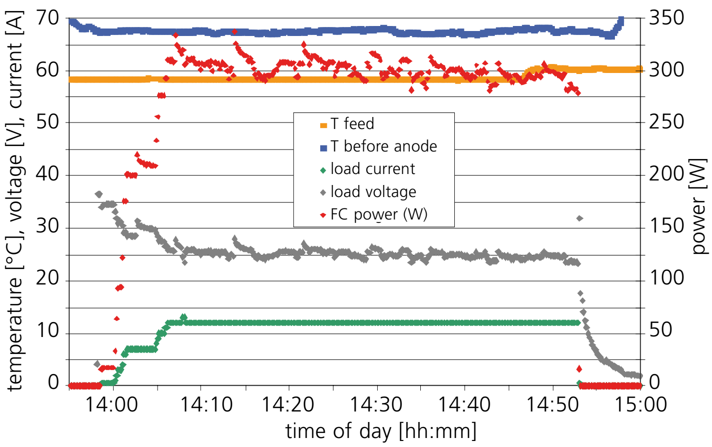
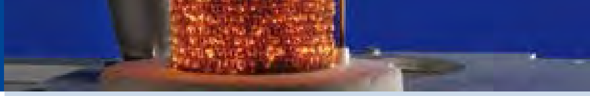


Fig. 3: Typical measured values for operation of the fuel cell with reformate gas. With a controlled current of 12 A (green), a voltage of about 25 V (grey) and power of about 300 W (red) are delivered by the fuel cell, depending on the amount of gas. The periodic fluctuations in the power are caused by periodic purging. The fuel cell is operated at a temperature of app. 58 °C. The cathode air is outlet with a temperature of about 65 °C.

Fig. 4: 3D view of the modular RFCS. The reformer module is located at the top (red), with the FC module below it (violet). The other three modules contain the electronics (blue) and the fuel tanks. The system has wheels and a handle to simplify transport. Individual modules can be removed for transport. The tanks can be simply replaced for refilling.



Fully Automatic Pyrolysis System for High-Temperature PEM Fuel Cell

We have developed a fully automatic pyrolysis system to supply hydrogen for high-temperature polymer-electrolyte membrane fuel cells (HT-PEMFC). It consists of two reactors in which pyrolysis and regeneration take place alternately. The product gas from the pyrolysis can be fed directly into a fuel cell system and converted there into electricity and heat. Gas purification is not necessary. Furthermore, the pyrolysis process does not require any processing water, so complex water purification and recovery steps are not needed.

Timo Kurz, Marc Lehmann,
Alexander Susdorf, Robert Szolak,
Christopher Hebling

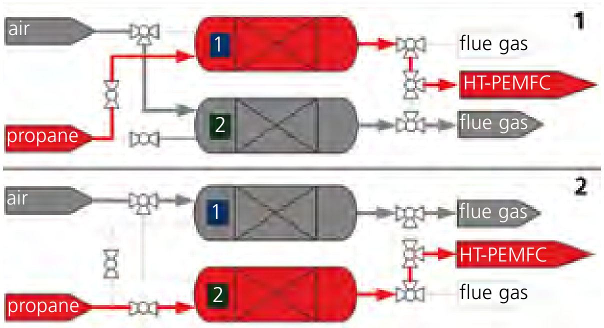


Fig. 1: Schematic diagram of the pyrolysis system. While pyrolysis takes place in the first reactor, the second reactor is regenerated (1) and vice versa (2).

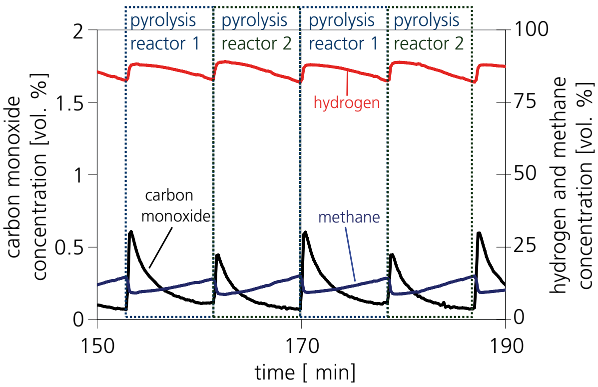


Fig. 2: Gas composition during propane pyrolysis in reactors 1 and 2. The pyrolysis temperature is 750 °C in both reactors. The pyrolysis time is 10 minutes in each reactor. The hydrogen concentration (right-hand ordinate scale) is greater than 80 vol. % even at the switching point. The carbon monoxide concentration (left-hand ordinate scale) always remains less than 0.6 vol. %.

Pyrolysis offers an alternative to conventional reforming. The fuel, e.g. propane, is catalytically converted to hydrogen, methane and carbon. The resulting carbon is combusted in a second step. To generate a continuous gas flow rate that is suitable for a fuel cell, two reactors are thus required, in which pyrolysis and regeneration occur alternately. The regeneration period is always shorter than the pyrolysis period. The changing conditions mean that the catalyst must meet stringent specifications. At Fraunhofer ISE, we have developed and optimised a catalyst for the pyrolysis system which is stable over long periods.

The active component of the catalyst consists of a cost-effective nickel alloy which is deposited onto a suitable substrate. At the beginning of each pyrolysis cycle, the catalyst is in the oxidised state and must first be reduced. The educt flow is used for the reduction. The stored oxygen is released at the beginning of the pyrolysis in the form of carbon monoxide and carbon dioxide. We have optimised the parameters of the pyrolysis system such that the carbon monoxide concentration is always less than 0.5 vol. % when the process switches between the two reactors. At the same time, the hydrogen concentration always remains above 80 vol. %. In contrast to the standard PEM fuel cell, the high-temperature PEM fuel cell does not require humidification of the input gases and tolerates carbon monoxide concentrations of more than 1 vol. % in the fuel gas. These properties make the HT-PEM FC ideal for combination with the pyrolysis system.

Direct Generation of Electricity from Ethanol

As an innovative type of fuel cell technology, we developed a demonstration system with a special fuel cell which generates electricity directly from ethanol. In this way, the advantages of ethanol as a fuel – widespread availability, high energy density and production from organic materials – can be used in a quiet and simple system for electricity generation.

Adam Halaburda, **Stefan Keller**, Julia Melke, Christopher Hebling

Development of a system to generate electricity directly from ethanol combines several aspects of Fraunhofer expertise. The main focus of our work at Fraunhofer ISE was characterisation of the system components, e.g. the fuel cell. We carried out tests in a special test rig under well-defined conditions and then used modern analytical techniques such as mass spectroscopy to provide high-quality, quantitative information. Fraunhofer ISE contributed significantly in this way to the success of the project. Among other aspects, we identified the cause for the initial strong degradation of the cell. The counter-measures which we recommended reduced the degradation period from days to months.

In addition, we developed a functional demonstration system, for which we prepared microcontroller-assisted operation management, a hybridisation concept with a rechargeable buffer battery, suitable power electronics and sensor circuits. The operation is completely automated, whereby the fuel cell voltage and current are constantly monitored. These data are used by the operation management system to prevent critical conditions which would impose a heavy load on the fuel cell or cause it to age prematurely.

The work is part of commercially orientated, preliminary strategic research that is internally funded by the Fraunhofer-Gesellschaft. The project team consists of Fraunhofer ICT (catalyst development), Fraunhofer IGB (membrane development), Fraunhofer IIS (electronics), Fraunhofer ISE (system integration and characterisation), Fraunhofer ISI (market analyses) and Fraunhofer IZM (pump and cell development).

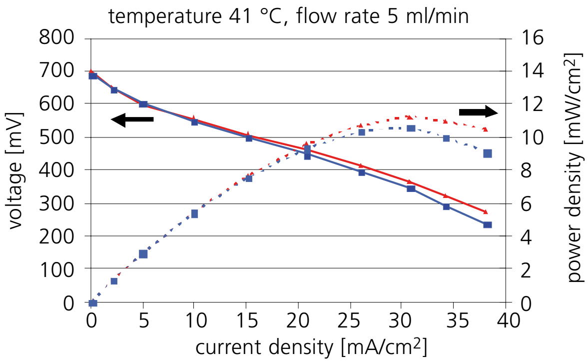


Fig. 1: The graph shows the dependence of the voltage (solid lines) and power (dashed lines) on the current density for two direct ethanol fuel cells. The goal of 10 mW per cm^2 of active cell area at 40 °C was clearly met. We were able to measure power densities of more than 7 mW/cm^2 even under conditions close to those of a realistic system, with a lower ethanol flow rate of app. 0.5 ml/minute and at ambient temperature. This results in a total power of 280 mW for the fuel cell stack consisting of four cells.

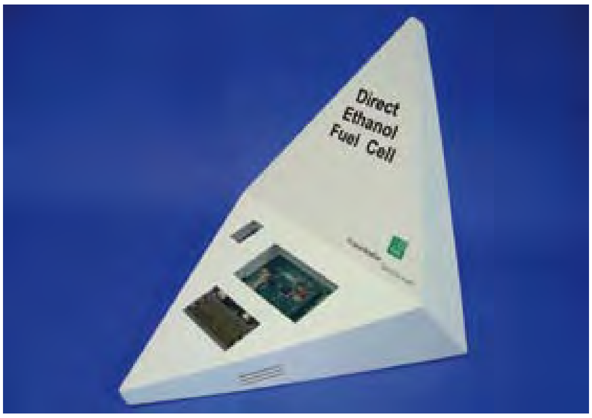
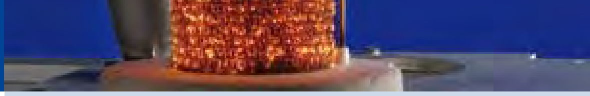


Fig. 2: A photo of the demonstration system developed during the project. The fuel cell stack with integrated pump electronics can be seen in the front section. The dimensions of this unit are app. 42 x 66 x 25 mm^3. The system was convincing, not only with its stable operation but also with its low parasitic power demand, which totalled around 8 % of the fuel cell power each for the electronics and the pump components.



System Simulation of Miniature Fuel Cell/Battery Hybrid Systems

Hybrid systems combining miniature fuel cells and batteries have a promising future. They combine the advantages of the fuel cell with those of the battery. Appropriate dimensioning of the hybrid system determines its efficiency and how well it competes with other storage-based or fuel cell systems. We prepare mathematical models of the systems so that detailed predictions and virtual experiments are feasible already at an early developmental stage.

Achim Christian, Friedrich Hagedorn,
Lynn Schickl, Kanin Suwannarat,
Mario Zedda, Christopher Hebling

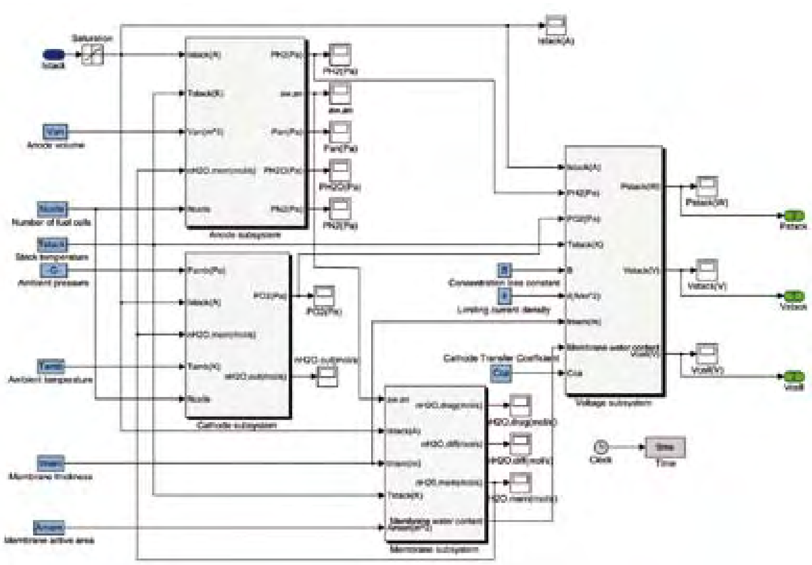
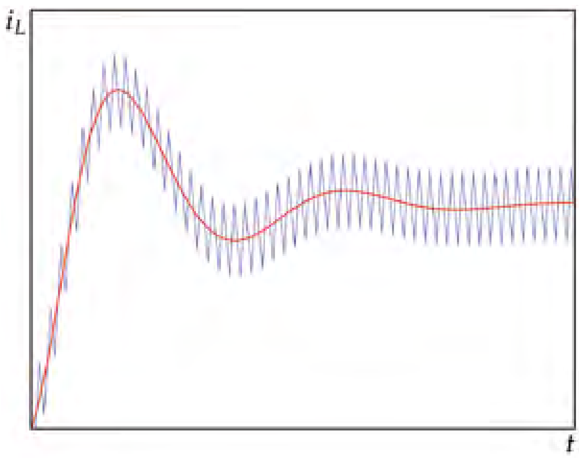


Fig. 1: Dynamic model of a planar, passive PEM miniature fuel cell with a passive, air-breathing cathode. The model was prepared in a clear graphical representation with function blocks and signal flow graphs using MATLAB®/Simulink®.



Our many years of experience in developing and characterising fuel cell systems, as well as our theoretical and experimental knowledge of processes within the fuel cell, form a solid basis for a new field, namely simulation of complete systems. To this purpose, we develop dynamic models of system components and combine these as needed in each case.

When complete systems are to be simulated, it is desirable to reduce the number of laboratory measurements and prototypes, which require appreciable investments of time and materials, to a minimum. To a large extent, we replace prototypes by mathematical models and measurements by numerical calculations. In the first instance, commercially available, standard industrial software such as MATLAB®/Simulink® is used. However, we retain a large degree of flexibility and also draw on open-source software. In the ideal case, the prototype finally serves only to verify the optimised model. The very complex, detailed models can be optimised with respect to computing time by the application of suitable approximation procedures.

At present, we are working on a dynamic model for a planar, passive, miniature PEM fuel cell in Simulink®, a design for a suitable DC/DC converter, a model for an energy-storage unit and the simulation of a novel efficient process to heat a high-temperature fuel cell.

The project is supported by the Fraunhofer-Gesellschaft.

Fig. 2: A miniature fuel cell/battery hybrid system needs voltage converters. The graph shows the coil current i_L, which is a significant quantity for designing a voltage converter, during initial transient oscillations. By using the averaged model (red line), about 95 % computing time can be saved for numerical solution compared to the more detailed model (blue line).

Kinetic Investigations of Direct Ethanol Fuel Cells

Kinetic investigations aid the analysis of mechanisms which lead to power losses in fuel cells. Knowledge of the results forms the basis for systematic optimisation. Impedance spectroscopy is applied to investigate the kinetics during fuel cell operation. The impedance spectra are analysed with the help of physical models to determine the kinetic parameters. Different reaction paths are taken into account in modelling the oxidation of ethanol. The reaction steps included in the model are derived from interpretation of the near-edge region of X-ray absorption spectra (XANES region).

Dietmar Gerteisen, Ulf Groos, **Julia Melke**, Marco Meyer, Friederike Schmid, Christopher Hebling

Fig. 1: Anode flow field of a fuel cell with the reference electrode configuration, which allows separate measurement of impedance spectra for the anode and the cathode.

To characterise PEM and direct alcohol fuel cells, we at Fraunhofer ISE have successfully applied the interpretation of impedance spectroscopy based on physical models for many years. The method has the advantage, compared to stationary measurements of characteristic curves, that simultaneously occurring processes can be excited with different frequencies and thus separated on the basis of different time constants.

By using reference electrodes, the procedure can be applied to analyse anode kinetics during operation, without the need for half-cell measurements. At the same time, the mutual coupling of the two half-cells is taken into account. This makes the method very suitable for validating models. The validated models can then be used to determine kinetic parameters under realistic conditions, and loss mechanisms derived from an understanding of the processes. This knowledge then supports the development of cells and systems.

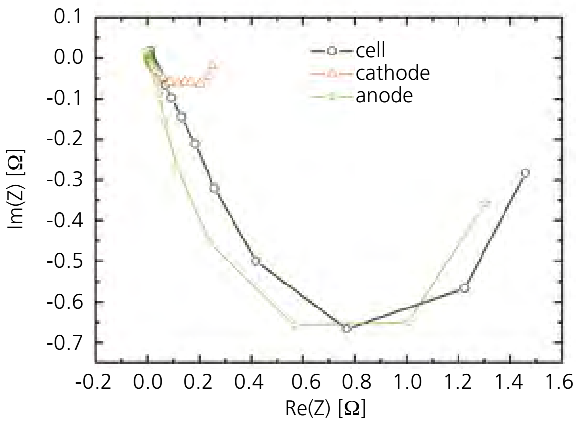
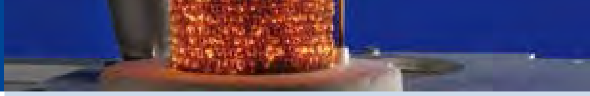


Fig. 2: Impedance of the anode, cathode and cell for a frequency range from 0.025 Hz to 10,000 Hz for a cell voltage of 0.2 V. The cell impedance is primarily determined by the anode impedance. As a result, the losses can be attributed predominantly to the anode kinetics.

At present we are investigating fundamental processes in direct ethanol fuel cells (DEFC). In the model for the DEFC, particularly the electrochemical oxidation of ethanol at the anode has been modelled in detail. To increase the predictive power of the model, the anode reaction is additionally investigated by X-ray absorption spectroscopy. The method provides information about adsorbates on the surface, from which reaction mechanisms can be derived.



Low-Cost – High-Tech: Miniature Fuel Cells Approaching Series Production

It has long been known that miniature fuel cells are highly efficient energy suppliers. Now we are preparing their transfer from the laboratory to production. We have developed a polymer housing which can be produced by injection moulding and which features mechanical strength corresponding to that of a thick steel plate. The cost-optimised production procedures for current collection and cell connection, as well as the special sealing of the fuel cells, have been patented by Fraunhofer ISE.

Thomas Jungmann, Ulf Groos, **Mario Zedda**, Christopher Hebling

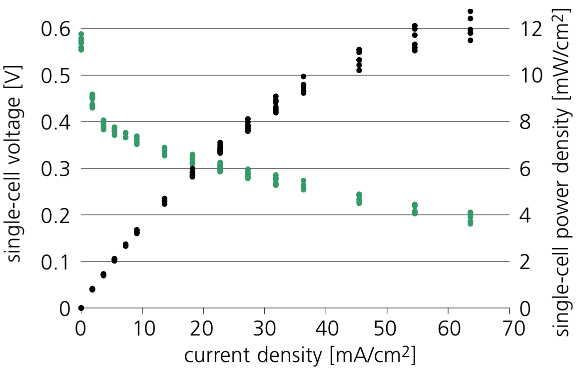


Fig. 1: Polarisation (green) and power (black) characteristic curves for an eight-cell direct methanol fuel cell module, operated with a 1 molar aqueous methanol solution and passive air supply at an ambient temperature of 22 °C. The nominal operating point for the single cells is at about 0.2 V. The entire module with an active area of 44 cm^2 supplies ca. 500 mW_{el} total power.

Fluid distributors for miniature planar direct methanol fuel cells will soon be ejected from injection-moulding equipment at a rate of seconds. The material used, a fibreglass-reinforced polymer, has an elasticity module which is 80 times higher than that of stainless steel, and is thus optimally suited for pressing the planar configuration of our fuel cells. A minimal pre-stress is already applied during the construction phase to regions that would relax mechanically. The two halves of the housing are joined to form a monolithic unit by ultrasonic welding. Cost efficiency and the feasibility of mass production were central issues in the development process.

This also meant that peripheral components were eliminated as far as possible. We therefore favour passive cathode operation for miniature fuel cells and implement the air supply via natural diffusion. Our planar configuration with the single cells mounted in one plane is particularly well suited to this approach.

Fuel cells with a planar configuration pose specific challenges concerning current collection, cell connection and sealing. To meet these challenges, we have developed a technology which is both functional and cost-effective. It allows complete cell units to be pre-assembled in series, independently of the housing plates.

We thank our partner, FWB GmbH, for constructive co-operation. The project was supported by the German Federal Ministry for Economics and Technology (BMWi).

Fig. 2: Planar fuel cells as far as the eye can see: Large production volumes thanks to injection-moulding technology. Applications for the small power supplies can be found wherever small industrial and consumer devices need to be operated for weeks and months independently of the grid. The longer the required operating time, the more advantageous it is to use methanol as a fuel rather than conventional battery-based storage units.

Redox-Flow Batteries – Electric Storage Systems for Regenerative Energy

Redox-flow batteries are excellently suited for intermediate storage of electricity in power grids or isolated systems with a high, fluctuating proportion of regenerative energy sources. With their advantageous properties, they present a promising alternative to conventional battery-based storage units or also fuel cells. At Fraunhofer ISE, we are optimising components for these systems and develop model-based control strategies for robust operation management.

Martin Dennenmoser, Daniel Frick, Beatrice Hacker, Martin Ohlinger, **Tom Smolinka**, Matthias Vetter, Christopher Hebling

Particularly the so-called all-vanadium redox-flow battery features essential advantages compared to conventional electric storage units: Separation of the conversion and storage units, high electric efficiency, good cycling stability and thus long lifetime, and no degradation effects in the electrolyte arising from cross-contamination via the membrane. The general operating principle of a redox-flow battery is shown in Fig. 1: When an all-vanadium redox-flow battery is charged, V^{3+} ions are reduced to V^{2+} on the anolyte side and V^{4+} ions are oxidised to V^{5+} on the catholyte side. The reverse reactions occur during discharging.

Within a Fraunhofer joint project, we have set up a test stand and constructed various test cells for materials characterisation and the optimisation of cell designs. The other project partners are Fraunhofer UMSICHT (project management), Fraunhofer ICT, Fraunhofer AST and Fraunhofer ISI. Furthermore, a multiple-cell battery with an active area of 250 cm^2 was designed and produced. This multiple-cell battery is intended for validation of the system models that have been developed in parallel (see article on page 76) and for determination of important technical parameters for system dimensioning. In addition to the development of improved system components such as the cell stack, the aim is to test simulation-based control concepts and thus to develop a robust operating strategy which ensures a long lifetime for the materials used.

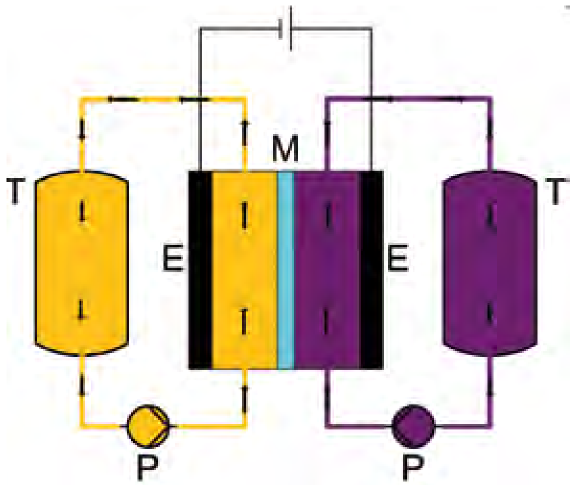


Fig. 1: Operating principle of a redox-flow battery. The electric energy is stored chemically in the form of dissolved redox couples in the two external tanks (T). The tank volume thus determines the energy content of the system. The battery power is defined by the size of the cell stack in the conversion unit. Circulation pumps (P) on both sides ensure an adequate supply of liquid electrolytes to the electrodes (E). The cathode and anode are separated by an ion-conducting membrane (M).

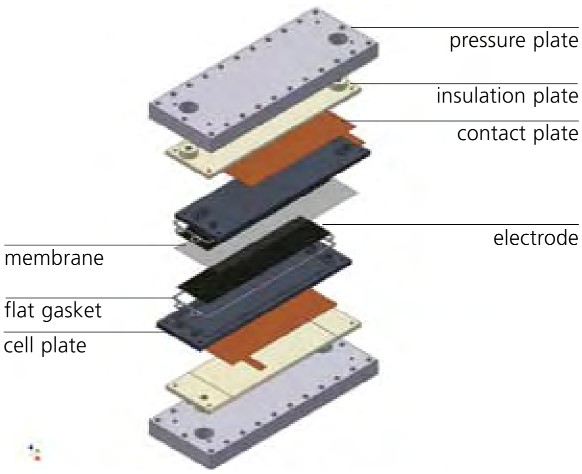
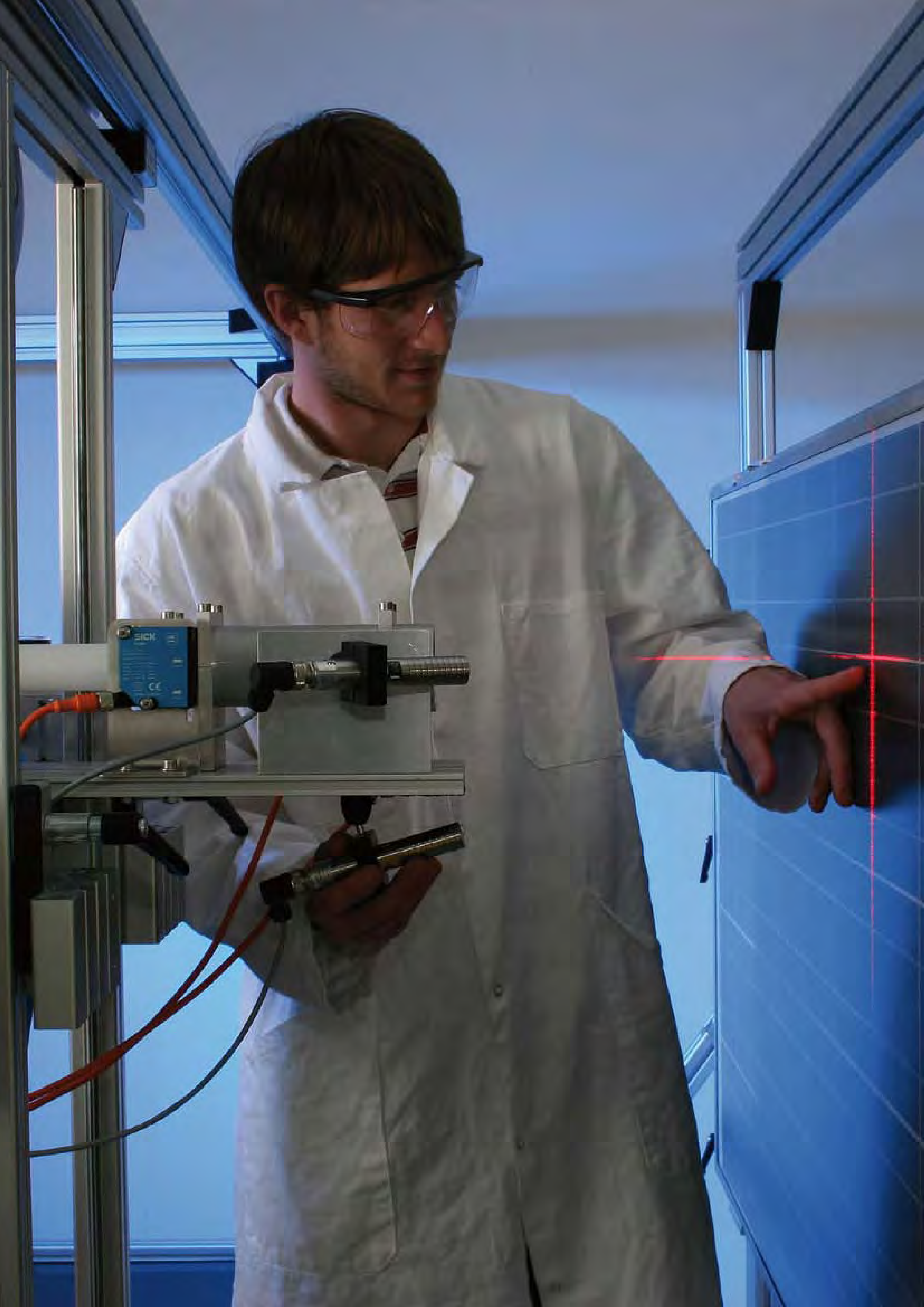


Fig. 2: Exploded drawing of a redox-flow cell for material characterisation. The active area amounts to 100 cm^2.


SICK

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 related testing and certification services to clients. At present, Fraunhofer ISE has four accredited testing units: the Testing Centre for Thermal Solar Systems, the Thermal-Optical Measurement Laboratory, the VDE-Fraunhofer ISE Test Centre for Photovoltaics and the ISE Calibration Laboratory CalLab. Our 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, e.g. 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:

- test stand for solar air collector testing
- 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
- hail test stand

The work of the Testing Centre for Thermal Solar Systems primarily concerns commissions from the industry to test collectors according to European collector standards such as the Solar Keymark Scheme Rules. 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. The range of services was extended in 2008 by a hail test stand with hailstones of real ice (see article on page 105).

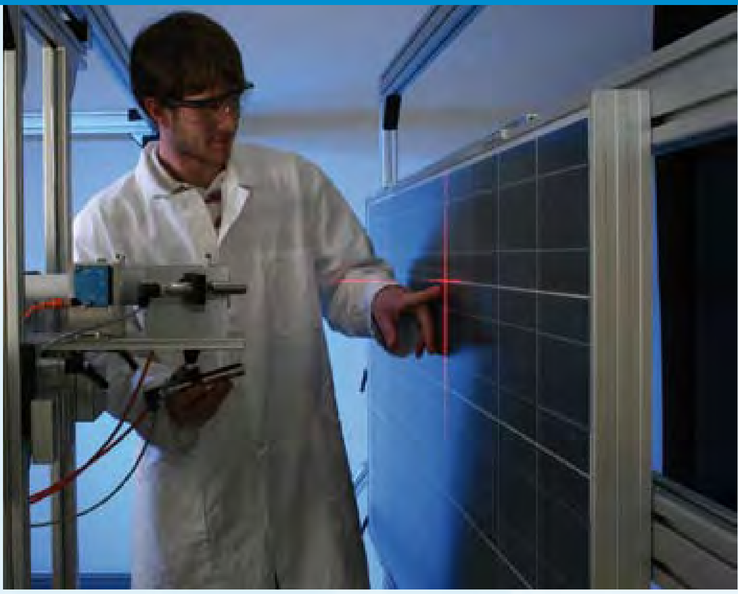
The Thermal-Optical Measurement Laboratory TOPLAB was accredited according to DIN EN ISO/IEC 17025 in 2006. It offers a comprehensive range of characterisation for innovative building components and materials to developers and planners of façades, façade components and windows, including shading devices (see article on page 106).

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 capacity and rooms for the Test Centre, which is operated jointly with the VDE Institute, were expanded significantly during 2008. The goal of the facility is to ensure the quality and reliability of PV modules, which is becoming an increasingly important issue. Within the joint operation of the Test Centre, Fraunhofer ISE is responsible for the relevant performance tests, while the VDE Institute carries out the safety tests and certification according to the usual standards. Tests are also carried out to accompany the development of PV modules and module components. The Test Centre is closely linked with ISE CalLab and with module development at the Institute. Similarly, it co-operates with module producers (see article on page 102).

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 PV 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 page 103).

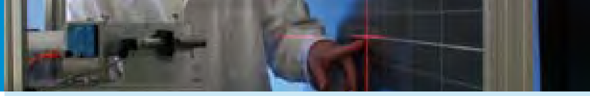
Service Units



The VDE-Fraunhofer ISE Test Centre for Photovoltaics moved into new rooms in 2008. This allowed the testing laboratory, which is operated jointly with VDE, to double its testing capacity and to offer new services. In addition to the specified IEC tests, a hail impact test can now be offered, using a hail gun that was developed at Fraunhofer ISE (see article on page 102).

Contacts

Quality assurance of PV systems			
	Yield predictions	Nicole Römer	Tel.: +49 (0) 7 61/45 88-55 75 E-mail: Nicole.Roemer@ise.fraunhofer.de
	System testing	Andreas Steinhüser	Tel.: +49 (0) 7 61/45 88-52 25 E-mail: Andreas.Steinhueser@ise.fraunhofer.de
	Monitoring	Klaus Kiefer	Tel.: +49 (0) 7 61/45 88-52 18 E-mail: Klaus.Kiefer@ise.fraunhofer.de
ISE CalLab			
	Cell calibration	Dr Wilhelm Warta	Tel.: +49 (0) 7 61/45 88-51 92 E-mail: Wilhelm.Warta@ise.fraunhofer.de
		Astrid Ohm	Tel.: +49 (0) 7 61/45 88-54 23 E-mail: Astrid.Ohm@ise.fraunhofer.de
	Module calibration	Klaus Kiefer	Tel.: +49 (0) 7 61/45 88-52 18 E-mail: Klaus.Kiefer@ise.fraunhofer.de
		Frank Neuberger	Tel.: +49 (0) 7 61/45 88-52 80 E-Mail: Frank.Neuberger@ise.fraunhofer.de
PV Module Testing			
	VDE-Fraunhofer Test Centre for Photovoltaics (TZPV)	Claudio Ferrara	Tel.: +49 (0) 7 61/45 88-56 50 E-mail: Claudio.Ferrara@ise.fraunhofer.de
Testing Centre for Thermal Solar Systems (PZTS)			
	Indoor and outdoor test stands for solar collectors	Matthias Rommel	Tel.: +49 (0) 7 61/45 88-51 41 E-mail: Matthias.Rommel@ise.fraunhofer.de
		Stefan Mehnert	Tel.: +49 (0) 7 61/45 88-53 54 E-mail: Stefan.Mehnert@ise.fraunhofer.de
	Solar air collector test stand	Matthias Rommel	Tel.: +49 (0) 7 61/45 88-51 41 E-mail: Matthias.Rommel@ise.fraunhofer.de
Measurement of building façades and transparent components			
	Thermal-Optical Measurement Laboratory (TOPLAB)	Tilmann Kuhn	Tel.: +49 (0) 7 61/45 88-52 97 E-mail: Tilmann.Kuhn@ise.fraunhofer.de
	Daylighting measurement rooms	Jan Wienold	Tel.: +49 (0) 7 61/45 88-51 33 E-mail: Jan.Wienold@ise.fraunhofer.de
Ventilation units and heat pumps			
	Test stand	Dr Benoît Sicre	Tel.: +49 (0) 7 61/45 88-52 91 E-mail: Benoit.Sicre@ise.fraunhofer.de
Photovoltaic system components			
	Inverter characterisation	Dr Bruno Burger	Tel.: +49 (0) 7 61/45 88-52 37 E-mail: Bruno.Burger@ise.fraunhofer.de
Qualification testing and optimisation of PV systems			
	Battery testing laboratory	Stephan Lux	Tel.: +49 (0) 7 61/45 88-54 19 E-mail: Stephan.Lux@ise.fraunhofer.de



VDE-Fraunhofer ISE Test Centre for Photovoltaics

With the growing diversity of photovoltaic modules now available, it is becoming increasingly important to test their reliability. In this context, the capacity of the existing Test Centre at Fraunhofer ISE was further expanded. The new rooms and equipment were officially commissioned in September 2008. The Test Centre for Photovoltaics is accredited as a "Testing Laboratory" for the "Certification Body", VDE, and carries out tests for product type approval complying with IEC 61215 and 61646.

Holger Ambrosi*, Stefan Brachmann, Ilie Cretu, **Claudio Ferrara**, Markus Heck, **Michael Köhl**, Kerstin Körner-Ruf, Georg Mülhöfer, Daniel Philip, Hans-Martin Henning

* PSE AG, Freiburg

Fig. 1: Climatic test chambers for temperature-cycling tests of modules.

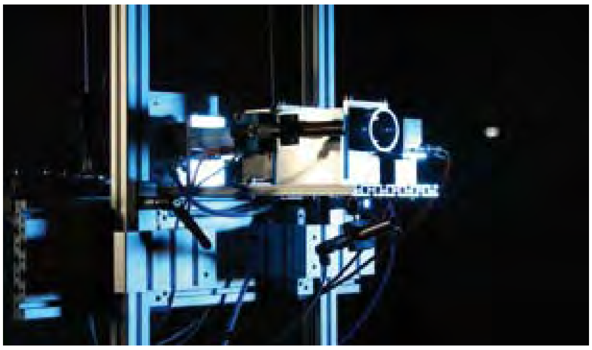


Fig. 2: Hail gun – developed and constructed by the staff of Fraunhofer ISE.

The rapidly growing demand for IEC-based testing for product type approval of photovoltaic modules was the incentive to significantly expand the capacity of the Test Centre that we run jointly with the VDE, and to co-operate still more closely in combining our areas of expertise. By acquiring walk-in testing chambers (Fig. 1), the testing capacity was increased by more than a factor of five.

The prescribed set of IEC tests which can be carried out at Fraunhofer ISE was completed by the design and construction of a hail gun complying with the standards (Fig. 2). The Test Centre is now also accredited by the IEC as a Certification Body Testing Laboratory (CB-TL) of the VDE.

Almost all of the testing laboratories are now located under a single roof in the newly extended Test Centre, so that the logistics have been improved enormously.

We have set up a laboratory facility with a continuous solar simulator for light-soaking modules at a controlled, constant module temperature in response to the increasing number of new thin-film module types. In addition, we have new measurement options for outdoor exposure as an alternative. In both cases, the output power is monitored continuously and the characteristic IV curves, the radiation intensity and the module temperature are measured frequently (4 times per hour).

To investigate damage to modules, non-destructive methods are used at the Test Centre, including electroluminescence (on entire modules) to detect damage to cells or cell connectors, and optical and Raman spectro-scopy for the encapsulation materials.

Quality Assurance for PV Systems

Comprehensive quality assurance is needed to ensure that the predicted yield for photovoltaic systems is obtained throughout the entire lifetime of the system. Fraunhofer ISE offers a wide spectrum of services from planning through to commissioning operation in order to maximise the quality of photovoltaic systems.

Klaus Kiefer, Frank Neuberger, Nicole Römer
Andreas Steinhüser

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, we provide information on the following points:

- Error analysis – How accurate are the results?
- Risk analysis – What factors could 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 allows maximum system yields to be achieved. We measure systems and determine their potential for optimisation.

System testing

To control the performance of large photovoltaic systems, 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, appropriate corrective measures can be taken in time to prevent major losses.

Calibration of Solar Cells and Modules

Accurate determination of the performance data 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.

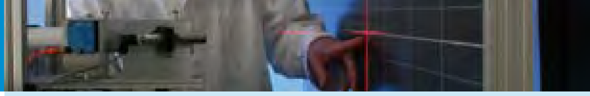
Patrick Blattert, Boris Farnung*, Jochen Hohl-Ebinger, Jürgen Ketterer, **Klaus Kiefer**, Katinka Kordelos, Frank Neuberger, Astrid Ohm, Johannes Otto, Peter Raimann, Willhelm Warta, Edgar Wolf, Jutta Zielonka

* PSE AG, Freiburg

ISE CalLab (www.callab.de) is one of the internationally leading photovoltaic calibration laboratories. Module and cell manufacturers commission us to calibrate their reference modules and cells for production lines according to international standards. The measurements are made with a Class A solar simulator according to IEC 60904-9. Both areas of ISE CalLab are accredited according to ISO/IEC 17025; the cell calibration has also been accredited by the Deutscher Kalibrierdienst (DKD). With the support of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the European Union (EU), and in co-operation with PV manufacturers, we work continuously on improving our measurement procedures and tolerances.

The range of services comprises:
- measurement of the spectral response of solar cells and reference modules
- measurement of the current/voltage characteristics for solar cells and modules under standard test conditions (STC, 1000 W/m^2, AM 1.5 and 25 °C)
- measurement of the temperature and intensity dependence of cell and module parameters
- determination of the open circuit voltage, short circuit current and fill factor, and rated power, current, voltage and efficiency value of modules and solar cells

Fig. 1: New laboratory for measurement of PV module performance.



Characterisation and Qualification Testing of Electric Components

In addition to photovoltaic cells and modules, Fraunhofer ISE measures, tests and evaluates 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.

Bruno Burger, **Stephan Lux**, **Robert Thomas**, 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 to our clients. Developers of charge controllers and charging devices can have their equipment tested and optimised together with the corresponding batteries.

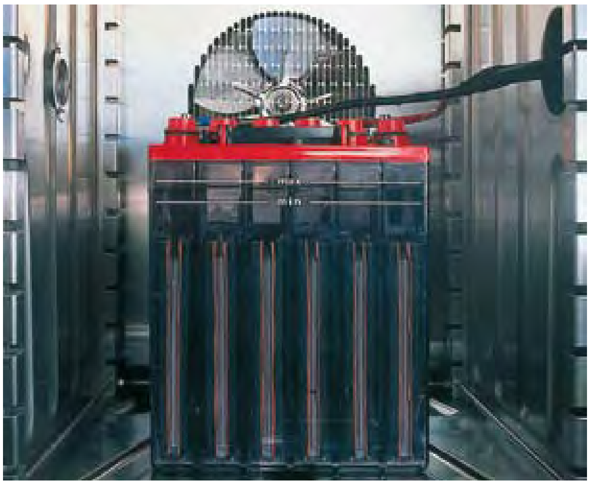


Fig. 1: In the climatic chamber, not only efficiency and capacity but also the aging and charging performance of storage batteries can be investigated under variable conditions.

Measurement and Testing of Ventilation Equipment and Heat Pumps

Fraunhofer ISE makes test-stand measurements for manufacturers and designers of compact ventilation units with integrated heat pumps. We can draw on broad experience from large-scale field tests to practically evaluate buildings and their energy supply systems.

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

* PSE AG, Freiburg

Test facility for compact ventilation units with integrated heat pumps

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 measurement results, we derive recommendations to optimise the components and their interaction. We support our clients in implementing new developments.

Monitoring

The evaluation of energy supply systems in occupied buildings provides reliable data on the real efficiency achieved in practice and enables weaknesses in operation, user behaviour and controls to be identified. At present, we are conducting a broadly based monitoring campaign for heat pump systems. Not only the metering technology but also the evaluation and assessment concepts are transferable to other types of technology.

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 in the laboratory 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

The Testing Centre for Thermal Solar Systems 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.

Korbinian Kramer, Stefan Mehnert, **Matthias Rommel**, Arim Schäfer, Wolfgang Striewe, Christoph Thoma

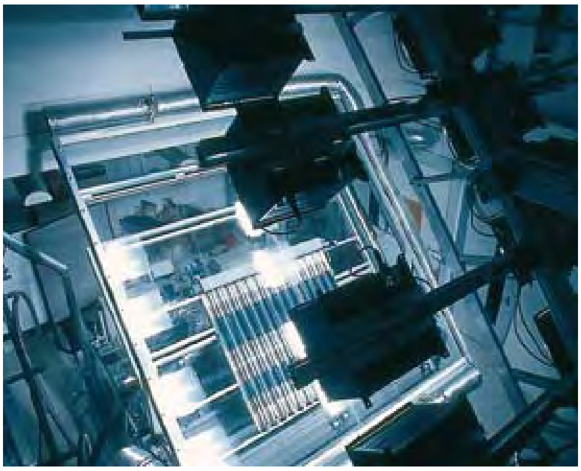


Fig. 1: Indoor test stand with solar simulator.

The Testing Centre for Thermal Solar Systems offers comprehensive measurement services for solar collectors and systems. We use a large outdoor test stand with a south-oriented area of more than 100 m^2 for exposure to weathering. For more than six years, we have operated an optimised tracker to measure the performance parameters of solar collectors. Test stands to determine the effect of rain, mechanical loads, thermal internal and external shocks complete the set of facilities at the Testing Centre that allow all of the tests specified for solar collectors in EN 12975-1,2:2006 to be carried out.

The Testing Centre for Thermal Solar Systems has been fully accredited by DAP according to ISO 17025 since 2005. With intensive staff involvement in boards and committees, the Centre is fully integrated into international solar thermal research and standardisation work.

Hail impact test stand

This year, we set up a new hail impact test stand in our laboratory. It allows us to shoot standardised hailstones with very good reproducibility and variable, well-defined velocities onto collectors with a wide range of geometrical configurations.

Test stand for systems and storage tanks

We have equipped a new laboratory to meet the growing demand for system investigations. It comprises an unshaded, south-oriented 80 m^2 testing area with an adjacent laboratory area of 56 m^2. It is used for parallel measurement of up to four complete hot water systems. The measurement units can be combined flexibly with each other, so that individual boundary conditions can be taken into account. In addition, the laboratory meets the specifications to carry out storage tank measurements according to EN 12977-3:2008.

Indoor collector test stand with a solar simulator

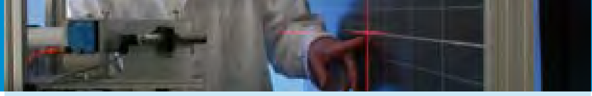
We have operated an indoor test stand with a solar simulator since 2002. Its great advantage, particularly for collector development, is the high reproducibility of the measurement conditions. This allows us to carry out targeted developmental work to improve collector constructions very quickly and efficiently.

Medium-temperature testing unit up to 200 °C

Our medium-temperature testing unit has been operating since 2006. With it, we can measure efficiency curves for operating 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, which can be used for outdoor measurements or integrated into the indoor test stand with the solar simulator. Our services include determination of air leakage rates, pressure loss measurements and determination of performance parameters.



Measurement of Building Façades and Transparent Components

Fraunhofer ISE offers 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, Johannes Hanek, Angelika Helde, **Tilmann Kuhn**, Werner Platzer, Jan Wienold, Helen Rose Wilson

Thermal-Optical Measurement Laboratory and Lighting Laboratory (TOPLAB)

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.

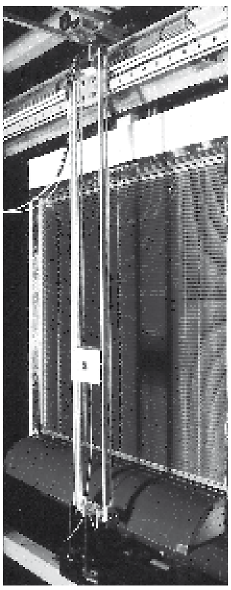


Fig. 1: Solar calorimeter to determine the total solar energy transmittance (g value). The corresponding methodology developed by Fraunhofer ISE has been accredited according to DIN EN ISO IEC 17025 since 2006.

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 DIN 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 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 are 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

Shelley Bambrook
University of New South Wales
Sydney, Australia
1.3.2008–31.1.2009
Research area: Building technology

Priscilla Braun
Universidade Federal de Santa Catarina UFSC
Florianópolis-SC, Brazil
1.4.2008–31.5.2009
Research area: Integration of PV systems and grid feedback

César Domínguez Domínguez
Instituto de Energía Solar de la Universidad Politécnica de Madrid, Spain
1.4.–30.6.2008
Research area: PV concentrator characterisation

Anthony R. Florita
University of Nebrasca-Lincoln
Omaha, Nebraska, USA
1.6.2008–31.7.2009
Research area: Building technology

Francesco Frontini
Politecnico di Milano
Milan, Italy
1.6.2007–30.9.2008
Research area: Building technology

Michele Liziero
Politecnico di Milano
Milan, Italy
16.8.2008–15.3.2009
Research area: Building technology

Marco Olcese
Instituto Nazionale di Fisica Nucleare
Rome, Italy
1.7.–15.9.2008
Research area: Solar cooling

Graziano Salvalai
Politecnico di Milano
Milan, Italy
16.7.2008–15.7.2009
Research area: Building technology

Marta M. Sesana
Politecnico di Milano
Milan, Italy
1.11.2008–30.4.2009
Research area: Building technology

Dr Vatch Shimpalee
University of South Carolina
Columbia, South Carolina, USA
2.–30.5.2008
Research area: Simulation of fuel cells

Prof. Dr Fariborz Taghipour
University of British Columbia
Vancouver, Canada
22.1.–31.7.2008
Research area: Simulation of miniature fuel cells

Heli Talvitie
Helsinki University of Technology
Helsinki, Finland
1.12.2008–30.11.2009
Research area: Defect migration due to tempering of silicon

Dr John Weidner
University of South Carolina
Columbia, South Carolina, USA
5.–30.4.2008
7.6.–10.7.2008
Research area: Modelling of fuel cells

Participation in National and International Organisations

Alliance for Rural Electrification
- Member

Arbeitskreis "Zukunftsthema Speicher" (Fraunhofer)
- Member

Bavaria California Technology Center (BaCaTec)
- Board of Trustees

Brennstoffzellen-Allianz-Baden-Württemberg (BzA-BW)
- Member and Executive Committee

BSW Arbeitskreis Ländliche Elektrifizierung
- Member

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

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"
- Arbeitskreis 221.1.4 "Errichten von Photovoltaik-Anlagen nach DIN VDE"

DGNB Deutsche Gesellschaft für Nachhaltiges Bauen e. V.
- Member

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

Deutsche Meerwasserentsalzung e. V. (DME)
- Member

Deutsche Solarthermie-Technologieplattform (DSTTP), Steering Committee
- Member

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

Deutsches Institut für Normung DIN
Fachnormenausschuss Heiz- und Raumlufttechnik (NHRS AA1.56) "Solaranlagen"
- Member

Fachnormenausschuss Lichttechnik (FNL 6) "Innenraumbeleuchtung mit Tageslicht"
- Member

Fachnormenausschuss Lichttechnik (FNL 21) "Spiegelmaterial für die Lichttechnik"
- Member

Normenausschuss Bau NABau 00.82.00 "Energetische Bewertung von Gebäuden"
- Member

Gemeinschaftsausschuss NABauNHRS
"Energetische Bewertung von Gebäuden"
- Member

Erfahrungsaustauschkreis Thermische
Solaranlagen und ihre Bauteile (EK-TSuB)
- Deputy Speaker

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

European Committee for Standardisation CEN
TC129/WG9
- Associate Member

European Centre for Power Electronics e. V.
(ECPE)
- Member

European H2/FC Technology Platform
- Member

European Photovoltaic Industry Association
(EPIA)
- Associate Member

European Renewable Energy Centres Agency
(EUREC Agency)
- Member

European Solar Thermal Technology Platform
(ESTTP), Steering Committee
- Elected Member

EU PV Technology Platform, Steering
Committee
- Vice-President

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

23rd European Photovoltaic Solar Energy
Conference (EUPVSEC), International Scientific
Committee
- Member

European Solar Thermal Industry Federation
(ESTIF)
- Member

EuroSun 2008 – 1st International Conference
on Solar Heating, Cooling and Buildings,
Scientific Committee
- Member

Euro Solar: The European Association for
Renewable Energy
- Member

Expertenkommission der Bundesregierung
"Forschung und Innovation"
- Member

Fachausschuss Tageslicht der Lichttechnischen
Gesellschaft (LitG)
- Member

Fachinstitut Gebäude-Klima (FGK)
Arbeitskreis "Expertenkreis Klimaschutz"
- Member

Fachnormenausschuss Lichttechnik (FNL 21)
"Spiegelmaterial für die Lichttechnik"
- Member

Fachverband Transparente
Wärmedämmung e. V.
- Member

Fesa e. V.
- Member

FIT Mikroenergietechnik
- Member and Executive Committee

FitLicht – Fördergemeinschaft innovative
Tageslichtnutzung
- Member

ForschungsVerbund Sonnenenergie (FVS)
- Member and Speaker

Forum für Zukunftsenergien
- Member

Fraunhofer-Allianz Energie
- Manager and President

Fraunhofer-Allianz Bau
- Member

Fraunhofer-Allianz SysWasser
- Member

Fraunhofer-Netzwerk Batterien
- Member

Fraunhofer-Netzwerk Intelligente Energienetze
- Co-ordination

Fraunhofer-Netzwerk Windenergie
- Member

Fraunhofer Zukunftsperspektive
Mikroenergietechnik
- Member and Executive Committee

Freiburger Verein für Arbeits- und
Organisationspsychologie
- Executive Committee

Fuel Cell Europe
- Member

Gettering and Defect Engineering in
Semiconductor Technology Conference
(GADEST), International Programme Committee
- Member

German Scholars Organization (GSO)
- President

Global Village Energy Partnership (GVEP)
- Member

IEC TC82 WG7 for IEC Qualification Standards:
Concentrator Photovoltaics (CPV)
- Member

Institut für Solare Energieversorgungstechnik
(ISET), Wissenschaftlicher Beirat
- Member

International Commission on Glass ICG, TC 10
"Optical Properties of Glass"
- Member

International Energy Agency IEA, Paris, France:
Solar Heating & Cooling Programme SHCP
- Task 37 "Advanced Housing Renovation"
- Task 38 "Solar Air-Conditioning and
  Refrigeration" (CEO)
- Task 39 "Polymeric Materials for Solar
  Thermal Applications" (CEO)

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"
  (CEO)

Photovoltaic Power Systems Programme
- Task 11: "PV Hybrids and Mini Grids"

International Science Panel on Renewable
Energies (ISPRE)
- President

ISES International Solar Energy Society (ISES)
- Member

Kompetenzfeld Photovoltaik NRW
- Member

Kompetenznetzwerk Brennstoffzelle NRW
- Member

Lichttechnische Gesellschaft
- Member

Mikrosystemtechnik Baden-Württemberg
(MST BW) – Advisory Board
- Member

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

Scientific Advisory Board of Nanometer
Structure Consortium (nmC)
- Member

Scientific Advisory Council of EURAC Research
- Member

Scientific Commission for the ENI Science and Technology Award
- Member

SEMI International Board of Directors
- Member

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

14th Semiconducting and Insulating Materials Conference (SIMC), International Scientific Committee
- Member

Stiftung Solarenergie – Advisory Board
- Member

Symposium Licht und Architektur – Scientific Committee
- Member

Symposium Photovoltaische Solarenergie – Scientific Committee
- Member

VDI Gesellschaft Technische Gebäudeausrüstung
- Richtlinienausschuss 4706

VDI Gesellschaft "Energie und Umwelt"
- Richtlinienausschuss VDI 4650, Blatt 1
- Richtlinienausschuss VDI 4650, Blatt 2

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

VDMA Arbeitskreis Industrienetzwerk Brennstoffzellen
- Member

Verband zu Energieeffizienz in Gebäuden
- Founding Member

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"
- Member

Weiterbildungszentrum WBZU "Brennstoffzelle", Ulm – Board of Trustees
- Member

Zentrum für Sonnenenergie- und Wasserstoff-Forschung ZSW
- Board of Trustees

Congresses, Conferences and Seminars organised in co-operation with the Institute

OTTI Energie Kolleg:
4. Anwenderforum Dünnschicht-Photovoltaik Module – Systeme – Anwendungen
Kloster Banz, Bad Staffelstein, 11.–12.2.2008

Workshop SiliconFOREST 2008
Fortschritte in der Entwicklung von Solarzellen-Strukturen und Technologien
Falkau, 24.–27.2.2008

23. Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein, 5.–7.3.2008

International Conference on Sustainable Cooling Systems
Vienna, Austria, 31.3.–1.4.2008

CLEO-PHASE
Conference on Lasers and Electro-Optics
San Jose, California, USA, 5.–9.5.2008

33rd IEEE Photovoltaic Specialists Conference
San Diego, California, USA, 11.–16.5.2008

Intersolar 2008:
4th PV Industry Forum 2008
Munich, 10.–11.6.2008
(Advisory Board)

Intersolar 2008:
OTTI-Seminar on Solar Air-Conditioning Experience and Practical Application
Munich, 11.6.2008

Workshop on Polygeneration, KTH (Royal Institute of Technology)
Stockholm, Sweden, 16.6.2008

NOW-Workshop 2008
Regenerativer Wasserstoff aus der Elektrolyse
Ulm, 7.7.2008

23rd European Photovoltaic Solar Energy Conference and Exhibition
Valencia, Spain, 1.-5.9.2008

BBR Kongress zur Klimatisierung von Büro- und Verwaltungsbauten – Fachveranstaltung zu den Aspekten des Sommerlichen Wärmeschutzes von Büro- und Verwaltungsbauten
Dresden, 30.9.2008

EnOB-Symposium "Auf dem Weg zu Nullenergie-Gebäuden – Erfahrungen und Impulse aus dem Förderschwerpunkt Energieoptimiertes Bauen"
Dresden, 1.–2.10.2008

Netzferne Stromversorgung mit Photovoltaik
Freiburg, 7.–9.10.2008

Solar Summits Freiburg
International Conference on Renewable and Efficient Energy Use
"Silicon Materials for Photovoltaics"
Freiburg, 22.–24.10.2008

EMV, Blitz- und Brandschutz für Solaranlagen
Regensburg, 5.–6.11.2008

5th International Conference on Solar Concentrators
Palm Desert, California, USA, 17.–19.11.2008
(Program Committee)

DBU-Workshop "Kälte aus Wärme"
Osnabrück, 2.–3.12.2008

ETG-VDE Workshop Ländliche Elektrifizierung
Frankfurt, 3.–4.12.2008

Dr Thomas Aicher
Dr Tom Smolinka
"Energieverfahrenstechnik"
Vorlesungen WS 07/08 und WS 08/09
Hochschule Offenburg
Studiengang Elektrotechnik/
Informationstechnik^Plus

Dr Dietmar Borchert
"Photovoltaik"
Vorlesung SS 08
TFH Georg Agricola zu Bochum
Fachbereich Maschinentechnik

Dr Bruno Burger
"Solar-Technologien"
Vorlesung SS 08
Berufsakademie Ravensburg
Studiengang Elektrotechnik-
Automatisierungstechnik

Dr Bruno Burger
"Leistungselektronische Systeme für regenerative Energiequellen"
Vorlesung WS 08/09
Universität Karlsruhe
Fakultät für Elektrotechnik und Informationstechnik

Dr Andreas Gombert
"Optische Eigenschaften von Mikro- und Nanostrukturen"
Vorlesung WS 07/08
Albert-Ludwigs-Universität Freiburg
Fakultät für Angewandte Wissenschaften

Sebastian Herkel
"Solare Energiesysteme"
Vorlesung SS 08
Staatliche Akademie der Bildenden Künste, Stuttgart
Studiengang Architektur

Sebastian Herkel
Florian Kagerer
Doreen Kalz
Dirk Jacob
Dr Jens Pfafferott
Jan Wienold
"Sonderkapitel Klimagerechtes Bauen"
Vorlesung SS 08
Hochschule Biberach
Studiengang Gebäudetechnik

Doreen Kalz
"Efficient Cooling in Low-Energy Non-Residential Buildings",
"Low-Energy Residential Buildings"
Lectures during SS 08
Hanyang University, Seoul/Ansan, Korea
Subject area: Environment Friendly and Sustainable Construction

Doreen Kalz
"Kühlung von Nichtwohngebäuden mit Umweltenergie"
Vorlesung SS 08
Hochschule Offenburg
Studiengang Versorgungstechnik

Dr Jens Pfafferott
"Energieeffiziente Lüftung"
Vorlesung SS 08
Universität Stuttgart
Studiengang Maschinenbau

Dr Jens Pfafferott
"Solares Bauen"
Präsenzveranstaltung SS 08 und WS 08/09
Universität Koblenz-Landau
Fernstudiengang Energiemanagement

Dr Werner Platzer
"Thermische Solarenergie"
Präsenzveranstaltung WS 08/09
Universität Koblenz-Landau
Fernstudiengang Energiemanagement

Dr Ralf Preu
"Photovoltaics"
Lectures during WS 08/09
University of Freiburg
Master's Programme: Renewable Energy Management

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

Dr Heribert Schmidt
"Photovoltaische Systemtechnik"
Vorlesung SS 08
Universität Karlsruhe
Fakultät für Elektrotechnik und Informationstechnik

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

Prof. Eicke R. Weber
Dr Stefan Glunz
"Photovoltaische Energiekonversion"
Vorlesung SS 08
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof. Eicke R. Weber
Dr Werner Platzer
"Solarthermie"
Vorlesung WS 08/09
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof. Gerhard Willeke
Dr Giso Hahn
"Solarzellen und Umweltaspekte bei deren Herstellung"
Seminar SS 08
"Halbleitertechnologie und Physik der Solarzelle"
Vorlesung WS 08/09
Universität Konstanz
Fachbereich Physik

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

Trade Fairs and Exhibitions

GET – Gebäude.Energie.Technik
Freiburg, 15.–17.2.2008

23. Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein
5.–7.3.2008

Hanover Trade Fair, HMI 2008
Hanover, 21.–25.4.2008

Intersolar 2008
International Trade Fair and Congress for Solar Technology
Munich, 12.–14.6.2008

Intersolar North America 2008
San Francisco, California, USA, 15.–17.7.2008

23rd European Photovoltaic Solar Energy Conference and Exhibition
Valencia, Spain, 1.–5.9.2008

f-cell 2008
Stuttgart, 29.–30.9.2008

glasstec
Düsseldorf, 21.–25.10.2008

electronica
Munich, 10.–14.11.2008

NHA Annual Hydrogen Conference and Hydrogen Expo
Sacramento, California, USA, 30.3.–4.4.2008

Doctoral Theses

Andreas Grohe
"Einsatz von Laserverfahren zur Prozessierung von kristallinen Silizium-Solarzellen"
(Application of lasers in processing of crystalline silicon solar cells)
Universität Konstanz
Konstanz, 2008

Stefan Henninger
"Untersuchungen von neuen hochporösen Sorptionsmaterialien für Wärmetransformationsanwendungen"
(Investigations on new, highly porous sorption materials for heat-conversion applications)
Albert-Ludwigs-Universität Freiburg
Freiburg, 2008

Martin Hermle
"Analyse von Silizium- und III-V-Solarzellen mittels Simulation und Experiment"
(Analysis of silicon and III-V solar cells by simulation and experiment)
Universität Konstanz
Konstanz, 2008

Marc Hofmann
"Rear surface conditioning and passivation for locally contacted crystalline silicon solar cells"
Universität Konstanz
Konstanz, 2008

Matthias Meusel
"Entwicklung von III-V-Mehrfachsolarzellen für die Anwendung im Weltraum"
(Development of III-V multi-junction solar cells for space applications)
Universität Konstanz
Konstanz, 2008

Stephan Riepe
"Verteilung lebensdauerlimitierender Defekte in kristallinem Silicium für Solarzellen"
(Distribution of lifetime-limiting defects in crystalline silicon for solar cells)
Universität Konstanz
Konstanz, 2008

Lisbeth Rochlitz
"Entwicklung, Untersuchung und Modellierung eines Mikroreformers als Teil eines Systems zur netzfernen Stromversorgung mit PEM-Brennstoffzellen im Bereich einiger 100 Watt"
(Development, investigation and modelling of a miniature reformer as a system component for off-grid power supply with PEM fuel cells in the several-hundred watt range)
Brandenburgische Technische Universität Cottbus (BTU)
Cottbus, 2008

Thomas Roth
"Analyse von elektrisch aktiven Defekten in Silicium für Solarzellen"
(Analysis of electrically active defects in silicon for solar cells)
Universität Konstanz
Konstanz, 2008

Gerald Siefer
"Analyse des Leistungsverhaltens von Mehrfachsolarzellen unter realen Einsatzbedingungen"
(Analysis of the power-generation performance of multi-junction solar cells under real application conditions)
Universität Konstanz
Konstanz, 2008

Evelyn Schmich
"High-temperature CVD processes for crystalline silicon thin-film and wafer solar cells"
Universität Konstanz
Konstanz, 2008

Martin Schubert
"Detektion von infraroter Strahlung zur Beurteilung der Materialqualität von Solar-Silicium"
(Detection of infra-red radiation to evaluate the material quality of solar silicon)
Universität Konstanz
Konstanz, 2008

Birger Zimmermann
"Inversion of the layer sequence in organic solar cells – physical and technological aspects"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2008

Joachim Jaus, Andreas Bett, Armin Bösch, Frank Dimroth, Hansjörg Lerchenmüller
"Solar cell module and procedure for its production"

Marc Hofmann, Stephan Kambor
"Solar cell with structured back-surface passivation layer of SiO_x and SiN_x, and procedure for production"

Oliver Schultz, Stefan Glunz, Martin Hermle
"Solar cell and solar cell module with improved back-surface electrodes, and procedure and production"

Andreas Bett, Joachim Jaus
"Photovoltaic module and its application"

Oliver Schultz, Filip Granek, Andreas Grohe
"Procedure to apply a structure to a semi-conductor component"

Daniel Kray, Jörg Bagdahn, Stefan Schönfelder
"Procedure for mechanical characterisation of production equipment for silicon wafers or solar cells"

Heribert Schmidt, Bruno Burger
"Inverter"

Michael Oszcipok, Mario Zedda
"Fuel cell configuration with shingled fuel cells and application purposes"

Michael Oszcipok
"Passive dilution unit for dilution of fuels"

Joachim Jaus, Andreas Bett, Michael Passig, Gerhard Peharz, Peter Nitz, Wolfgang Graf
"Solar cell assembly with reflective secondary optics"

Timo Kurz
"Fuel cell system with adsorption heat storage unit for heating and gas drying"

Mario Zedda, Michael Oszcipok, Alexander Dyck, Ulf Groos, FWB Kunststofftechnik GmbH
"Production of planar electrochemical converters"

Wilhelm Warta, Martin Kasemann
"Contact-free characterisation of semiconductor structures by deliberate partial shading"

Emily Mitchell, Stefan Reber, Evelyn Schmich
"Concept and procedure for production of back-surface contacted thin-film solar cells"

Benoit Sicre, Thore Oltersdorf, Michael Hermann
"Distribution connector for interpenetrating multi-channel fluid-guiding devices"

Michael Hermann, Benoit Sicre, Thore Oltersdorf
"Procedure for production of a component with ribs for heat transfer and component produced in this manner"

Joachim Jaus, Andreas Bett
"Solar cell assembly integrated into a base-plate"

Steffen Eccarius, Mario Zedda, Christoph Ziegler
"Local adaptation of proton conductivity (MEA segmentation)"

Harry Wirth
"Compact solar concentrator"

Heribert Schmidt, Bruno Burger
"Inverter, particularly for thin-film modules"

Christian Wachtel, Matthias Krieg, Thomas Jungmann, Michael Oszcipok
"Coupled tank-absorber system for passive CO_2 absorption in direct alcohol fuel cells"

Peter Nitz
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Martin Schubert, Martin Kasemann, Wilhelm Warta, Peter Würfel
"Procedure and configuration for measurement of the diffusion length of charge carriers in semiconductors (cells/wafers) taking the surface into account experimentally and for measurement of series resistances"

Philipp Rosenits, Thomas Roth, Stefan Glunz
"Procedure to determine the lifetime of excess charge carriers in a semiconductor layer"

Harry Wirth
"PV modules with tempered solar cells"

Damian Pysch, Stefan Glunz
"Hetero-junction solar cells with a tunnel aluminium oxide (HALO)"

Martin Kasemann, Martin Hermle, Filip Granek
"Procedure and measurement of surface recombination rates in semiconductors"

Kolja Bromberger, Bettina Lenz
"Thermo-pneumatic micro-valve on the basis of phase change material"

Markus Glatthaar, Stefan Rein, Jonas Haunschild
"Luminescence scanner for characterisation of silicon solar cells"

Michael Hermann, Stefan Gschwander
"Automated heat transport system"

Valentin Radtke, Jonas Bartsch, Matthias Hörteis
"Light-induced galvanic pulsed deposition to reinforce metal contacts of solar cells"

Kolja Bromberger, Bettina Lenz
"Configuration of a thermo-capillary micro-pump with the possibility of dosing and mixing different materials"

Kolja Bromberger, Bettina Lenz
"Miniature water separator based on capillary effects"

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"Passive thermosensitive micro-valve"

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"Fuel cell configuration and procedure for its production"

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"Method to eliminate the effect of reflection in photoluminescence lifetime measurements of non-planar silicon wafers"

Patents Granted

Andreas Georg, Wolfgang Graf, Josef Steinhart, Volker Wittwer
"Optically transparent lightweight building component"

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

Ferdinand Schmidt, Hans-Martin Henning, Gunther Munz, Gerald Rausch, Andrea Berg, Norbert Rodler, Cornelia Stramm
"Adsorption heat pump, adsorption chiller and adsorber element for these applications"

Alexander Susdorf, Peter Hübner, Jürgen Koy, Angelika Heinzel, Klaus Wanninger, Albert Chigapov
"Ce/Cu/Mn catalysts"

Daniel Kray
"Procedure and device to dry a processed object and/or to maintain the dry state during liquid-guided processing of an object"

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

Hans-Martin Henning, Walter Mittelbach
"Car air-conditioning units with adsorption heat pumps"

Bruno Burger, Hansjörg Lerchenmüller
"Inverter with integrated controls for a tracker"

Christian Bichler
"Thermal storage unit and application of the thermal storage unit in a heating system with a solar system and heat pump"

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

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Andreas Grohe, Jan-Frederik Nekarda, Oliver Schultz
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Frank Dimroth
"Transparent contact and procedure for its production"

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Tilmann Kuhn, Christoph Mayrhofer, Jürgen Frick, Michael Hermann, Jan Wienold, Volker Wittwer
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2.1.2008
Water for the world's poorest

15.1.2008
Fraunhofer ISE sets new record for inverter efficiency – SiC transistors increase efficiency of PV systems

20.1.2008
The Sun and Success: On Track and in Focus – Concentrix Solar awarded "Innovation Award of the German Economy"

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Screen-printed solar cells

1.2.08
Electricity from a thin film

22.2.2008
Professor Joachim Luther appointed as CEO of the Solar Energy Research Institute of Singapore SERIS

29.2.2008
Eni Award 2008 – Science & Technology Solar Cell Researchers at Fraunhofer ISE distinguished with prestigious Italian award

3.3.2008
Well insulated means well heated

10.3.2008
Marketing Electricity from Distributed Generation – European Project seeks New Solutions

2.4.08
Electricity and gas consumption at a glance

11.4.2008
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15.4.2008
Portable Fuel Cells Soon to Have Certification Seal – Fraunhofer ISE and VDE cooperate in the certification of fuel cell systems

28.5.2008
Fraunhofer and MIT establish research center for renewable energy

5.6.2008
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10.6.2008
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Topic: Silicon materials for photovoltaics

19.6.2008
Eni Award 2008 ceremony in the presence of Italian president Giorgio Napolitano – Solar Cell Researchers at Fraunhofer ISE distinguished with prestigious Italian award

3.7.2008
37.6 % – European Record Efficiency for Solar Cells from Fraunhofer ISE

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21.10.2008
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Editors
Marion Hopf
Karin Schneider (Head)
Press and Public Relations

External Photographers
Michael Eckmann, Freiburg
Guido Erbring, Köln
Guido Kirsch, Freiburg
Margrit Müller, Freiburg
Joscha Rammelberg, Freiburg
Claudia Seitz, Sankt Märgen
Fraunhofer ISE
Fraunhofer IWM Halle
Stirling Power Module GmbH

Translation from the German
Dr Helen Rose Wilson, Freiburg

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Joachim Würger, Freiburg

Editorial Address
Fraunhofer Institute for
Solar Energy Systems ISE
Press and Public Relations
Heidenhofstr. 2
79110 Freiburg
Germany
Tel. +49 (0) 761/45 88-51 50
Fax. +49 (0) 761/45 88-93 42
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([1]: University of Konstanz, Department of Physics, Konstanz, Germany)
([2]: now with Berlin Solar GmbH, Berlin Germany)
([3]: also with Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany)
([4]: ECN – Solar Energy, Petten, The Netherlands)
([5]: IHP/BTU Joint Lab, BTU Cottbus, Cottbus, Germany)

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([1]: University of Konstanz, Department of Physics, Konstanz, Germany)
([2]: also with Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany)
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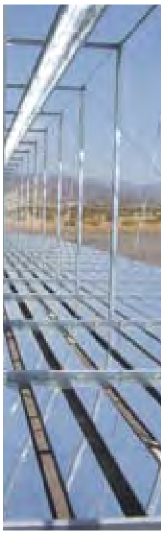
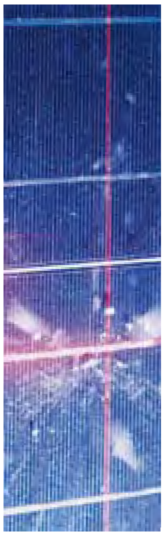
left title photo
FRESDEMO test collector at the Plataforma Solar de Almería in Spain. Measurement of this collector serves as the basis for techno-economic evaluation of Fresnel technology in comparison to parabolic throughs in solar-thermal power plants.

centre title photo
PV module during a hail impact test at the VDE-Fraunhofer ISE Test Centre for Photovoltaics. The hail canon was developed specially by Fraunhofer ISE for this test stand.

right title photo
A newly developed oil evaporator (in the background) is able to convert heating oil completely into vapour, without forming residues. The heating oil vapour is then used as the fuel for a gas burner (in the foreground).

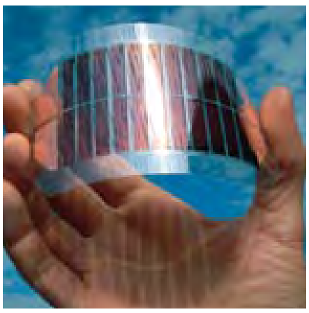




In addition to this annual report, more information can be found at our web site www.ise.fraunhofer.de

**Conferences and Trade Fairs in 2009
with Fraunhofer ISE participation**

- 14. Symposium Licht und Architektur,
  Kloster Banz, Bad Staffelstein, 12.–13.2.2009
- 24. Symposium Photovoltaische Solarenergie,
  Kloster Banz, Bad Staffelstein 4.–6.3.2009
- Hannover Messe, Stand Fraunhofer-Allianz Energie,
  Hannover, 20.–24.4.2009
- 19. Symposium Thermische Solarenergie,
  Kloster Banz, Bad Staffelstein, 6.–8.5.2009
- Intersolar, München, 27.–29.5.2009
- Intersolar North America,
  San Francisco, USA, 14.–16.7.2009
- 3rd Heat Powered Cycles Conference,
  Berlin, 7.–9.9.2009
- 15th International SolarPACES Symposium,
  Berlin, 15.–18.9.2009
- 24th European Photovoltaic Solar Energy Conference
  and Exhibition, Hamburg, 21.–25.9.2009
- f-cell Forum, Stuttgart, 28.–29.9.2009
- 3rd International Conference on Solar Air-Conditioning,
  Palermo, Italien, 30.9.–2.10.2009
- Solar Summits Freiburg: Solar Buildings, Freiburg,
  14.–16.10.2009



Fraunhofer Institute for
Solar Energy Systems ISE
Heidenhofstr. 2
79110 Freiburg
Germany

Tel. +49 (0) 7 61/45 88-0
Fax. +49 (0) 7 61/45 88-90 00
info@ise.fraunhofer.de
www.ise.fraunhofer.de