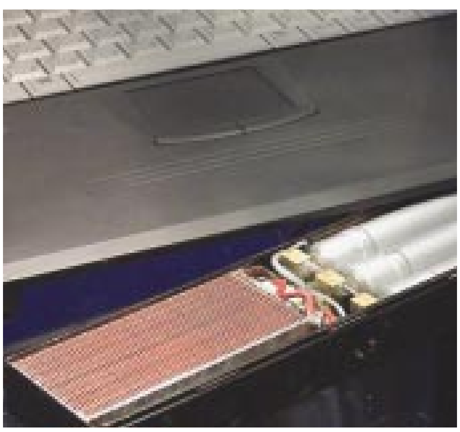
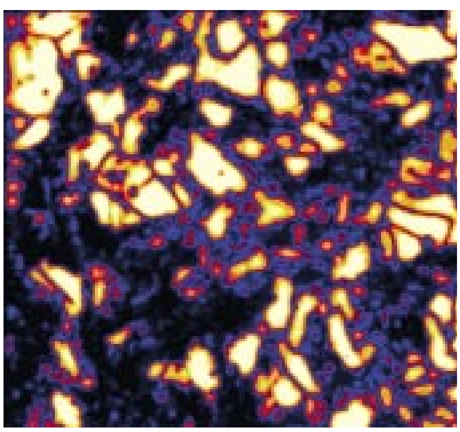
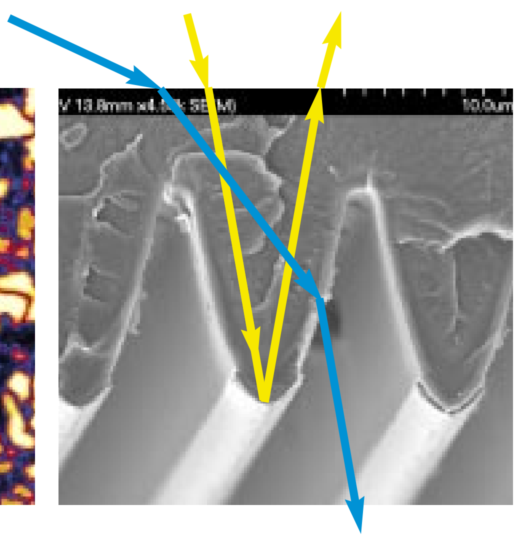
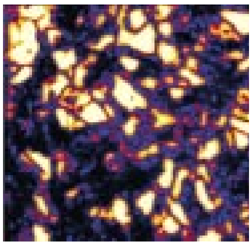
Fraunhofer Institut
Solare Energiesysteme

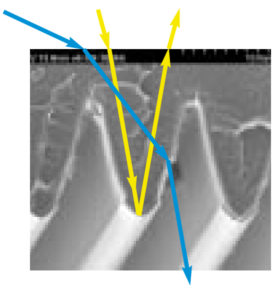
Achievements and Results
Annual Report 2002

Integration of a fuel-cell system into a laptop computer. Prototype development by Fraunhofer ISE with CEM Clean Energy Technologies Inc. and LG-Caltex Oil, Korea. The cell stack consists of 27 individual cells on top of each other. A highly efficient voltage converter (97 %) provides exactly the right output voltage (article on p. 56).



Spatial distribution of the minority charge carrier lifetimes over a 100 x 100 mm^2 multicrystalline silicon wafer, measured with Carrier Density Imaging (CDI). With the help of a digital camera operating in the medium infrared, the time for recording lifetime images with good spatial resolution was reduced to a few seconds (previously hours). This makes it feasible to apply this measurement technology industrially for process control during solar cell production (article on p. 43).



Scanning electron micrograph of a micro-structure for roof glazing. The structure reflects direct sunlight (yellow) but transmits diffuse light from the sky (blue). Integrated into a glazing unit, it protects against overheating and provides daylight for the room (article on p. 20).

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

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

Table of Contents

The current annual report from our Institute is the first which is structured according to the business areas that the Institute addresses. In the last two years we have established professional strategic planning at Fraunhofer ISE, which allows us to focus our work more sharply on our R & D market. We perceive our market now as being structured in five business areas:

Buildings and Technical Building Services
Solar Cells
Off-Grid Power Supplies
Grid-Connected Renewable Power Generation
Hydrogen Technology

In future, this structure will guide our marketing in the R & D and service areas, our external presentation and targeted, continuous strategic planning of our research and technological development. However, we have retained our well-tried department structure parallel to the grouping according to business areas. The departments are responsible for concrete structuring of our scientific work and the organisation of laboratory operation. Beyond that – a very important aspect for a large research institute – the departments offer a smaller-scale "home base" for our staff. This double-track system of departments and business area grouping has proven its value at Fraunhofer ISE, despite the more complex structure; we will continue with it in future.

Fraunhofer ISE again grew noticeably in 2002: The staff numbers increased by about 10 %. As our new premises were already too small for the entire Institute when we occupied them in 2001, this renewed growth could easily have led to major problems with finding sufficient space. Fortunately, with active support from the Fraunhofer Headquarters, we were able to lease a 6000 m^2 block of land with several buildings on the opposite side of the street to our new building. We also intend to use this area in the coming years to expand production technology for optical coating, micro-structured surfaces and solar cells.

One component of the Institute staff growth was among undergraduate and post-graduate students. We are currently mentoring 47 undergraduates from Technical Colleges and Universities, and are supported by 48 doctoral candidates in our research work. On the one hand, this demonstrates the scientific and technological attraction of the Institute, on the other hand, it also reflects our involvement in academic teaching. Eleven scientists from our Institute are currently teaching at Universities and Technical Colleges (see p. 94 of this annual report).

As in the past few years, this year we can also proudly report that a leading scientist at Fraunhofer ISE has been appointed as a professor. At the beginning of 2003, Dr Karsten Voss will accept a Chair for Building Science and Building Services Technology at the University of Wuppertal. On behalf of the entire Institute, I would like to congratulate Dr Voss heartily and explicitly thank him for all that he has achieved for the Institute over many years. Dr Voss' successor in the area of Solar Building will be an experienced and enthusiastic scientist from Fraunhofer ISE, Sebastian Herkel.

As already indicated in last year's annual report, Dr Tim Meyer became the Head of the Department for Electrical Energy Systems on 1st January, 2002. Under his leadership, the department profile has been sharpened during 2002, particularly in the areas of electronics, dispersed electricity generation and stand-alone power supply systems.

My thanks go to all members of the Institute staff for their creative, highly motivated and successful work. Some particularly outstanding results of their co-operative efforts are highlighted on p. 9 of this annual report. Their wholehearted efforts for technical applications of solar energy and Fraunhofer ISE deserve undisguised admiration. I am especially grateful to those representatives of industry, ministries and the European Union, whose commissions demonstrated their interest and trust, and ultimately made our work possible.

Prof. Joachim Luther

Institute Profile

The Fraunhofer Institute for Solar Energy Systems ISE conducts research on the technology needed to supply energy efficiently and on an environmentally sound basis in industrialised, threshold and developing countries. To this purpose, the Institute develops systems, components, materials and processes for the following business areas: buildings and technical building services, solar cells, off-grid power supplies, grid-connected renewable power generation, and hydrogen technology. The Institute's work ranges from basic scientific research relating to solar energy applications, through the development of production technology and prototypes, to the construction of demonstration systems. The Institute plans, advises and provides know-how and technical facilities as services. The Institute is integrated into a network of national and international co-operation. Among others, it is a member of the Solar Energy Research Association (Forschungsverbund Sonnenenergie) and the European Renewable Energy Centres (EUREC) Agency. There is particularly close co-operation with the Albert Ludwig University in Freiburg.

Research and Services Spectrum

The Fraunhofer Institute for Solar Energy Systems ISE is a member of the Fraunhofer-Gesellschaft, a non-profit organisation, which occupies a mediating position between the basic research of universities and industrial practice. The Institute finances itself with applied research projects and services concerning the technical application of renewable energy sources. Whether it concerns a major project or brief consultancy work, the working method is characterised by its clear relevance to practice and orientation toward the wishes of the client.

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

The aim of introducing the quality management system was to achieve optimised and transparent organisation of our project and research work. A positive response, particularly concerning acquisition at the international level, has confirmed the Institute's decision to adopt this measure.


SGS

Certificate

DIN EN ISO 9001: 2000

ISO 9001

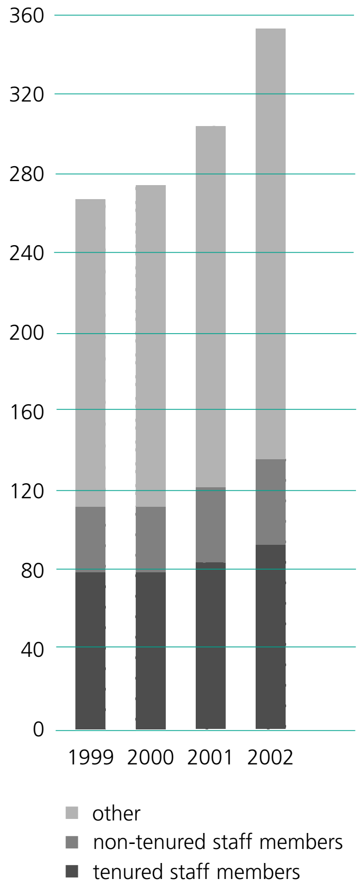
Since 2002, the organisational structure of Fraunhofer ISE has had two main components which mutually complement each other: departments and a grouping according to business areas. R & D marketing, external presentation of the Institute and above all, our strategic planning are structured according to the five business areas the Institute addresses. The four scientific departments are responsible for the concrete organisation of work and laboratory operation. Most scientific and technical staff are based in the individual departments. The photo above shows the Heads of the scientific departments and the Director of Fraunhofer ISE. From left to right: Tim Meyer, Gerhard Willeke, Joachim Luther, Christopher Hebling and Volker Wittwer.

Internal Organisational Structure of Fraunhofer ISE

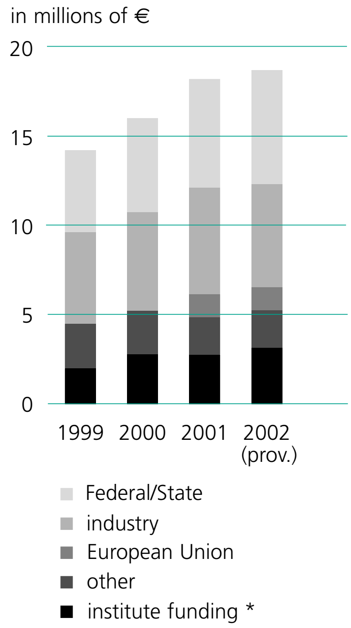
Institute Director	Prof. Joachim Luther	
Deputy Director	Dr Volker Wittwer	
Departments	Electrical Energy Systems Dr Tim Meyer	+49 (0) 7 61/45 88-52 16
	Energy Technology Dr Christopher Hebling	+49 (0) 7 61/45 88-51 95
	Solar Cells – Materials and Technology Dr Gerhard Willeke	+49 (0) 7 61/45 88-52 66
	Thermal and Optical Systems Dr Volker Wittwer	+49 (0) 7 61/45 88-51 43
Financial and Technical Services	Wolfgang Wissler	+49 (0) 7 61/45 88-53 50
Press and Public Relations	Karin Schneider	+49 (0) 7 61/45 88-51 47
Strategic Planning	Dr Carsten Agert	+49 (0) 7 61/45 88-53 46

The Institute in Figures

Personnel development



Income

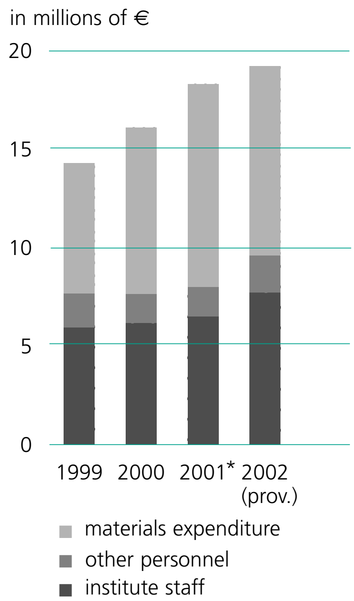


* not including funding for personnel and other expenses related to the move in 2001

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 2002, 48 doctoral candidates, 69 undergraduate students, 7 apprentices, 87 scientific and 6 other assistants were employed at the Institute. In this way, Fraunhofer ISE provides essential support to the education system.

In addition to the expenditure documented in the graph, the Institute made investments of 4.4 million euros in 2002.

Expenditure



* not including personnel and other expenses related to the move

Research and Development

- miniature Compound Parabolic Concentrators (CPC) for effective solar-control systems produced photolithographically for the first time
- micro-structured prismatic systems with gaschromic coatings demonstrated as effective, semi-transparent devices for glare protection and solar control
- rendering plaster with integrated, micro-encapsulated paraffins developed as a heat-storing component for buildings without air conditioning, and brought to market maturity
- efficiency of large-area collector systems improved by new pump units which are controlled on the basis of simulations
- small, compact heating and ventilation units prove themselves in a field test as excellent technology for heating solar passive houses
- laser-assisted procedure reduces the processing time for back-surface contacts on high-efficiency Si cells to 1 s
- screen-printing solar cell process resulting in an efficiency value of 15 % successfully established for large, multicrystalline Si wafers
- 70 µm thin wafers processed with conventional procedures to solar cells with an efficiency value of 20.5 %
- 5 x 5 cm^2 wafer-equivalent thin-film solar cell with an efficiency value of 13 % produced with a simple industrial process applied to a p++ Cz wafer made by direct epitaxy
- thermography camera and lock-in technology accelerate the characterisation of crystalline silicon wafers by a factor of more than 100
- laboratory production facility constructed for durably sealed, dye solar cell modules with an area of 30 x 30 cm^2
- test organic solar cells (0.5 cm^2) achieve an efficiency value of 2 %
- new circuit topology for inverters (HERIC® Highly Efficient and Reliable Inverter Concept) successfully demonstrated with an efficiency value of up to 96.5 %
- reformer for a stationary fuel-cell heating unit developed and constructed for co-generation of heat and electricity from natural gas
- 50 W miniature fuel-cell system developed as a laptop power supply and integrated into the battery compartment
- flat fuel-cell system (50 W) including power conditioning developed for integration behind the monitor of a laptop
- methanol fuel cell developed with a power density of 35 mW cm^{-2} at ambient conditions
- fully automated pressure electrolyser with a power of 2 kW developed and constructed
- petrol reformer developed for mobile applications

University Appointments and Prizes

Dr Karsten Voss has accepted a professorship at the University of Wuppertal, Chair of Building Science and Building Services Technology.

In the competition for the "Fuel Cell Innovation Prize 2002", Dr Christopher Hebling received the "f-cell award in bronze" for the contribution on a "Miniature PEM fuel-cell system as a power supply for a digital camcorder". The development of the miniature fuel-cell system for the camcorder is the focus of work by the Fraunhofer Initiative on Miniature Fuel Cells.

On 22nd November 2002, Thomas Werber received an award of honour from the Fachhochschule Aachen for his thesis entitled "Design, Construction and Commissioning of a Reformer to Generate Hydrogen for PEM Fuel Cells".

Dr Gerhard Willeke was appointed an honorary member of the Freiburger Materialforschungszentrum FMF at the University of Freiburg on 11th October, 2002.

Fraunhofer ISE was nominated as one of the five finalists for the "World Technology Network Award for Energy 2002", which was presented on 23rd July, 2002 in New York.

Clients

The Fraunhofer Institute for Solar Energy Systems has co-operated successfully for years with clients from a wide range of business sectors and company sizes.

Clients, who have agreed to publication of their names:

- ACR GmbH, Niedereschbach
- Adam Opel AG
- Aixtron GmbH, Aachen
- Akkumulatorenfabrik Sonnenschein GmbH (Exide German Group), Büdingen
- Ambient Recording, Munich
- Ansaldo, Genoa, Italy
- Applied Films, Alzenau
- AstroPower Inc., Newark, USA
- Autotype Ltd., Wantage, UK
- Badenova AG, Freiburg
- BASF AG, Ludwigshafen
- Bau Info Center Lüftungstechnik, a subsidiary of Schwörer Haus KG, Hohenstein
- Bayer AG, Krefeld-Uerdingen
- Beratung für Batterien und Energietechnik - BBE, Osterode
- Bess Europe, Zulte, Belgium
- British Petroleum BP Solar International, Sunbury, UK
- Bug-Alu Technik AG, Kennelbach, Austria
- Bundesministerium für Bildung und Forschung BMBF, Berlin (German Federal Ministry of Education and Research)
- Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, BMU, Bonn (Ministry for the Environment, Nature Conservation and Nuclear Safety)
- Bundesministerium für Wirtschaft und Technologie BMWi, Bonn (German Federal Ministry of Economics and Technology)
- Bundesverband Leichtbetonzuschlag-Industrie e.V., Stuttgart
- Caparol Farben, Lacke, Bautenschutz, Ober-Ramstadt
- Centrotherm GmbH, Blaubeuren
- Club zur ländlichen Elektrifizierung, C.L.E., Freiburg
- Creavis GmbH, Marl
- Daimler-Chrysler AG, Stuttgart
- Degussa-Hüls AG, Hanau
- DETA Batterien, Bad Lauterberg
- Deutsche Bundesstiftung Umwelt, Osnabrück (German National Foundation for the Environment)
- Deutsche Everlite GmbH, Wertheim (Main)
- Deutsche Gesellschaft für Technische Zusammenarbeit GmbH GTZ (German Society for Technical Co-operation), Eschborn
- Deutsche Solar GmbH, Freiberg
- Deutscher Alpenverein DAV (German Mountaineering Club), Munich
- E.ON Energie AG, Hanover and Munich
- Econzept Energieplanung GmbH, Freiburg
- EDAG Engineering + Design AG, Fulda
- Eichhorn, Thanhoffer & Thanhoffer OEG - ETT, Vienna, Austria
- EKRA Maschinenfabrik GmbH, Bönnigheim
- Energie Baden-Württemberg AG, EnBW, Karlsruhe
- Epichem Ltd., Merseyside, UK
- Ersol AG, Erfurt
- European Union EU, Brussels, Belgium
- Flabeg Holding GmbH, Gelsenkirchen
- Flughafen Köln/Bonn GmbH
- Ford AG, Cologne
- Fresnel Optics GmbH, Apolda
- G+H Isover, Ladenburg
- Gebäudemanagement Schleswig-Holstein (GMSH), Kiel
- Grammer KG, Amberg
- GreenONEtec, Ebenthal, Austria
- Greenpeace Germany, Hamburg
- Grundwert Verwaltungs- und Projektentwicklungs-GmbH (GVP), Frankfurt
- H.C. Starck Ceramics GmbH & Co. KG, Selb
- Hagen Batterie, (Exide German Group), Soest
- Heraeus Quarzglas GmbH & Co. KG, Kleinostheim
- Hochbauamt der Stadt Mannheim, Mannheim
- Hüppe Form, Oldenburg

- IBC Solartechnik, Bad Staffelstein
- Institutt for energieteknikk - Norges internatsjonale energiinstitutt IFE, Kjeller, Norway
- Instituto de Energía Solar IES, Madrid, Spain
- Interoptix Inc., San Jose, USA
- Interpane E & BmbH & Co. KG, Lauenförde
- Kostal GmbH + Co. KG, Dortmund
- Liebherr Aerospace AG, Lindenberg
- M + W Zander GmbH, Stuttgart
- Maico Haustechnik, Villingen-Schwenningen
- Master Flex AG, Gelsenkirchen
- Maxit Baustoff- und Kalkwerk Mathis GmbH, Merdingen
- Merck KGaA, Darmstadt
- Messer Mahler IGS, Stuttgart
- MHH Solartechnik GmbH, Tübingen
- MHZ-Hachtel, Leinfelden-Echterdingen
- Ministerium für Wissenschaft und Forschung, Baden-Württemberg, Stuttgart
- Moonlight, Wehr
- MVV Energie AG, Mannheim
- Okalux Kapillarglas GmbH, Marktheidenfeld
- OMG AG, Hanau
- Philips Medical Systems DMC GmbH, Hamburg
- Prof. Michael Lange, Berlin
- Prokuwa Kunststoff GmbH, Dortmund
- PV Silicon AG, Erfurt
- RENA Sondermaschinen GmbH, Gütenbach
- Resol Elektronische Regelungen GmbH, Hattingen
- Robert Bosch GmbH, Stuttgart
- Roth + Rau AG, Wüstenbrand
- RWE Power AG, Essen
- RWE Solar GmbH, Alzenau
- RWE Space Solar Power GmbH, Heilbronn
- RWTH Aachen, Aachen
- Saint Gobain G+H Isover, Ladenburg
- Saint Gobain Glass, Herzogenrath
- Schott Rohrglas GmbH, Mitterteich
- Siemens & Shell Solar Deutschland GmbH, Munich
- Solar World, Bonn
- Solar-Application GmbH, Freiburg
- Solarenergieförderverein Bayern e.V., Munich
- Solar-Fabrik GmbH, Freiburg
- Solvis GmbH, Braunschweig
- Sorpetaler Objekte GmbH, Sundern-Hagen
- Stadt Freiburg, Universitätsklinikum, Freiburg
- Stadtwerke Karlsruhe, Karlsruhe
- Steca GmbH, Memmingen
- Stiftung Energieforschung Land Baden-Württemberg
- Sto AG, Stühlingen
- Süd-Chemie AG, Munich
- Südwestrundfunk, Landesstudio Mainz
- Sunways, Constance
- Suptina Grieshaber, Schapbach
- Trama Tecno Ambiental, Barcelona, Spain
- Transénergie, Lyon, France
- Truma AG, Munich
- TRUMPF Laser GmbH & Co. KG, Schramberg
- University of New South Wales, Centre for Third Generation Photovoltaics, Sydney, Australia
- Vegla GmbH, Aachen
- Velux A/S, Vedbaek, Denmark
- Viega GmbH Co. KG, Attendorn
- Wagner & Co., Cölbe
- Warema Renkhoff GmbH, Marktheidenfeld
- Webasto AG, Munich
- Wilo GmbH, Dortmund
- Wirtschaftsministerium Nordrhein-Westfalen
- World Bank, Washington, USA
- Würth Solar GmbH & Co. KG, Marbach am Neckar
- Zentrum für Sonnenenergie- und Wasserstoff-Forschung ZSW, Stuttgart/Ulm
- Zibell, Willner & Partner, Berlin

International Co-operation

We co-operate with international partners in a constantly increasing number of projects.

- Air Liquide S.A., Sassenage, France
- Altai Centre for Non-Traditional Energy and Energy Saving, Barnaul, Russia
- Aplicaciones Tecnicas de la Energía S.A. – ATER SA, Valencia, Spain
- Arge Erneuerbare Energie, Gleisdorf, Austria
- Australian Cooperative Research Centre for Renewable Energy – ACRE, Perth, Australia
- Australian National University – ANU, Canberra, Australia
- BPP Teknologi LSDE, Technical Implementation Unit, Energy Technology Laboratory, Serpong Tangerang, Indonesia
- British Petroleum BP Solar International, Sunbury, UK
- Centre de Caderache – CEA-GENEC, Saint-Paul-lez-Durance, France
- Centre for Renewable Energy Sources CRES, Pikermi, Greece
- Centre National de la Recherche Scientifique CNRS, Palaiseau/Meudon/Strasbourg/ Marseille/Montpellier, France
- Centre Scientifique et Technique du Bâtiment CSTB, Grenoble, France
- Centro de Investigación en Energía y Agua, CIEA, Las Palmas de Gran Canaria, Spain
- Centro Elettrotecnico Sperimentale Italiano Giacinto Motta SpA – CESI, Milan, Italy
- Chloride, Madrid, Spain
- CIEMAT Instituto de Energías Renovables IER, Madrid, Spain
- Compagnie Européenne d'Accumulateurs CEAC, Gennevielliers, France
- Consejo Superior de Investigaciones Cientificas CSIC, Madrid, Spain
- Det Norske Meteorologisk Institutt, Bergen, Norway
- Ecole des Mines, Paris (Centre d'Energétique, Sophia Antipolis), France
- Ecole Nationale des Travaux Publics de l'Etat ENTPE, Lyon, France
- Eidgenössische Materialprüfungs- und Forschungsanstalt – EMPA, Dübendorf, Switzerland
- Ente per le Nuove Technologie, l'energia e l'ambiente – ENEA, Rome, Italy
- ENECOLO, Mönchaltorf, Switzerland
- Energy Research Centre of the Netherlands – ECN, Petten, the Netherlands
- Esbensen Consulting Engineers, Virum, Denmark
- European Union EU, Brussels, Belgium
- Greencell, Seville, Spain
- Guangzhou Institute of Energy Conversion GIEC, Guangzhou, China
- HCT Shaping Systems, Cheseaux, Switzerland
- Hebrew University, Jerusalem, Israel
- Hochschule für Technik und Architektur, Burgdorf, Switzerland
- Inabensa, Seville, Spain
- Instituto Catalan de Energía ICAEN, Barcelona, Spain
- Instituto de Energía Solar IES, Madrid, Spain
- Instituto de Investigaciones Electricas, Cuernavaca, Morelos, Mexico
- Instituto Nacional de Tecnica Aerospacial "Esteban Terradas" INTA, Madrid, Spain
- Instituto National de Engenharia e Tecnologia Industrial INETI, Lisbon, Portugal
- Instituto Tecnológico y de Energías Renovables ITER, Teneriffe, Spain
- International Energy Agency IEA, Paris, France
  Photovoltaic Power Systems
  Programme PVPS:
  - Task 5: Grid Interconnection of Building-Integrated and Other Dispersed PV Power Systems
  - Task 7: Photovoltaic Power Systems in the Built Environment
  - Task 9: PV Deployment in Developing Countries

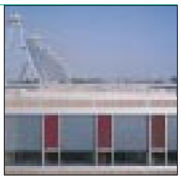
Solar Heating & Cooling Programme SHCP:
- Task 21: Daylight in Buildings
- Task 25: Solar Assisted Air Conditioning of Buildings
- Task 27: Performance of Solar Building Envelope Components
- Task 28: Sustainable Solar Housing
- Task 31: Daylighting Buildings in the 21st Century

- International Solar Energy Society ISES, Freiburg
- Interuniversity Microelectronics Centre IMEC, Leuven, Belgium
- Ioffe Institute, St Petersburg, Russia
- Joint Research Centre ISPRA, Ispra, Italy
- Kema Nederland B. V., Arnhem, the Netherlands
- Laboratoire Charles Fabry de l´Institut d´Optique, CNRS, Orsay, France
- Lawrence Berkeley National Laboratory, LBNL, Berkeley, USA
- National and Kapodistrian University of Athens, Greece
- National Institute for Chemistry, Ljubljana, Slovenia
- National Renewable Energy Laboratory NREL, Golden, USA
- Naval Research Laboratory, Washington, USA
- Nedstack, Arnhem, the Netherlands
- NLCC Architects Sdn., Kuala Lumpur, Malaysia
- Norsk Enøk og Energi AS, Drammen, Norway
- Nuvera Fuel Cells, Milan, Italy
- Oxford Brookes University, Oxford, UK
- Photowatt SA, Bourgoin-Jallieu, France
- Pillar Joint-Stock Co., Kiev, Ukraine
- Politechnika Lódzka, Lodz, Poland
- Politechnika Krakowska, Cracow, Poland
- RISOE - National Laboratory, Roshilde, Denmark
- Rutherford Appleton Laboratory, Oxfordshire, UK
- S.E. del Acumulador Tudor S.A., Madrid, Spain
- SAMSUNG Corp., Yongin, Korea
- Scanwafer AS, Høvik, Norway
- Solarenergie Prüf- und Forschungsstelle, Rapperswil, Switzerland
- Swedish National Testing and Research Institute, Boras, Sweden
- TNO Building and Construction Research, Delft, The Netherlands
- Tokuyama Corporation, Yamaguchi, Japan
- Topsil Semiconductor Materials, Frederiksand, Denmark
- Total Energie, La Tour de Salvagny, France
- Trama Tecno Ambiental, Barcelona, Spain
- Universidad de la Laguna, La Laguna, Tenerife, Spain
- Università degli Studi di Genova, UGDIE, Genoa, Italy
- University of California, Berkeley, USA
- University of Cyprus, Nikosia, Cyprus
- University of New South Wales UNSW, Sydney, Australia
- University of Reading, UK
- University of San Juan UNSJ, Argentina
- University of Stockholm, Sweden
- University of Strathclyde, UK
- University of Uppsala, Sweden
- University of Utrecht, the Netherlands
- University of Zurich, Switzerland
- Velux A/S, Vedbaek, Denmark
- Vergnet S.A., Ingré, France

Board of Trustees

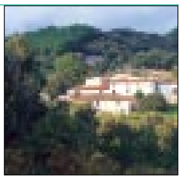
The board of trustees assesses the research projects and advises the Institute directorate and the Executive of the Fraunhofer-Gesellschaft with regard to the working programme of Fraunhofer ISE.
Status: 31st December, 2002

Buildings and Technical Building Services

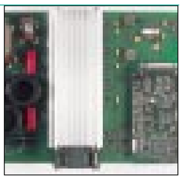


Solar Cells

Off-Grid Power Supplies

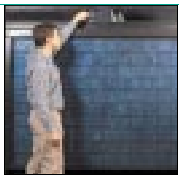


Grid-Connected Renewable Power Generation

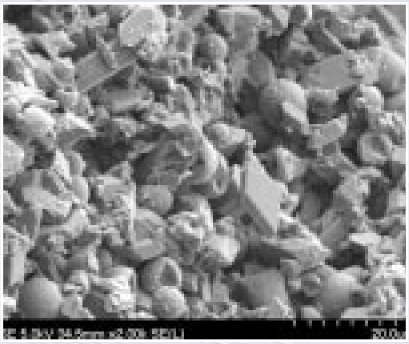


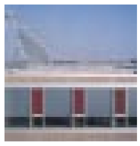
Hydrogen Technology

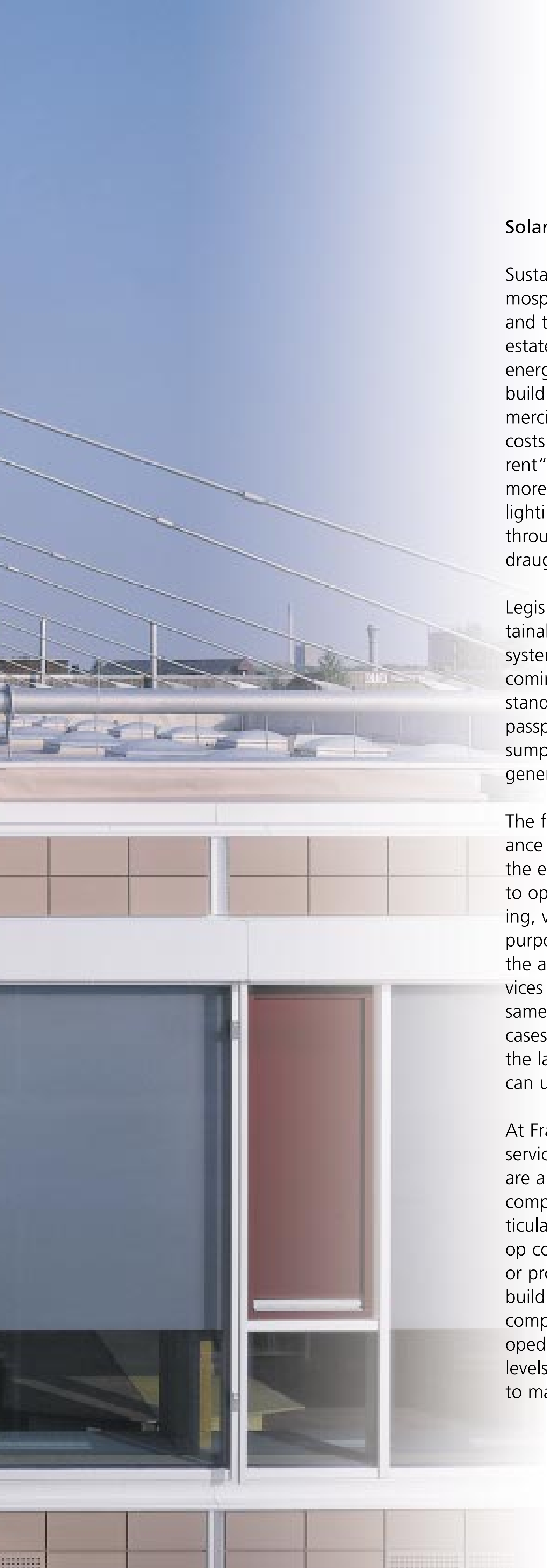
Service Units



Buildings and Technical Building Services







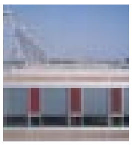
Solar Building Brings Benefits

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

Legislation is supporting the trend toward sustainable building. Thus, three million heating systems in Germany must be renovated in the coming years, because they no longer meet the standards for energy efficiency. Or the energy passport: It will make the specific energy consumption of buildings transparent also to the general public.

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

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



These tasks rely on co-operation between many disciplines: materials research and thin-film development, rational use of energy, simulation, planning, monitoring, development of components such as windows or walls, and of solar systems for heat and electricity. Miniature heat pumps and, in future, decentralised energy generators such as small fuel cells are growing in importance as suppliers of heat and electricity in the building sector.

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

Working in a team together with architects, professional planners and industrial representatives, we plan the buildings of today and develop the buildings for tomorrow. We help to shape international boundary conditions within the International Energy Agency IEA in programmes on solar air-conditioning, solar building and the long-term durability of components. In this way, we are always informed about the current technical standards. This, together with our international contacts, allows us to support our clients in market introduction.

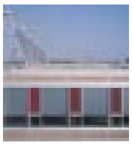
We are constantly developing our equipment and measurement procedures further. Some examples include:

- large laser exposure benches, to produce microstructures over areas of up to 60 cm x 80 cm
- vacuum deposition system for quasi-industrial production of large-area (140 cm x 180 cm), complex coating systems on glass, polymer films and metals
- optical laboratories for characterisation and analysis in materials development
- test laboratories to determine physical and technical properties of collectors, thermal storage tanks, windows and wall systems
- measurement technology for on-site quality control in buildings.

In order to investigate the user acceptance of building solutions, we also involve test persons.

The experimental work is accompanied by ongoing development of simulation programs. They are the pre-requisite for further optimisation of materials and systems.

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



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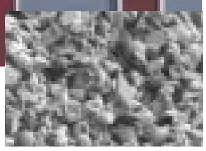
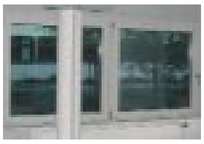
SOLVIS zero-emission factory. The illustration shows the facade with vacuum insulation (red), light-scattering glazing (grey) and inlet air vents (perforated blocks). The solar collectors are part of the roofing support structure (article on p. 32). Architects: Banz+Riecks, Bochum; Photo: C. Richters

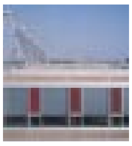


Scanning electron micrograph of micro-encapsulated phase-change materials (spheres) in rendering plaster, enlarged app. 2000x. The average diameter of the capsules is about 8 µm.



Electrochromic window glazing. Fraunhofer ISE has installed test windows in one of its own offices for user acceptance studies.

Visual inspection of a surface-structure grating. The master structures, which are produced at Fraunhofer ISE, are replicated in polymers and sol-gel films.



Development of Solar Control Glazing with Optically Functional Microstructures

Transparent areas of the building envelope have become a feature of modern architecture with its focus on natural lighting. Innovative systems for efficient seasonal control of the natural fluxes of light and energy are in demand. We develop microstructures which selectively control visible and solar radiation. In particular, they reflect undesired radiation in summer outwards.

Benedikt Bläsi, Christopher Bühler, Andreas Georg, Andreas Gombert, Wolfgang Hoßfeld, Jörg Mick, Peter Nitz, Harald Lautenschlager, Christian Schetter, Günther Walze, **Volker Wittwer**

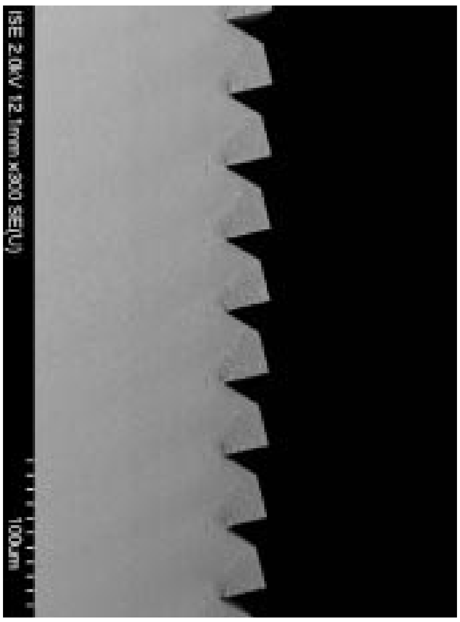


Fig. 1: Scanning electron microscope (SEM) image of a microprism array replicated in plastic. The prism period is 50 µm. The external light is incident from the upper left.

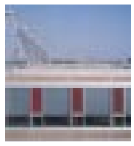
The welcome function of large glazed areas in winter, namely of transmitting large amounts of light and heat into a building, can become a problem in summer. The excess light and heat must often be obstructed by complicated measures or removed by air-conditioning units with a high expenditure of energy. The aim is thus an effective, seasonally dependent solar transmittance for the envelope. As the sun is higher in the sky during summer than in winter, our approach is to make the facade transmittance dependent on the solar altitude.
To achieve this, we use the light-redirecting effect of transparent materials with a prismatic surface structure. The transmittance can be additionally altered with switchable coatings.

Prismatic solar control systems are not new. Prisms with dimensions of several millimetres are arranged in rows to obtain large-area systems. The solar radiation incident from a certain angular range is totally internally reflected by the prism facets. Daylight which is incident on the solar control system from angles other than the direct solar radiation is transmitted. In some cases, one orientation of the prism facets is also coated with a reflector to guide the light.

Until now, the size of the prisms presented difficulties: the systems were relatively large, heavy and also expensive. Our goal, therefore, was to make the structures smaller. With structure dimensions of app. 0.1 mm or less, the solar control systems can already be integrated into relatively thin films or sheets in glazing units. This not only avoids the disadvantages of existing prismatic solar control systems mentioned above; the microprisms also present a homogeneous appearance. This is particularly important for facades that are oriented to the south-east or south-west: In this case, the line of intersection between the solar ecliptic plane and the facade is not horizontal but inclined. In order to deflect the solar radiation according to the solar altitude at the appropriate season, the solar control system has to be correspondingly inclined. These sloped lines in macroscopic structures often disturb the architectural impression but with microstructures, this effect is not externally visible.

Miniaturisation of the structures raised questions concerning the production process and the physical limits. How small could the prisms become before diffraction effects significantly detracted from their performance? We applied the most accurate physical method, rigorous diffraction theory, to obtain the answer. The results show that the structure dimensions can indeed be smaller than 0.1 mm, although diffraction effects already appear at this size. However, the extent to which diffraction effects limit the optical function varies greatly, depending on the structure form and the structure type, especially those with partially mirrored surfaces. Using rigorous diffraction theory, we can now also optimise the structure forms.

Microstructured films or sheets can be produced with well-established microreplication processes. However, it is still difficult to produce the master form. One possibility is by diamond-tip tooling - turning, milling or planing. Figure 1 shows a prism array which probably can only be made in this form by tooling.



Another possibility is to apply interference lithography in the production of prismatic or similar structures. Laser rays are split, expanded and superimposed. An interference pattern results, which is used to expose a light-sensitive photoresist coating. Development of the exposed photoresist layer leads to a surface structure which can be transferred onto a polymer material in further replication steps such as embossing.

Although the superposition of two laser rays can result only in a light-dark striped pattern, an astounding variety of very complex microstructures can be generated by interference lithography if multiple exposure or superposition of more than two rays is applied. The photoresist-coated plate can be tilted and also turned between two subsequent exposures (fig. 2). If diffusing plates are introduced into the optical path, stochastic structures can be produced. Interference lithography also allows different structure components, e.g. periodic and stochastic structures, to be mixed or superimposed.

Interference lithography can create homogeneous structures over large areas. To date, homogeneous microstructures for solar control systems have been produced over areas of 37 cm x 37 cm. Other types of structures have already been made over areas of 0.5 m^2 at Fraunhofer ISE. We are working to increase the area further, so that the number of films or sheets which have to be mounted adjacent to each other for applications is kept as small as possible.

By applying the described procedure, we have developed microstructures for solar control systems with partial visibility. Flat zones between the structures allow visual contact to the outside world (fig. 3). Figure 4 shows a periodic prismatic structure which functions as seasonally dependent solar control, and consists of "sawteeth" with a superimposed stochastic envelope. The aim of this trick, for which a patent claim has been filed, is to suppress the coloured effects that can arise from refraction or diffraction. The glazed unit made in this way, with its seasonally dependent solar control, has the elegant appearance of satin-finished glass.

Further optical functions can be obtained by vacuum-coating the microstructured films. Certain facets of the structures can be coated selectively by using an inclined deposition source. To date, we have investigated metal coatings as reflectors and WO_3 for gaschromic, switchable systems.

Switchable gaschromic microstructured systems (fig. 5) offer the advantage that the transmittance depends on the sun's position and can also be switched actively if desired. As well as this additional flexibility compared to "conventional"

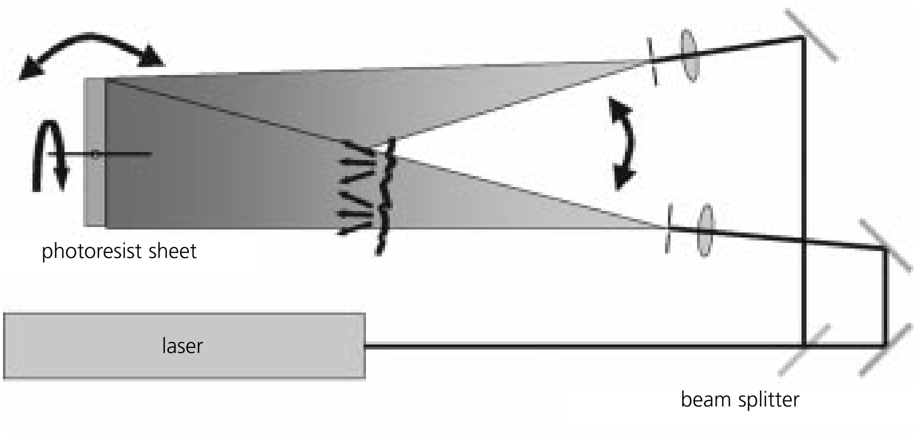


Fig. 2: Optical configuration and possibilities to influence the resulting structure profiles in interference lithography.

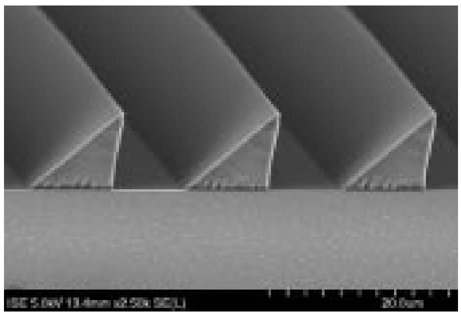


Fig. 3: SEM image of a microprism array in photoresist, affording partial visibility. The prism period is 17 µm.

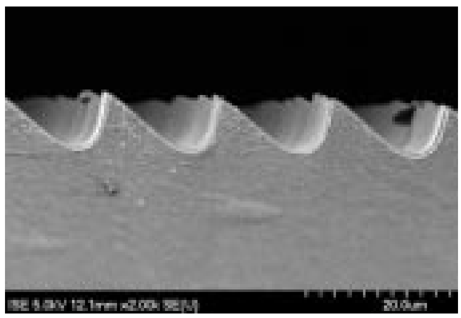
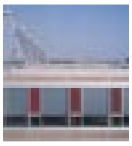


Fig. 4: SEM image of prismatic structures replicated in plastic, which provide seasonal solar control. The structuring process using interference lithography allows a stochastic envelope to be superimposed on the periodic structure (visible in the photo as a variation in height of the "sawteeth"). The resulting glazed unit has the appearance of glass with a satin finish. The prism period is 17 µm.



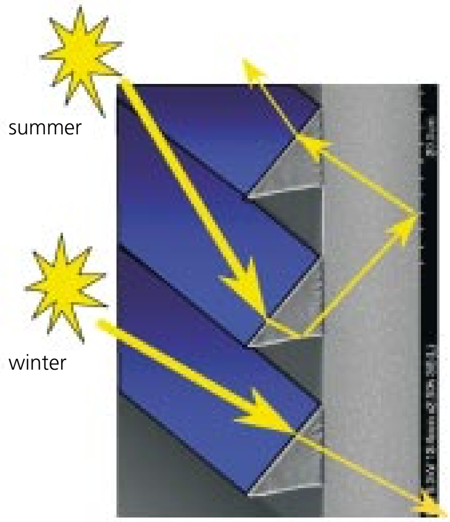


Fig. 5: Schematic representation of a "combined" solar-control microstructure, offering a slightly restricted view of the external environment. In addition to total internal reflection of sunlight in summer, some of the winter sun can be absorbed.

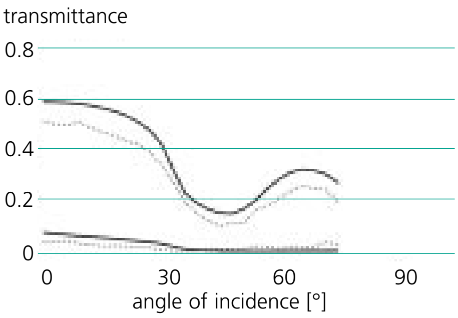


Fig. 6: Direct-hemispherical transmittance of a switchable glazing unit as a function of the incident angle, for light (solid line) and solar radiation (dotted line). Bleached - upper two curves, coloured - lower two curves. The whole area of this microstructured prototype is covered with a gaschromic coating.

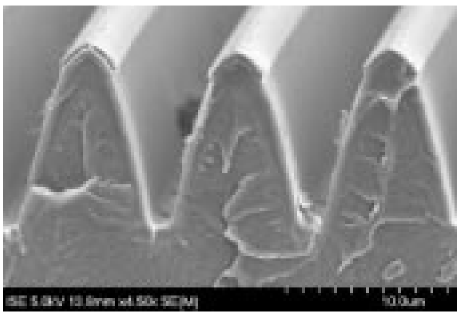
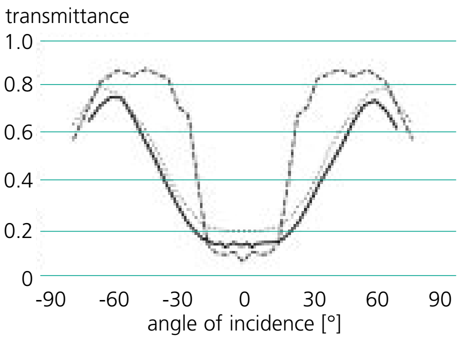


Fig. 7: SEM image of a Compound Parabolic Concentrator (CPC) replicated in a polymer. The "ridges" are selectively coated with metal. The prism period is 10 µm (see also cover photo).

gaschromic windows or glazed units with uncoated microstructures, "combined" systems offer the potential for meeting the stringent requirements for glare protection in offices with computers. The coating can be deposited on selected facets, as shown in fig. 5, or applied over the entire area. Figure 6 shows the angular dependence of measured transmittance values for a microstructured glazing prototype that was gaschromically coated over the whole area.

Another microstructure which is produced with interference lithography consists of Compound Parabolic Concentrators (CPC's). They concentrate direct sunlight from a certain angular range onto their mirrored collector area, so that it is reflected. Simultaneously, they have a high transmittance for diffusely incident skylight, which is desirable to provide daylight to the room.

Figure 7 shows the SEM image of a CPC structure which was produced by interference lithography and replicated in a transparent polymer. Evaporation from an inclined source succeeds in selectively coating even the smallest structures, on the order of micrometres, applying a reflective surface to the collector areas of a CPC.

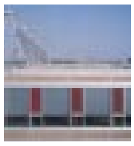


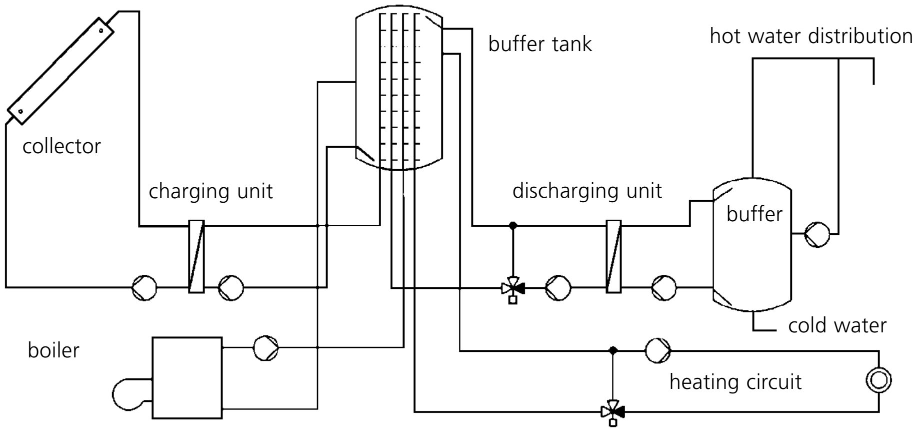
If this structure is installed in sloped roof glazing, it reflects radiation from a range of incident angles which can be freely chosen by varying the geometry of the CPC walls. The reflective angular range for the investigated structures is about 40°, so that if they are mounted in a roof sloped at 35°, they will reflect direct radiation throughout the whole summer half-year. In figure 8, the solid line shows the transmittance measurement while the dotted line shows the simulation result for a CPC structure of the type shown in fig. 7. The dashed line indicates the potential for improvement, i.e. the transmittance of an ideal structure. The optimal function can be approached in the foreseeable future.

In the "Nanofab" joint project, which was supported by the German Federal Ministry of Education and Research BMBF, we investigated microstructures manufactured by tooling processes. In the "Mikrofun" basic research project, which was funded by the German Federal Ministry of Economics and Technology BMWi, we developed and demonstrated production methods applying interference lithography and partial vacuum deposition of microstructures.

Follow-up projects to implement these ideas in glazing products are currently being planned in close co-operation with industry.

Fig. 8: Direct-hemispherical transmittance of sheets or films which are microstructured with CPC's. The measured values for the structure shown in fig. 7 (solid line) are compared with the simulation of this structure (dotted line) and the theoretically achievable optimum of an ideal structure with an ideally reflective coating (dashed line).





Development of Industrially Pre-Fabricated Compact Units for Large Thermal Solar Systems

Among recently installed solar systems for free-standing homes, the share of combined systems, i.e. for domestic hot water combined with solar-assisted space heating, is increasing continuously. A similar trend is anticipated in the near future also for large thermal solar systems with collector areas exceeding 100 m^2.

Stephan Buschmann, Konrad Lustig,
Matthias Rommel, Christof Wittwer

With the aid of simulation models, we investigate the fundamental system variants which come into question for such systems. We dimension the components and develop control strategies. In doing so, a central role is allocated to the development of a heating source and distribution unit, which optimises the co-ordination between pumps and heat exchangers via a controls system.

Two compact units of this type with a newly developed, cross-linked control system were installed for test purposes in the "Vauban" system belonging to the Freiburg Student Services (140 m^2 collector area). By connecting the control system to the Internet, we were able to access the systems on the one hand, and on the other, to check the system yield on the basis of radiation data available via the Internet.

The simulation studies are being made with ColSim, a program which was conceived by Fraunhofer ISE especially for developing controls. It works with a time base of one year, which is necessary for system characterisation of solar systems. At the same time, it reproduces the control dynamics with a time resolution in the range of seconds. The software has a modular structure and is implemented in portable ANSI-C code. Thus, the modules can also be used in microcontroller-based controls systems.

The modules of the cross-linked controls systems for the compact units were also developed in the simulation environment, before they were transferred to the intended system.

The integration of dynamic system models into the controls is also becoming increasingly important for two reasons: The controls systems are becoming more and more powerful, and system operation can be controlled by "real time identification".

Control of the yield is particularly important for hybrid solar systems, where a conventional energy supply is also present to meet the demand: Without control, a defect in the operation of the solar system would not be immediately detected due to the constant availability of the conventional energy supply.

The work is supported by the German Federal Ministry of Economics and Technology BMWi.

Fig. 1: System diagram for a combined system. In relatively large solar arrays, not only domestic hot water but also the space heating circuit of the building can be supplied via the hot water buffer tank. The system is always equipped with a heating boiler (two heat sources, two heat sinks).

Fig. 2: Configuration of the compact unit for the distribution side, to transfer heat from the solar heated buffer tank to the domestic hot water circuit (photo: PAW company).

Specifications for Pipe-Connection Techniques in the Solar Circuit of Thermal Solar Systems

The temperature loads which collector components must withstand are relatively well known. By contrast, the demands on the pipe connections which are used in the solar circuit have not been investigated in any detail previously. We have now done this and defined appropriate specifications. This allows manufacturers of piping and connection components to adapt their products better to the requirements of solar technology.

Joachim Koschikowski, **Matthias Rommel**, Arim Schäfer, Vitali Schmidt, Yan Schmitt

The heat transfer medium in the solar circuit is an important component of thermal solar systems. This applies both to the "normal", energy-collecting operating state and also to the "stagnation" state. A stagnation state occurs whenever the system tank has reached the maximum allowed temperature, so that although solar radiation is still incident on the collector, the pump of the solar circuit must be switched off. This can become necessary to avoid calcium deposits in the solar heat exchanger or temperatures exceeding 100 °C in the buffer tank.

Depending on the construction type, temperatures between 200 °C and 300 °C can occur in the absorber of a (dry) collector when exposed to maximum solar radiation. When a system is in stagnation, the fluid evaporates. The vapour also enters the piping of the solar circuit.

We have investigated the stresses which arise due to the associated temperature and pressure loads in the piping. Our new, large-scale solar simulator provides excellent experimental conditions for conducting relevant experiments. From the results, we were able to derive the specifications for piping connections intended for use in solar systems. In doing so, we proved that fractional distillation of the water-glycol fluid occurs under stagnation conditions. This means that the demands on the pipe connections in the solar circuit are higher than assumed previously. The temperatures which occur are higher than the saturated steam temperature of water at the maximum system pressure. The distance which the steam travels within the pipes of the solar circuit depends strongly on the piping configuration of the individual collectors and the connection of the collectors within the array. If the collector array drains poorly, the steam penetrates significantly further than has been assumed up to now. With our results, it is now possible to accurately determine which connections in a thermal solar system have to withstand particularly high temperatures.

Using the solar simulator, we can conduct comparable investigations for other components and operating states of thermal solar systems on commission to clients.

The project was commissioned by the German Copper Institute (DKI) together with PSE GmbH, manufacturers of connection components and a solar company, and was supported by the German Federal Foundation for the Environment (DBU).

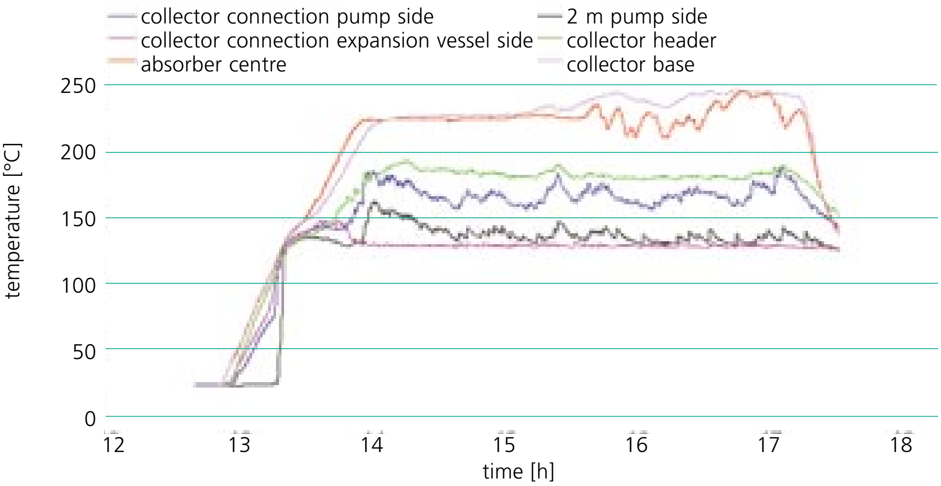
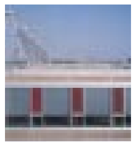


Fig. 1: Measurements with the laboratory solar simulator. Even at a distance of more than 2 metres from the collector inlet or outlet, temperatures occur which are significantly higher than the saturated vapour temperature of the water-glycol mixture.



Micro-Encapsulated Phase-Change Materials for Walls

The heat capacity of lightweight buildings can be drastically increased by incorporating phase change materials (PCM) into the construction materials. It is often desirable to increase the heat capacity so that temperature peaks, particularly those occurring on hot summer days, can be flattened out. In lightweight buildings such as new office complexes, this reduces the need for air conditioning and increases user comfort.

Hans-Martin Henning, **Peter Schossig**, Alexandra Raicu*, Thomas Haussmann

Using building simulation tools, we have identified suitable application areas for this type of product.

Wall samples have been measured by equipping two identical, lightweight test rooms of the facade test facility (fig. 1) with comprehensive measurement instruments and PCM products. The test cells have a typical lightweight construction: plasterboard sheets on a wooden framework, with insulation which is mounted on the PU (polyurethane) walls of the cabins. One of the test cells had an additional 6 mm thick rendered layer containing PCM. The reference cell had a conventional rendered layer without PCM. Both test cells have controlled ventilation and external venetian blinds. They were both subjected to the same programme of experiments.

The measured wall and air temperatures are shown in figures 2 and 3 respectively for three consecutive days in summer 2002. It is evident that the temperatures in the PCM cell increase significantly more slowly than in the reference cell in the melting range of the PCM (24 - 27 °C). After 27 °C has been reached, the temperatures increase at a parallel rate in both cells, so that a temperature difference of up to 4 K at the maximum is achieved. In addition, the PCM shifts the temperature maximum by about an hour back to 6 p.m.. The temperatures in the PCM cell are higher during the night. The latent heat stored in the PCM must be removed by adequate nocturnal ventilation.

These measurements allow us to directly determine the PCM effect quantitatively, as the effects of different users or other boundary conditions are absent. The experimental results were used to validate and refine a computer model. We use the improved model to identify further application areas in comprehensive parameter studies.

The statistics over a 20-day period in fig. 4 show that when the shading was controlled and the nocturnal ventilation was sufficient, the air temperature exceeded 28 °C for 50 hours in the reference cell, but only for 5 hours in the PCM cell.

The data obtained from the test facility clearly demonstrate the potential of building materials with PCM to reduce the air-conditioning demand and increase comfort.

The first products with integrated PCM will enter the market in 2003.

The joint project with BASF, DAW, maxit and Sto is supported by the German Federal Ministry of Economics and Technology BMWi.

Fig. 1: Facade test facility of Fraunhofer ISE: The two lightweight cells are positioned above each other (centre of photo).

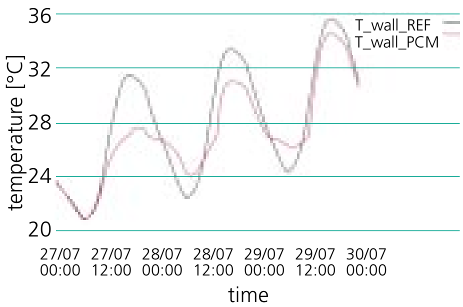


Fig. 2: Wall temperatures in the reference cell (black) and the cell with a 6 mm thick PCM layer (red).

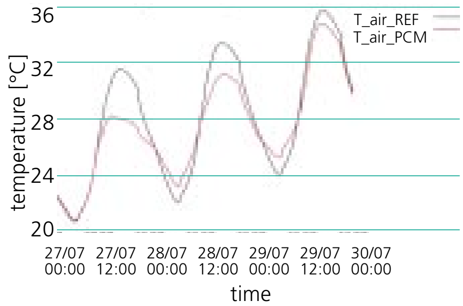


Fig. 3: Air temperatures in the reference cell (black) and the cell with a 6 mm thick PCM layer (red).

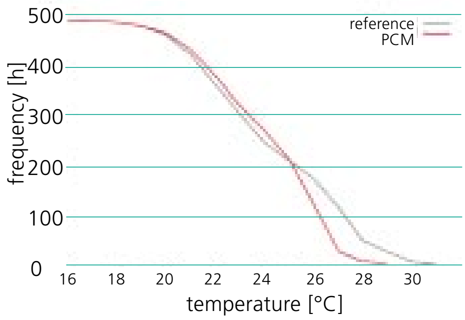
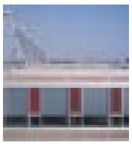


Fig. 4: Cumulative frequency distribution of the air temperatures in the cells; this indicates the number of hours that a given temperature is exceeded. Reference cell (black) and PCM cell (red).

* PSE GmbH Forschung Entwicklung Marketing, Freiburg



Desiccant Cooling System for Mediterranean Climates in combination with Heat/Electricity Co-Generation

The climate of the coastal regions of Mediterranean countries is characterised by high outdoor air temperatures combined with high air humidity in summer. We are co-operating with Italian partners to develop energy-saving air-conditioning technology, which combines desiccant cooling processes with heat/electricity co-generation.

Hans-Martin Henning, Tim Selke*, Edo Wiemken

* PSE GmbH Forschung Entwicklung Marketing, Freiburg

Clearly, air conditioning in summer plays a still more important role in Mediterranean countries than in Central Europe. Particularly in coastal regions, the outdoor air is often very warm and humid at the same time. Thus, dehumidification is particularly important in the conditioning of fresh air. Desiccant cooling processes with sorption wheels are still possible under these conditions; however, evaporative cooling can be applied only to a limited extent due to the high air humidity.

At present, we are co-operating with Italian partners to develop a complete building services system for small and medium-sized, non-residential buildings in these climatic zones: Electricity generation, heating, cooling and ventilation, with a co-generation plant as the central component. In summer, the waste heat of the co-generation plant is used for sorptive dehumidification of the air. Figure 1 shows a new configuration that we developed for connecting the air-conditioning components, and fig. 2 shows the process representation in a temperature-humidity diagram for humid air. This configuration uses energy so efficiently that compared to conventional technology, the primary energy consumption for the air conditioning is reduced by 30 %. A pilot plant is currently being installed in the office building of the Palermo gas utility. The "MITES" project on "Micro Trigeneration System for indoor air-conditioning in the Mediterranean Climate" is supported by the European Union. Our project partners are the Palermo gas utility (AMG) and the Fiat Research Centre (CRF) in Torino.

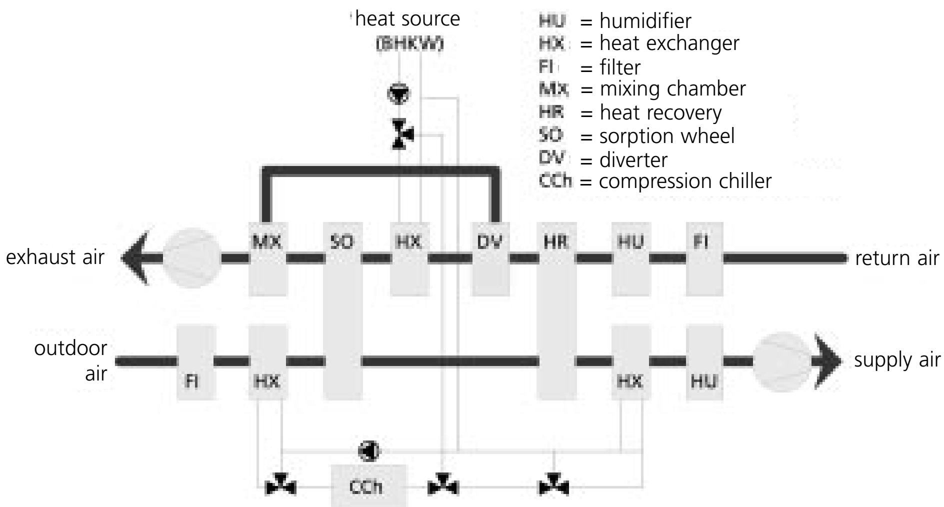


Fig. 1 (above): Schematic diagram of the air-handling unit with sorptive air dehumidification.

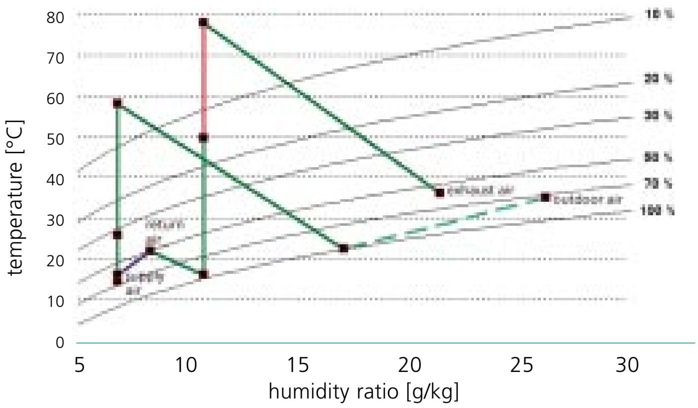
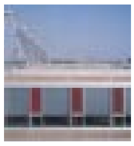


Fig. 2 (below): Temperature-humidity diagram corresponding to fig. 1. In contrast to conventional desiccant cooling, an air cooler (HX in fig. 1, lower left) is introduced before the sorption wheel (SO). The former pre-cools and dries the very hot and humid outdoor air. As indicated by the dashed line of fig. 2, this process occurs at a high temperature level, so that the cooling machine can operate with a high evaporator temperature. Next, the air is sorptively dehumidified down to the desired humidity for the inlet air and again cooled to the desired inlet air temperature by an air cooler. As no further air dehumidification is required, again the cooling machine can operate with a high evaporator temperature, so that cold air is provided with high efficiency (coefficient of performance). The sorption material in the wheel is regenerated with the waste heat from the co-generation plant (red, vertical line from 50 °C to 78 °C in fig. 2).



Development of a Novel, Modular Solar Air Collector

Solar air collectors offer systems-technological advantages regarding the risk of freezing and collector stagnation. Despite this, their share of the market is low. To make solar air collectors more attractive also for free-standing and semi-detached houses, we developed a novel, modular solar air collector last year. We carried out the development on commission to and in co-operation with the Grammer-Solar+Bau company.

Carsten Hindenburg,
Volker Kallwellis*, Thorsten Siems,
Flaviu Marton

The starting point was a commercial solar collector to heat air for larger buildings (e.g. hall heating). These collectors are heavy compared to conventional flat-plate collectors. In addition, production is not highly automated due both to the small numbers produced so far and the absorber construction, consisting of 36 adjacent rectangular canals.

Our response was to develop a new collector, which is significantly less heavy, has a high thermal efficiency value and allows cost-effective production. The specific collector weight was reduced by 20 % to 24 kg m^{-2}. As the new modules are also smaller to allow better handling, the weight per module has even decreased by 36 % to 48 kg. A further benefit is that the new collector can be installed very simply and quickly. The special absorber, for which a patent claim has been lodged, consists of only one piece. That saves material and simplifies production considerably.

We have measured several prototypes with the new indoor solar air collector test stand at Fraunhofer ISE, allowing us to optimise them within a short development period. The new test stand is integrated into the indoor solar collector test stand (article on p. 85), and is available for measurements with reference to EN 12975-2 and development of solar air collectors. Figure 1 shows a schematic diagram of the test stand.

The new collector will already be available on the market from early summer, 2003.

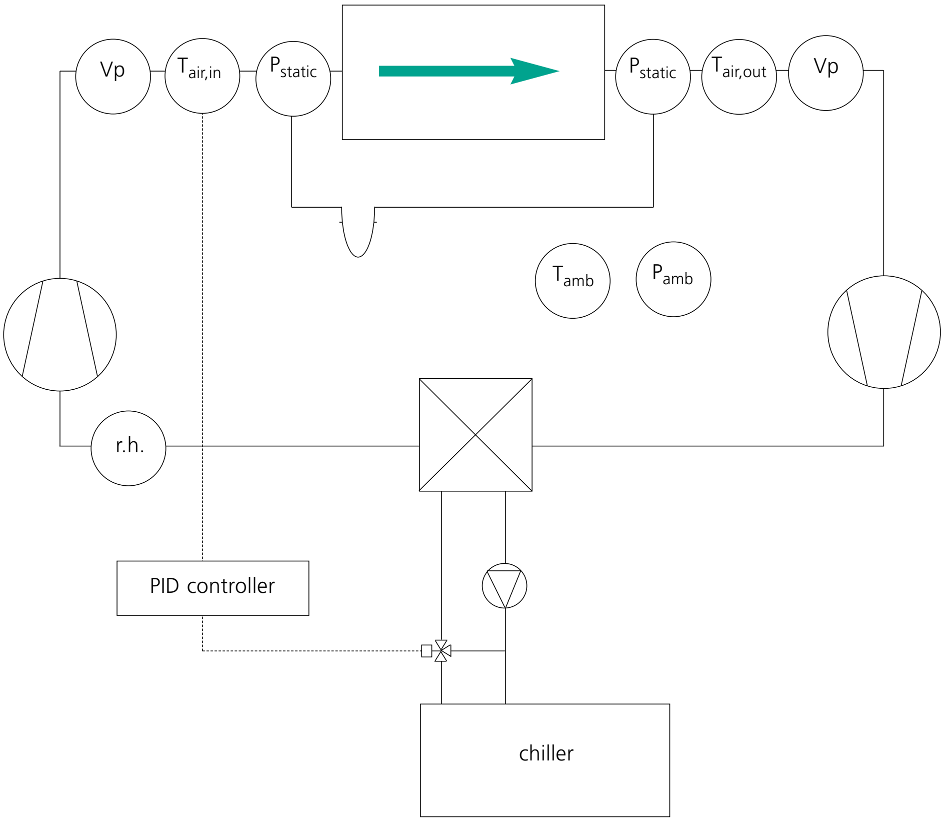
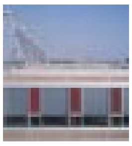


Fig. 1: Schematic diagram of the solar air collector test stand. The collector is integrated into a closed air circulation loop. Measured data for the inlet and outlet temperature and the mass flow (gas flow meter) allow the energy balance of the collector and thus the thermal efficiency value to be calculated. Two fans and gas flow meters - one each before and after the collector – are available, so that different hydraulic configurations and their effect on the collector efficiency can be investigated. In addition, the leakage behaviour of solar air collectors can be studied. Pressure losses in solar air collectors which depend on the volume current can also be measured.

* PSE GmbH Forschung Entwicklung
Marketing, Freiburg



Demonstration and Energy-Relevant Evaluation of Innovative Facades

Measurement values from the laboratory alone are often inadequate when planners, investors and building users want to assess the advantages and disadvantages of facade alternatives. For example, how are the energy consumption and comfort affected? Do new developments show the effects which were predicted? Realistic demonstration and analysis procedures answer these questions.

Georg Bopp, Sebastian Bundy, Tilmann Kuhn, **Werner Platzer**,
Helen Rose Wilson*, Jan Wienold

A future-orientated building envelope reduces thermal losses, optimises daylighting and uses solar energy to create a pleasant indoor climate. In this way, the installed power and the energy consumption of heating and cooling equipment can be minimised. However, how can completely different product developments such as switchable glazing, transparent insulation or solar shading be evaluated?

Fig. 1: View through gaschromic glazing with temperature and radiation sensors, in the facade test facility.

* Interpane E&BmbH, Lauenförde

Basically, two cases should be distinguished:

- If a specific building project is concerned, we can provide information for this object using simulations. This helps, for instance in the conception phase, to optimise the building.
- If a product is to be evaluated, e.g. for marketing, independently of a specific building, we work with representative reference data for buildings, building services technology and user behaviour.

We offer various options for evaluating and demonstrating building facades. On the one hand, we are co-operating internationally to develop representative reference procedures for simulation within IEA Task 27. Using the facade test facility, we verify how well laboratory data can be transferred to building simulation (figures 1 and 2). On this basis, we can compare different facade variants comprehensively and rationally (fig. 3). The German Federal Ministry of Economics and Technology BMWi supports the development of the methodology and participation in Task 27.

On the other hand, the new Solar Building Innovation Centre SOBIC offers the possibility to monitor the interaction between innovative facades and appropriate building services technology in three real office rooms, and to demonstrate them to the public at the same time.

Fraunhofer SOBIC is a joint demonstration centre of the Fraunhofer Institutes for Building Physics IBP and Solar Energy Systems ISE, located at two sites. The focus in Freiburg is on office and commercial buildings, whereas the satellite in Fellbach concentrates on private houses. The new building there in the "Private House and Garden" exhibition centre was officially opened at the end of October. The Freiburg SOBIC is currently still situated in the Fraunhofer Institute for Solar Energy Systems ISE. In autumn of 2003, it will move into the new "solar info center" near the Freiburg Exhibition Grounds.

The aim of Fraunhofer SOBIC is to transfer research results on energy-efficient and solar building rapidly to industry and consumers. Manufacturers, planners and decision-makers will receive comprehensive advice and in-service training. In addition, they can become acquainted with products and procedures directly in use or in realistic demonstration models.

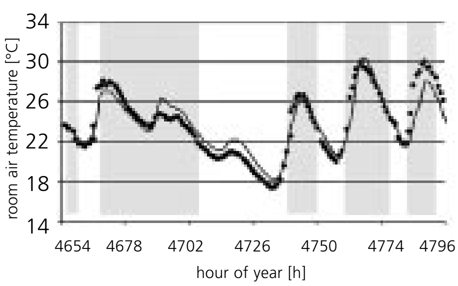


Fig. 2: Validation of the facade model for gaschromic glazing by comparing simulated and measured indoor air temperatures in the facade test facility (July; grey shaded areas: glazing in the coloured state; solid line: simulated data; dots: measured data).

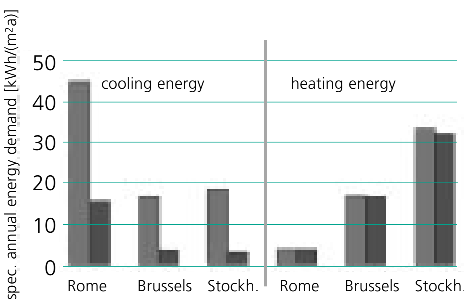
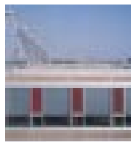


Fig. 3: Comparative simulations of the annual energy demand with respect to the usable floor area for the basic variant of the reference office, air cooling operative on weekdays to maintain a maximum air temperature of 26 °C (red: standard insulating glazing, blue: gaschromic insulating glazing - switching temperature of 24 °C).



Development of Sun-Shading Systems

In most cases, sun-shading systems are needed if daylight and solar heat are to be used effectively in buildings. Particularly in office buildings, solar control in summer plays a key role in the function of the building envelope due to the high internal heat loads. We have developed new sun-shading systems and demonstrated their improved properties with prototypes.

Tilmann Kuhn, Christopher Bühler

We develop new products with an integrated approach which takes the following aspects into account:

- very good solar control properties in summer
- high visual comfort (glare protection, view retention, daylighting, neutral colour rendering, darkening options)
- high reliability, independent of user behaviour
- low costs, particularly materials and production costs
- aesthetic requirements
- compliance with technical boundary conditions
- protection against fire, noise, weather and burglary

Of course, these criteria cannot all be optimised simultaneously. For each individual case, we aim to find the solution which best meets the potential requirements of the users and the boundary conditions set by the manufacturer.

In co-operation with the Hüppe Form company from Oldenburg, an internal venetian blind with a completely new geometric form for the slats was developed (fig. 1), which is characterised by the following properties:

- very good solar control function compared to other internal systems
- robust control performance (fig. 2)
- good view retention due to the new form and the near-horizontal slat position allowed by the reduced slat spacing
- good daylighting
- good glare protection, also when the slats are tilted
- economic price
- good darkening and very low luminance when fully closed

In co-operation with the Clauss Markisen company from Bissingen-Ochsenwang, a completely new type of external stainless steel screen was developed (fig. 3). Starting from the idea of producing a retractable screen from roll-formed stainless steel rods, the rod geometry and surface texture were developed and optimised by Fraunhofer ISE (fig. 4). The screen is characterised by the following properties:

- very good solar control effect
- meeting the highest aesthetic demands. This subjective and intangible criterion also plays a major role in the selection of materials.
- reduced luminance on the inner surface of the screen due to the optimised rod form and surface texture.
- good view retention.

Fig. 1: New slat for a venetian blind, offering optimised solar control and robust control performance.

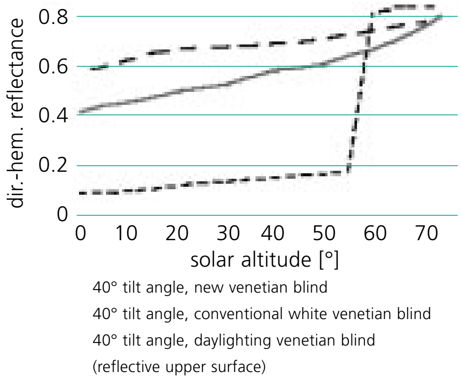


Fig. 2: The constantly high reflectance of the slat is the reason for the good solar control effect and the robust response to control variations.

Fig. 3: Stainless steel screen with new rod geometry and surface.

Fig. 4: An operative sample of the new stainless steel screen offering view retention.

Solar Building - Residential Buildings

With the introduction of the German energy-saving regulation EnEV in February 2002, the energy-planning perspective for buildings has broadened to include efficient building services technology and the integration of regenerative energy sources. Exhaust air heat pumps in compact ventilation and heating units are conquering a continually growing market. Heat/ electricity co-generation at the lowest power levels is opening up new horizons. The costs and benefits are evaluated critically before a product enters the market.

Andreas Bühring, Peter Engelmann, Christian Reise, **Christel Russ**, Benoit Sicre, Karsten Voss

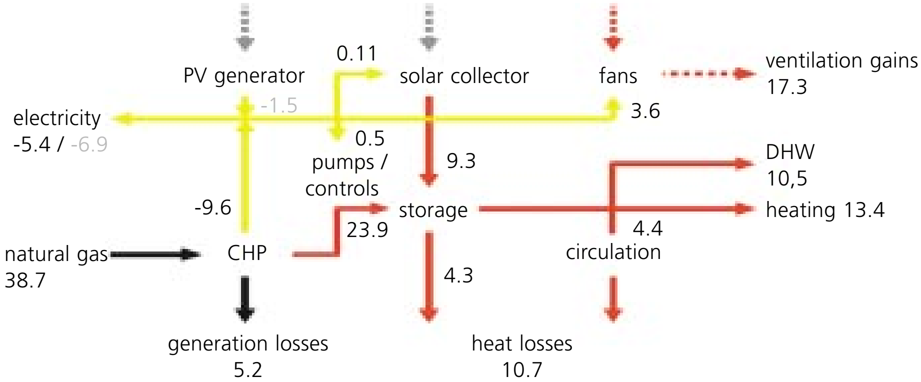


Fig. 1: Energy flow diagram and measured consumption values during the period from 1.3.2001 to 28.2.2002 for 19 apartments in the passive residential block of the "Wohnen + Arbeiten" building co-operative in Freiburg-Vauban. The numbers in kWh $m^{-2}a^{-1}$ refer to the heated living area of 1428 m^2. On the left-hand side is shown the end energy consumption of electricity and natural gas, on the right-hand side is the energy used for heating, ventilation and domestic hot water. The losses are indicated at the bottom, the gains from the regenerative energy used are shown at the top. The electricity consumption route in the conversion process from the end energy to the energy used is shown in yellow, the conventional fuels in black and the heat generated in the process in red.

Evaluation of demonstration projects

Multi-storeyed residential buildings were the focus of our work in 2002 within the International Energy Agency IEA. We are co-ordinating the evaluation of demonstration buildings with one single methodical approach. As an example, fig. 1 shows the annual energy flow diagram for the first multi-storeyed passive residential building in Germany. Its primary energy consumption of 26 kWh $m^{-2}a^{-1}$ is 75 % lower than the requirement of the EnEV; the associated additional costs amounted to 15 % of the construction costs. Other building projects, ranging in scale up to complete settlements, confirm primary energy coefficients between 25 and 35 kWh $m^{-2}a^{-1}$. The work is part of IEA SHCP Task 28 / ECBCS Annex 38 on "Sustainable Solar Housing".

To complement this work, we began to monitor the passive house of the "ISIS" building co-operative, also in the new suburb of Freiburg-Vauban, with support from the German Federal Foundation for the Environment (DBU) and the industry (fig. 2). We are concentrating on a comparative evaluation of innovative ventilation and heating technology in multi-storeyed buildings.

Fig. 2: Monitoring of the house belonging to the "ISIS" building co-operative began in winter 2002. Architecture: M. Hansen, Freiburg. The building facade illustrates design options for passive buildings.

Compact ventilation and heating units

These ventilation units with heat recovery also include an exhaust air heat pump. They replace the conventional heating system in a passive house and also serve to provide domestic hot water, usually in combination with a solar collector. We co-operated with industrial partners in developing this leading heating technology for solar passive houses. We drew on experience with free-standing houses to develop a still more compact unit for use in multi-storeyed housing. Computer simulations were applied to select the components and determine their optimal connection. We validated the results with our test stand for compact ventilation and heating units. Applying specified boundary conditions with different tanks and water withdrawal profiles, we conduct both stationary and dynamic investigations according to the European standard, EN 255. The first experimental prototype has been tested since the autumn of 2002 in the "ISIS" passive house (fig. 3).

At present, we are investigating further improvements of the heat pump (cooling medium heat extractor for heating drinking water, natural cooling agents, cooling function), the heat recovery process, the controls and additional functional modules.

This work is part of the "NEGEV" project on new integrated energy supply concepts for buildings, which is supported by the German Federal Ministry of Economics and Technology BMWi.

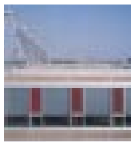


Fig. 3: The first compact ventilation and heating unit designed for a whole storey by the Maico company, being tested in the ISIS passive house as an experimental prototype with a simplified design. The compact unit is not larger than a combined refrigerator/freezer, and can be located inside the flat, e.g. in the bathroom, without occupying too much space.

On commission to a local utility, EnBW, we are determining the most important energy coefficients for 78 subsidised solar passive houses with heat pump technology. The statistical average electricity consumption in buildings with compact ventilation and heating units is significantly lower than in those with other forms of heating technology. You can find the detailed monitoring report at our Internet site www.ise.fhg.de

Fuel-cell heaters

In contrast to fossil-fuelled heat/electricity co-generation plants, fuel cells can readily be scaled down, making them eminently suitable for future applications in decentralised energy supply systems. They produce heat and electricity from fossil fuels (natural gas, heating oil, possibly also biogas) via hydrogen as an intermediate product. They offer the potential for high fuel conversion efficiency values. On the other hand, their waste heat potential is in competition with measures to reduce heating consumption (thermal insulation) and to supply heat from solar energy (collectors). To investigate the interaction of these effects, we are developing new simulation models for fuel-cell heaters in the low power range and control strategies, which combine the economic optimum with ecologically desirable approaches. One goal of our work is to propose suitable payment models for electricity. The work is part of a joint project for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, BMU and led by the German Centre for Space and Air Travel DLR.

Integration of Photovoltaic Systems into Buildings

A good number of examples document how the value of a building has been raised by the successful integration of photovoltaics. With our detailed knowledge of national and international technical regulations, we can facilitate the entry of companies into foreign markets.

Thomas Erge, **Hermann Laukamp**, Karsten Voss, Edo Wiemken

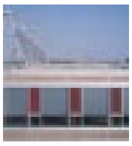
Four photovoltaic systems, which have been integrated in different ways into the new premises for Fraunhofer ISE, demonstrate that customised modules can be constructed such that all aspects of aesthetics, architecture, thermal insulation, daylighting and electricity yield can be taken into account and successfully harmonised.

We met with experts from institutes and companies from the most significant photovoltaic countries to discuss our experience with building-integrated photovoltaics. The discussion revealed many examples of high-quality buildings where photovoltaics had been successfully integrated.

Fig. 4: Sawtooth roof with integrated photovoltaics in the atrium of the new building for Fraunhofer ISE.

This work was part of the PVPS programme of the International Energy Agency IEA. It is documented in the final reports of IEA Task 7, to be found under www.iea-pvps.org. Task 7, on the "Integration of Photovoltaic Systems in the Building Sector", addressed architectural aspects of photovoltaics on buildings, mounting systems for buildings, construction law, training material for architects, planning tools, reliability and operating experience, optimisation of the electric circuits, non-technical barriers, installation potential on buildings and strategies for marketing and dissemination.

From the discussion of technical questions and regulations, we know the relevant specifications for photovoltaic systems in the participating countries very thoroughly. We can use this knowledge and the contacts made to facilitate the entry of interested companies into the corresponding markets. The work of Fraunhofer ISE was supported by the German Federal Ministry of Economics and Technology BMWi.



Solar Building - Commercial Buildings

Combining optimal working conditions with a low energy consumption is the essence of our work for commercial buildings. In addition to our involvement in building planning, we also undertook further monitoring and cross-sectional projects in 2002.

Sebastian Herkel, Jens Pfafferott, Christian Reise, Christian Reetz*, Roland Schregle, Augustinus Topor*, Karsten Voss, Jan Wienold

Fig. 1: Facade and roof construction of the SOLVIS zero-emission factory (Photo: C. Richters).

* PSE GmbH Forschung Entwicklung Marketing, Freiburg

SOLVIS zero-emission factory

Rational energy planning and electricity-saving technical building services mean that the new production building for the SOLVIS GmbH & Co KG company will draw its energy entirely from regenerative sources in future. In addition to solar systems for electricity and heat, a heat/electricity co-generation plant fuelled with rapeseed oil meets the energy demand. With the rapeseed oil production being CO_2 neutral, this results in a "zero-emission factory". The predicted primary energy demand for heating, ventilation, air conditioning and lighting is about 90 kWh $m^{-2}a^{-1}$. In the planning process, which was supported by the German Federal Ministry of Economics and Technology BMWi, we co-operated with solares bauen GmbH in Freiburg to develop the energy concept and plan the solar components. We applied dynamic building and lighting simulation to clarify wide-ranging questions about optimal working conditions.

Measurement programme at the new premises for Fraunhofer ISE

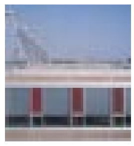
The energy demand of the new premises for Fraunhofer ISE is being determined with a two-year monitoring programme in co-operation with the Technical College in Biberach. We are concentrating on examining the various concepts for passive cooling. Another aim is to describe user behaviour with respect to solar shading, electric lighting and window ventilation with models. We use these models to improve the prediction accuracy of our simulation calculations and thus the planning reliability. The results are part of our contribution to IEA Task 31, "Daylighting Buildings in the 21st Century". The work is supported by the German Federal Ministry of Economics and Technology BMWi as part of its SolarBau programme.

SolarBau:MONITOR

Within the same SolarBau programme, which is running from 1995 to 2005, we have been co-operating with the University of Karlsruhe and the solidar architectural office in Berlin in accompanying the demonstration building projects with research. With a goal for the annual primary energy consumption of less than 100 kWh $m^{-2}a^{-1}$ for heating, hot water, ventilation, cooling and lighting, the programme is paving the way for the EU guideline on "Total energy efficiency of buildings", which is currently under discussion. As all of the projects have avoided conventional air-conditioning for the whole building, we are comparing the different ways of achieving "passive cooling" (see below). As well as analysing the measurement results, a questionnaire on user acceptance of passive cooling was formulated in 2002. The results from four projects are already available and confirm high user acceptance, but highlight different aspects.

The central instrument for disseminating information to professionals in the field is our Internet site, www.solarbau.de. One of several new aspects is that the information is now available in English and French, as well as German.

As part of the "Building Networks" project within the EU SAVE programme, we have recently started to extend comparative energy monitoring to a large number of buildings throughout Europe.



Passive cooling

If active cooling in summer is not implemented, the indoor climate in a building is determined by the relationship between heat sources (sun, equipment, occupants) and heat removal (ventilation), taking the heat capacity of the building object into account.

In 2002, we investigated the theory and practice of heat removal with nocturnal ventilation in four buildings of the subsidised SolarBau programme. Long-term measurement data from monitoring programmes formed the starting point (fig. 2). By adding measurement campaigns in selected rooms - air exchange rate measurements with a tracer gas, thermography, spatially resolved temperature measurements in rooms and components - we succeeded in making more detailed experimental analysis. Parameter models and building simulation are applied to analyse the results of long-term and short-term measurements, so that a physically accurate description of nocturnal ventilation can be established. This allows us to demonstrate the opportunities and limitations of passive cooling. In order to achieve high planning reliability, we take account of natural ventilation also in combination with forced mechanical ventilation in the simulation model.

In our new Fraunhofer “Solar Building Information Centre SOBIC“, we have equipped three office rooms with concrete walls that can be thermostatted by embedded water pipes and a heat recovery system for nocturnal heat removal. In addition, we also have the alternatives there of operating nocturnal ventilation and solar air-conditioning.

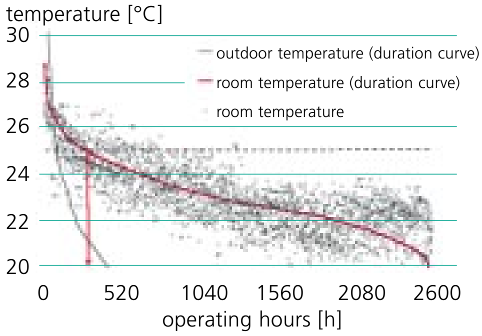


Fig. 2: Measured room temperature during working hours from July 2001 to June 2002 in the building of DB Netz AG in Hamm. The order of the plotted room temperatures is determined by the outdoor temperatures. The room temperature correlates directly with the outdoor temperature only for outdoor temperatures exceeding 26 °C. The room temperature exceeds 25 °C for only 280 hours of the year.

Further development of software tools to describe innovative daylighting systems

One of the central work packages in a project funded by the German Federal Ministry of Economics and Technology BMWi is integration of a forward ray-tracing procedure into the RADIANCE lighting simulation software. This so-called photon-mapping algorithm has been incorporated into the simulation environment. The work in 2002 concentrated on validating the new procedure. To this purpose, not only analytical and numerical procedures but also measurements on a scale model were employed (figures 3 and 4).

The manufacturers and planners involved in the project participated in two workshops which we organised together with our project partner, Fraunhofer IBP.

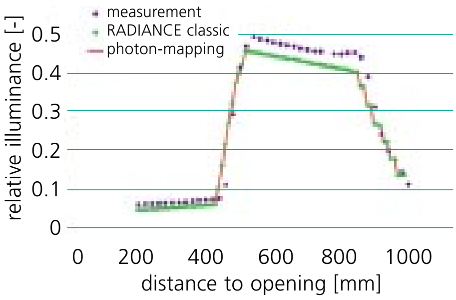


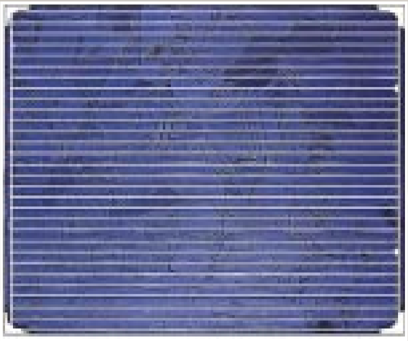
Fig. 3: Comparison of measurement and simulation for the scale model.

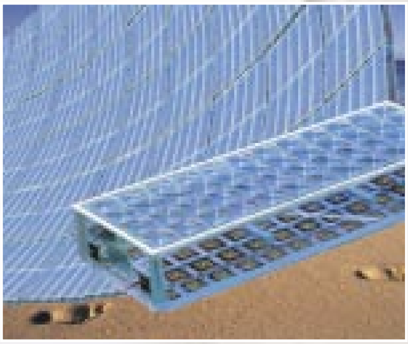
Fig. 4: Visualisation as the result of a lighting simulation calculation with a reflective blind slat.

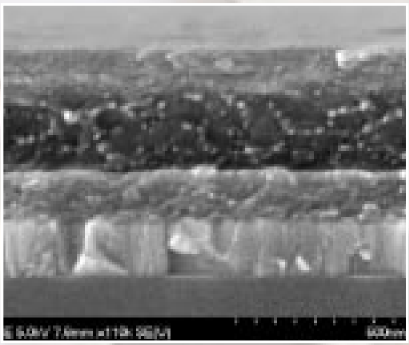
Location	building concept	indoor climate simulation	lighting simulation	consultancy/development	product testing	quality control	monitoring
Bonn	o	o	o	o			o
Regensburg		o	o	o			
Hamm						o	
Basle				o	o		
Zürich				o	o		
Vienna	o	o					

Fig. 5: Further projects in 2002.

Solar Cells







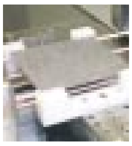
Electricity from Solar Cells – a Global Growth Market

Photovoltaics is experiencing a real boom all over the world, with growth rates exceeding 20 %. In Germany, the renewable energy law and the 100,000 Roofs Programme led to the new installation of around 80 MW power in 2001 alone - only a few years ago, this was the size of the entire global market.

More than 90 % of solar cells are made of crystalline silicon, and the share is increasing. 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 reduce consumption of the expensive raw material, the silicon wafers are becoming thinner and thinner. Despite this, we still achieve constantly high efficiency values by appropriately adapting the cell structure. We are leading the way in producing high-performance solar cells of extremely thin, flexible 50 µm wafers, which can already be processed completely in our pilot line. We are also already working on processes to produce these thin wafers directly from crystals.

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



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

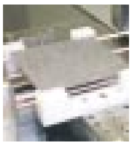
Dye and organic solar cells represent a third segment of materials. In particular, the technology for dye solar cells has developed beyond the laboratory scale over the last few years. However, long-term stability and the upscaling of this technology to module areas exceeding 0.5 m^2 must still be demonstrated.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

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

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

We use the following facilities for our work:

- clean-room laboratory for Si and III-V semiconductors
- standard solar cell technology
- industrially relevant production line (screen-printing, pad-printing, in-line RTP oven, in-line RTP diffusion oven)
- chemical vapour deposition of Si, RTCVD
- MOVPE for III-V epitaxy
- semi-automated production of dye solar cells and modules
- plasma etching system
- optical heating systems for silicon production and processing
- thin-film technology: plasma deposition, evaporation, galvanisation, contacting
- characterisation of materials: X-ray diffraction, charge carrier lifetime measurements, photoluminescence, ellipsometer, IR Fourier spectrometer, glow discharge mass spectrometer, scanning electron microscope with EBIC, ECV profiling, MW-PCD, MFCA, DLTS, CDI, CV, SPV, sheet resistance mapping, stripping Hall, SRP
- characterisation of solar cells: I-V characteristic curve measurement, SR, LBIC, PCVD, MSC, diffusion length mapping, shunt analysis



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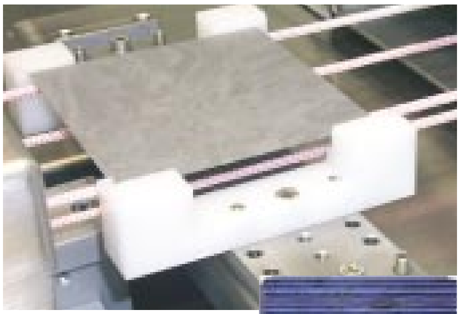
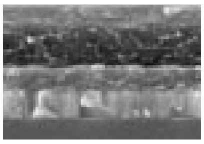


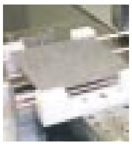
Walking string transport for production of crystalline Si solar cells (article on p. 44).

Epitaxial wafer equivalent on a highly doped silicon wafer, resulting in a cell efficiency value of 13.2 % (article on p. 39).

FLATCON® module for a concentration of 500 suns (article on p. 40).



Scanning electron micrograph showing the layer configuration of an organic solar cell (article on p. 47).



Novel and Highly Efficient Solar Cell Structures for Crystalline Silicon

By far the largest share of solar cells produced world-wide is based on monocrystalline or multicrystalline silicon wafers. In order to remain competitive in future against thin-film technology, one cost factor in particular must be reduced further: the silicon wafer itself. It accounts for 40 – 50 % of the module costs. Apart from efforts to reduce costs in growing the silicon crystals, the major focus is on the thickness of the wafer. Wafers with a thickness of about 330 µm are still used in most industrial processes today. The breakage probability is low and the yield is correspondingly high.

Stefan Glunz, Andreas Grohe, Franz J. Kamerewerd, Henner Kampwerth, Joachim Knobloch, Daniel Kray, Ji Youn Lee, Antonio Leimenstoll, Andreas Mohr, Daniela Oßwald*, Ralf Preu, Stefan Rein, Elisabeth Schäffer, Eric Schneiderlöchner, Oliver Schultz, Siwita Wassie, Wilhelm Warta, Gerhard Willeke

Efforts have increased recently to reduce the wafer thickness and thus the module cost. Two challenges have to be met: (1) fragility and (2) solar cell efficiency. The fragility is mainly determined by the mechanical properties of the wafer, but of course is also affected by the "stress" acting on the wafer during solar cell production. The change in the solar cell efficiency observed when the thickness is reduced mainly depends on the solar cell structure used. We are working intensively on questions concerning the critical mechanical parameters, the optimal cell structure for thin wafers and their industrial implementation.

Interestingly, the mechanical properties of the wafer do not appear to worsen continually when the thickness is reduced. Below a certain thickness, the wafers become flexible, which greatly reduces the probability of breakage (fig. 1). Unfortunately, wafers of this thickness cannot presently be produced directly, but are made by removing material from thicker wafers, which of course does not contribute to cost reduction. Thus, we are developing new methods to produce very thin wafers.

In order to develop solar cell concepts and handling procedures for thin wafers in parallel, our group has recently acquired two pieces of equipment to mechanically thin down thick wafers. Using the wafers prepared in this way, we can develop optimal solar cell processes for a great variety of thicknesses. The relatively poor absorption of light in crystalline silicon, which in principle demands a cell thickness of more than 500 µm, is a particular challenge. In order to convert all of the light as efficiently as possible into charge carriers even in thin cells, the internal reflection within the cell must be very good. A passivated back surface is particularly successful. Unlike the usual case, the back-surface metallisation is not in contact with the whole area of the silicon wafer, but is separated from it by a thin silicon dioxide layer. This is perforated at only a few points to make the electrical contact. The structure is almost a perfect mirror and has excellent electrical properties in addition. We have already achieved an efficiency value of 20.7 % with a wafer that was only 70 µm thick.

The cell structure used for this could only be prepared in the laboratory up to now. Now it has become possible for the first time to apply it in an industrial process, using our novel LFC (laser-fired contacts) technology, as reported in the Annual Report for 2001.

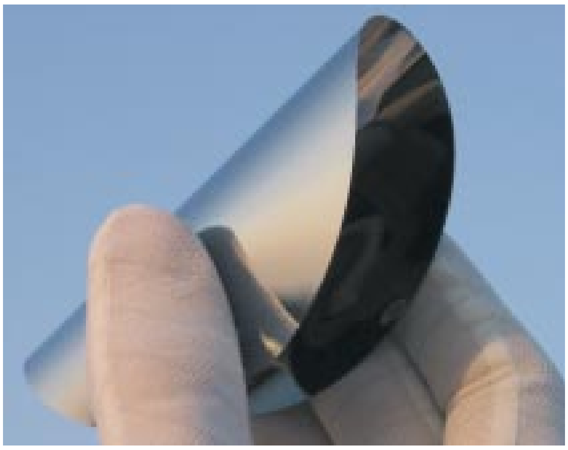
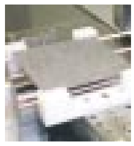


Fig. 1: Thin flexible wafer, with a thickness of only 25 µm, for which we are developing highly efficient solar cell structures.

* University of Freiburg, Freiburger Materialforschungszentrum FMF



Thin Crystalline Silicon Films as Wafer Equivalents

The question of silicon reserves as the raw material for silicon wafers is decisive for solar cell production. We offer the "wafer equivalent" as an answer to this question.

Stefan Reber, Albert Hurrle, Achim Eyer, Friedrich Lutz, Sandra Bau, Thomas Kieliba, Fridolin Haas, Norbert Schillinger, Miroslawa Kwiatkowska, Elke Gust

The market for crystalline silicon solar cells is growing constantly. The supply of waste raw silicon from microelectronic production cannot keep up with the growing demand. There is the threat of a supply bottleneck. We are developing alternatives which require significantly less silicon material and can also be produced more cheaply.

Our concept is the "wafer equivalent". From the outside, it looks like a silicon wafer. However, the active zone is limited to a thin silicon film with a thickness that is 90 % less than conventional wafers. We have set ourselves the goal of being able to process the wafer equivalent in exactly the same way as a normal silicon wafer to produce a solar cell. This offers the major advantage that it can be introduced into the existing production structures without requiring changes in the technology, as a fully equivalent substitute for the silicon wafer. That will save costs and increase the acceptance of the silicon thin-film technology enormously.

We are following two approaches to prepare wafer equivalents: The first and quickest approach is to deposit a high-quality epitaxial silicon layer at high temperatures onto a substrate of inexpensive silicon (fig. 1). Suitable substrates include waste wafers from the electronic component industry or wafers of inexpensive, highly doped silicon. This "epitaxial" wafer not only looks like a normal silicon wafer but also behaves almost identically. The efficiency values of 13 % already achieved with industrial solar cell technology are close to those achieved with conventional wafers (fig. 2).

The second approach offers somewhat more freedom: A silicon layer is deposited onto a conductive (ceramic) substrate, and then melted and recrystallised to improve the quality. The resulting crystals in the silicon layer are just as large as in the best multicrystalline silicon wafers. Thus, the potential for the efficiency value is similarly high. The "ceramic" wafer equivalent needs more processing steps for its production but offers more freedom in the choice of substrate (e.g. ceramic, inexpensive silicon) and processing method, which can result in lower costs. The efficiency values in the laboratory at present are still somewhat lower than with the first approach, but are still very promising, being 9 % on inexpensive ceramic.

Each approach has its own advantages. The cost will ultimately determine which one becomes established.

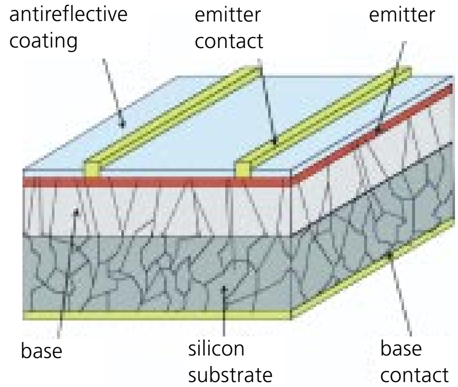


Fig. 1: The simplest configuration for a wafer equivalent: A thin silicon layer is grown epitaxially on an inexpensive silicon substrate.

Fig. 2: Epitaxial wafer equivalent on a highly doped silicon wafer with an area of 21.16 cm^2 and an efficiency value of 13.2 %.

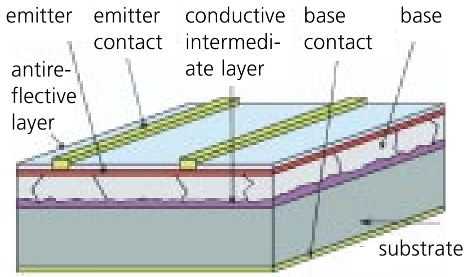
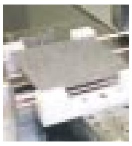


Fig. 3: Configuration of a wafer equivalent on a conductive foreign substrate with a conductive intermediate layer.



III-V Space and Concentrator Solar Cells

We are developing multi-junction solar cells to achieve high efficiency. Cells of this type are used for satellites in space or in terrestrial concentrator systems. In addition to cells, we also develop the concentrating optics and trackers. Prototypes of concentrator modules are tested under real conditions.

Carsten Baur, **Andreas W. Bett**, Armin Bösch, Martin Breselge, Marc Chenot, Frank Dimroth, Gerrit Lange, Gergö Létay, Astrid Ohm, Matthias Meusel, Sascha van Riesen, Gerald Siefer, Thomas Schlegl, Sivita Wassie

Metal-Organic Vapour Phase Epitaxy (MOVPE)

The basis for producing solar cells of III-V semiconductor materials is geometrically ordered deposition on a substrate, epitaxy. Metal-organic compounds and hydrides serve us as source materials. The epitaxial layer is grown on up to eight 4" substrates in a commercial reactor. This reactor is produced by the Aixtron company in Aachen (2600G3), and is also used industrially. Figure 1 shows a diagram of the equipment we use. The large number of metal-organic sources means that we can grow many different III-V semiconductors. This year, we have extended the system again. It was particularly important to add the characterisation method EpiRas, which means that we can now observe growth behaviour in situ. This allows us to understand the deposition process better and to optimise it more quickly. The growth rate is now determined directly on the basis of oscillations detected in the reflectance. An example for the change of the reflectance at a certain wavelength with time during deposition is shown in fig. 2.

We also use EpiRas to analyse the composition of the substrate surface before and during growth and to control the reproducibility from run to run.

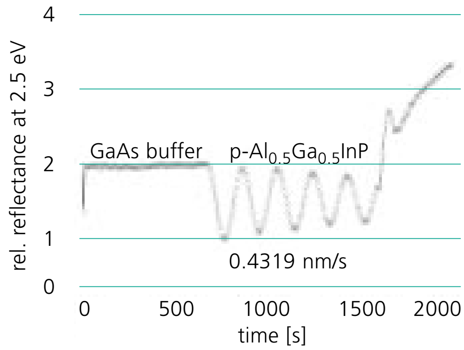


Fig. 2: Example of an EpiRas measurement. Analysis of the oscillations allows the growth rate to be determined in situ. The oscillations result from light reflection from the boundaries of materials with different refractive indices.

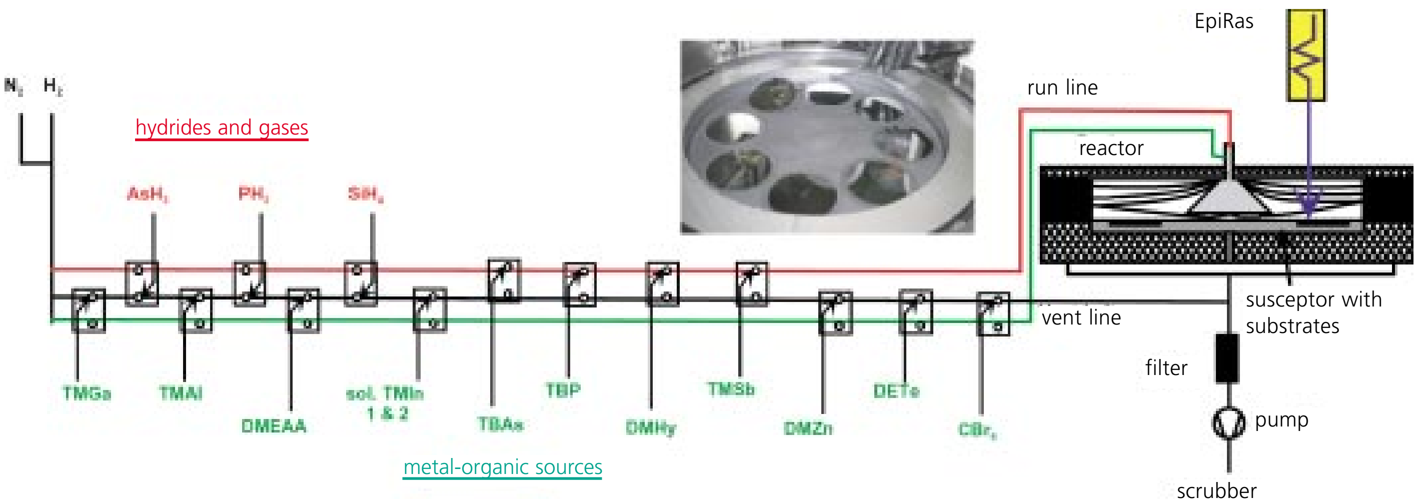
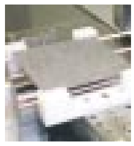


Fig. 1: Diagram of the AIX2600 MOVPE equipment used at Fraunhofer ISE. The large number of sources and the possibility for analysis (EpiRas) in situ should be noted.



Triple cell development for space solar cells

One focus of our work was the development of processes for monolithic triple solar cells that are suitable for industrial application. To this purpose, we use MOVPE to grow a complex series of GaInP and GaInAs layers on a Ge substrate. During this growth process, a pn junction is created within the Ge itself. The individual cells of GaInP, GaInAs and Ge are internally connected in series via tunnel diodes. This year, we achieved an efficiency value of more than 25 % for illumination with the AM0 extraterrestrial solar spectrum (fig. 3). This is a European record.

FLATCON® modules

FLATCON® stands for "Fresnel lens all-glass tandem cell concentrator" and describes our developments in concentrator module construction. We emboss the Fresnel lens, the concentrating optical component, directly into a thin silicone sheet. We developed the procedure together with the Ioffe Institute from St Petersburg in Russia. The module housing consists completely of glass. We use GaInP/-GaInAs tandem cells as concentrator solar cells. They have a diameter of 2 mm and are optimised for a concentration factor of 500. 48 cells are connected to form one module. Two modules mounted on a tracker are shown in fig. 4.

Using the FLATCON® modules, we have measured an efficiency value exceeding 22 % under real application conditions, i.e. without a temperature correction. The module temperature was about 25 K higher than the ambient temperature. A FLATCON® module with an aperture area of 768 cm^2 generated more than 13 W electric power when exposed to a radiation intensity of 759 W m^{-2} (fig. 5).

We are grateful to ESA-ESTEC, DLR and RWE Space Power Solar GmbH for financially supporting our work on space solar cells. The developments on concentrator solar cells are funded by the German Federal Ministry of Economics and Technology BMWi, the State of Baden-Württemberg and RWE Space Power Solar GmbH.

Fig. 4: FLATCON® modules mounted on the tracker on the Fraunhofer ISE roof.

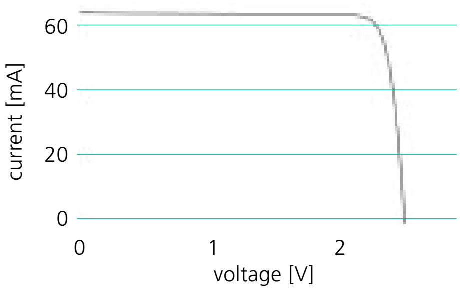


Fig. 3: Light IV characteristic curve for a 4 cm^2 monolithic GaInP/GaInAs/Ge triple cell for the extraterrestrial AM0 spectrum. η=25.5%, FF=86.8%, I_{sc}= 16.02 mA/cm^2, V_{oc}=2.51 V.

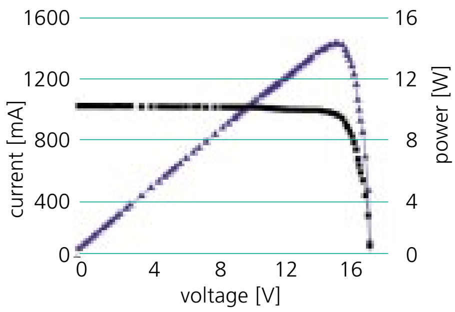
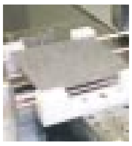


Fig. 5: The FLATCON® modules shown in fig. 4 have an efficiency value of more than 22.7 % for a radiation intensity of 759 W m^{-2} and an ambient temperature of 17.5 °C.



Lifetime Spectroscopy to Analyse Defects in Silicon

Lifetime spectroscopy is a relatively new, particularly informative method to analyse defects in silicon which serve as recombination sites. Our group recently made important advances in using this technology.

Stefan Glunz, Patrick Lichtner, Stefan Rein, Wilhelm Warta

More than 90 % of the solar cells manufactured world-wide are made of crystalline silicon. An important approach to reduce the production costs is to increase the cell efficiency. As the material quality plays a decisive role for the efficiency, it is essential to analyse the electrically active defects which are generated either during the silicon production or the solar cell manufacturing process. "Deep-Level Transient Spectroscopy" (DLTS) is generally regarded as one of the most sensitive methods to detect and analyse even extremely low concentrations of electrically active defects. Nevertheless, even defect concentrations below the detection limit of DLTS can have a strong influence on the charge carrier lifetime. The charge carrier lifetime is the average time which e.g. a photo-induced minority charge carrier "survives" after the light has been switched off.

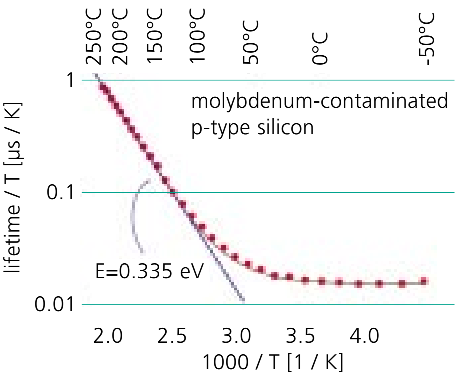


Fig. 1: Result of a TDLS measurement on a silicon sample with molybdenum impurities.

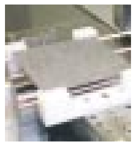
As the charge carrier lifetime is very sensitive to electrically active defects, lifetime measurements are particularly well suited to investigate the material quality. In addition to purely qualitative analysis, defects can also be identified directly if the dependence of the charge carrier lifetime on the temperature and the charge carrier density is analysed. This method is known by the name of lifetime spectroscopy and has only recently been introduced by several leading photovoltaic groups.

In contrast to DLTS, it is a contact-free method, so that both defects which are already present in the raw silicon material and also those which are unintentionally created during the solar cell process can be analysed particularly easily. This provides important information for the further development of silicon solar cells.

We were able to make important progress recently particularly in temperature-dependent lifetime spectroscopy (TDLS). The basic principle is that the recombination activity of a defect decreases with increasing temperature, so that the lifetime increases. If the measured charge carrier lifetime divided by the temperature is plotted against the inverse temperature 1/T in an Arrhenius plot, a linear section is found at higher temperatures with a gradient that is directly proportional to the energy level of the defect in the investigated material. The energy level of a defect in the band gap is in turn the most important "fingerprint" to identify it.

Figure 1 shows results from a typical TDLS measurement. The linear section at high temperatures can be clearly recognised. Its gradient "reveals" the energy level of the investigated defect, in this case 0.335 eV. In addition, our newly developed analytical routine allows us to obtain decisive information about the capture cross-sections of the defect from the TDLS measurement. We can then identify the defect unambiguously, molybdenum in this case.

We have already applied the method successfully to many types of defect (Fe, Cu, Ni, Mo, ...). It is a technique which not only determines that something "went wrong" in the production of the silicon crystal or the solar cell, but also diagnoses what it was!



Analysis of Spatially Distributed Losses in Silicon Solar Cells

During the past year, we investigated the relationship between the material quality of multicrystalline silicon, its changes in the solar cell process and the output power performance of solar cells. We succeeded in transferring essential results to industrial practice.

Martin Hermle, Jochen Dicker, Jörg Isenberg*, Stephan Riepe, Roland Schindler, Martin Schubert, **Wilhelm Warta**

The solar cell simulation program PC1D is an excellent tool to calculate the output power properties of monocrystalline silicon solar cells from the material quality and technology-dependent parameters, so that the potential of a material can be assessed. PC1D is a one-dimensional simulator, i.e. it assumes lateral homogeneity for all properties. However, often already the raw material for multicrystalline solar cells exhibits extreme fluctuations in quality. Even for solar cells of monocrystalline material, local problem zones (short circuits, higher transverse conduction losses) also arise in real industrial manufacturing processes.

We are co-operating with partners from research and industry to develop a program package which extends the proven capabilities of PC1D to laterally inhomogeneous solar cells. We have already written research versions of the corresponding programs for two-dimensional simulation. They are now being tested with cells from various steps of the cell production process used by industrial partners. In parallel, a software developer is preparing a user-friendly, marketable version of the program.

We are also working on the necessary measurement instruments to obtain reliable data for process control. We successfully adapted the new lifetime measurement technique CDI (Carrier Density Imaging), which we introduced last year, for use with real samples from industrial solar cell production. An important intermediate step in production is the emitter diffusion. With completion of this step, the most significant changes in the charge carrier lifetime have occurred. Expensive subsequent steps can be avoided if lower-quality silicon material is sorted out at this point.

Now we can apply CDI to characterise wafers after emitter diffusion. This technique offers the essential advantage of extremely short measurement times in comparison to other spatially resolving procedures. An example for a CDI lifetime measurement of a 100 x 100 mm^2 multicrystalline wafer with highly doped emitters on both surfaces is shown in fig. 1. The measurement time was 100 s.

The influence of the temperature load in the solar cell process was investigated for groups of parallel wafers . They were subjected to the standard industrial emitter diffusion process at different temperatures and the surfaces were passivated after removal of the highly doped layers. Figure 2 shows examples of frequency distributions (determined from CDI lifetime images).

The initial lifetime of 1.5 µs was already significantly improved here with the lowest temperature. Degradation occurs increasingly at higher diffusion temperatures. As solar cell technology improves, this type of effect will gain in importance. We can offer experience and equipment to material manufacturers to optimise their crystallisation process.

The work in the PORTRAIT project (Solar Cell Performance Optimisation Relating Process Tracking by Imaging Techniques with Modelling) is supported by the EU.

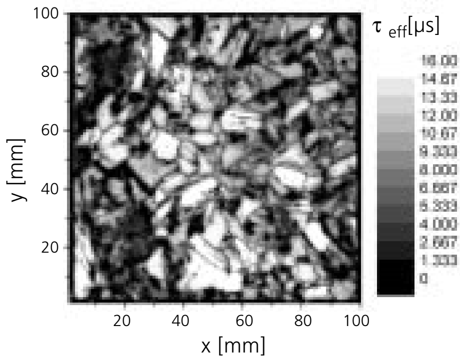


Fig. 1: CDI lifetime measurement of a wafer after emitter diffusion.

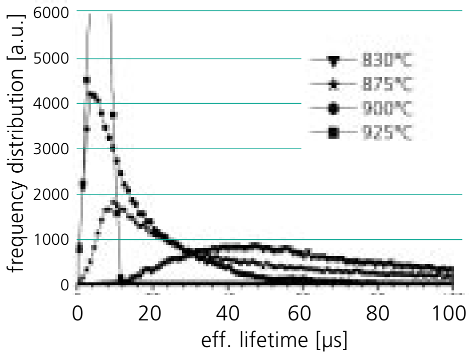
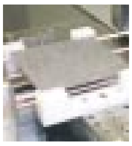


Fig. 2: Lifetime distributions after emitter diffusion at 830, 875, 900 and 925 °C for material from the top of a multicrystalline Si block.

* University of Freiburg, Freiburger Materialforschungszentrum FMF

1 Supported by the German Federal Ministry of Economics and Technology BMWi within the "KOSI" project.



Low-Contamination Transport for Industrial High-Temperature Processing of Silicon Solar Cells

Together with the Centrotherm company, we are developing a novel system to transport silicon wafers through high-temperature processing zones, particularly for phosphorous diffusion. This transport system drastically reduces the contamination problems of silicon wafers in in-line ovens. By using it, we achieve efficiency values exceeding 15 % for solar cells made of industrial multicrystalline silicon material.

Daniel Biro, Gernot Emanuel, Andreas Grohe, Marc Hofmann, Dominik Huljic, Christopher Kopisch, Jochen Rentsch, Isolde Reis, Eric Schneiderlöchner, Wolfram Sparber, Winfried Wolke, **Ralf Preu**

Over the last four years, the crystalline silicon solar cell has become a mass product. More than 100 million are produced world-wide each year. The advantages of using production processes with a rational material flow are obvious for mass production on this scale. From this perspective, in-line production is ideal, i.e. the wafers move continuously through the various processing stations.

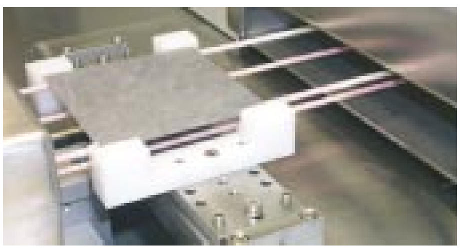


Fig. 1: Wafer input for the walking string transport system.

It is not always possible to achieve the same results with continuous technology as by simultaneous processing of large batches of wafers. One example up to now was the formation of the emitter. It is created by introducing phosphorous atoms into the region near the surface of the silicon wafers. To do this, the wafers are coated with a thin layer of a dopant material containing phosphorous. Then, they are heated to a temperature of 850 to 900 °C, which results in diffusion of the phosphorous, but also of other materials, into the silicon. In particular, the introduction of metal atoms into the extremely pure silicon grid considerably reduces the power output of the finished solar cells.

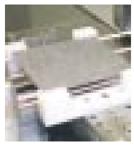
For lack of alternatives, temperature-resistant metal chain bands have been used to transport wafers through the ovens for industrial, in-line production. The chain bands cause undesired contamination by contact and abrasion particles. In addition, the high thermal mass of the chains leads to long heating and cooling periods. This in turn increases the floor area needed, the ovens become very long. Thus, the process adapted from the semiconductor industry, diffusion in a closed cylindrical oven, has still dominated up to now, although the material flow is much less favourable.

This is the point where we introduced technology for which we have filed a patent claim together with the Centrotherm company: walking string transport.

Instead of the metal chain bands, we use two pairs of temperature-resistant strings, on which the silicon wafers are placed. The string pairs are suspended from two support frames outside the high-temperature zone, and can move independently of each other, both 30 cm horizontally and 2 cm vertically. The wafers lie on the upper string pair, which is moved in the transport direction, while the lower string pair is moved in the opposite direction until it returns to its original horizontal position, where it is raised and takes over the wafer transport. The periodic process and appropriate choice of the string speed ensure completely continuous transport.

We have already constructed two single-track laboratory systems at Fraunhofer ISE with this transport system. Our analyses of the material quality of processed wafers proved that - in contrast to the metal chain bands - the degree of contamination is negligible. Thus, we now use this system in the standard diffusion equipment of our pilot line. This allowed us to increase the efficiency value of mc silicon solar cells, which are produced with industrially relevant processes, to above 15 %.

As a response to the high demand from industry for in-line ovens with walking string transport, we have developed a four-track system with the Centrotherm company. We are constructing this as a demonstration system at Fraunhofer ISE. The German Federal Ministry of Economics and Technology BMWi is supporting this joint project, in which the Fraunhofer Institute for Production Technology IPT and the ACR company are also participating. The latter is involved with developing and constructing the automation components.



Laboratory and Service Centre, Gelsenkirchen

With our in-line pilot production line, we have developed a production process for multicrystalline silicon solar cells, and have also set up two texturing procedures for monocrystalline and multicrystalline silicon in our production line. A measurement system for quick detection of shunts was developed.

Nico Ackermann, Christoph Ballif, **Dietmar Borchert**, Markus Dabruck, Andreas Gronbach, Ali Kenanoglu, Stefan Müller, Stefan Peters, Alexander Poddey, Markus Rinio, Mark Scholz, Jörn Suthues, Roland Schindler, Gerhard Willeke, Thomas Zerres

In its in-line pilot production line for screen-printed multicrystalline silicon solar cells, the Laboratory and Service Centre in Gelsenkirchen operates a plasma facility which allows deposition and etching processes to be carried out at the standard frequency of 13.56 MHz over an area of 45 x 45 cm^2 for the first time. The homogeneity of the deposited silicon nitride is better than 5 % over the entire area, and better than 3 % over a solar cell with an area of 12.5 x 12.5 cm^2.

Light penetration into the solar cell is significantly improved if the cell surface is textured. One method to achieve this is to create random pyramids on the surface of monocrystalline material, which is done by anisotropic etching with a hot potassium hydroxide/isopropanol mixture. This mixture is difficult to handle in mass production, as large amounts of the isopropanol evaporate. We looked for an alternative etching solution without isopropanol. Using a sodium carbonate solution, which contains a small amount of sodium hydrogen carbonate, we were able to reduce the reflectance as much as with the standard potassium hydroxide/isopropanol mixture (fig. 1).

Whereas random pyramids can be etched with alkaline solutions on monocrystalline silicon due to the crystal geometry, this does not work on multicrystalline silicon. Acidic etching solutions are used here. Based on a modified commercial etching mixture, we have developed a solution which leads to an increase in current of 4 % in multicrystalline silicon solar cells.

The high throughput of modern production lines increasingly demands that the manufacturer has measurement technology available on site. The methods employed must be robust, simple to operate, and quickly provide an unambiguous result. In the Laboratory and Service Centre in Gelsenkirchen, we have followed the development of the FAKIR system for rapid measurement of sheet resistance with a new measurement system which meets the specifications for speed and clarity.

It is a system to detect shunts, which supplies an image giving an overview of all relevant shunts within a few seconds. The system operates with a temperature-sensitive liquid-crystal film. Two or three seconds after a reverse voltage of typically 1 to 10 V has been applied, localised higher currents flow at the position of internal shunts, which heat up the solar cell more strongly at these points. This leads to a visible colour change in the liquid-crystal film (fig. 2). Three different cell sizes can be measured with our system, without needing to modify the equipment.

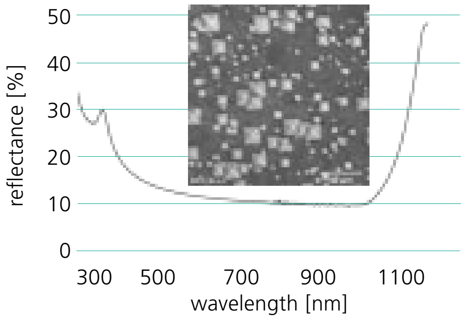


Fig. 1: Reflectance spectrum for a silicon surface after etching with a sodium carbonate solution. Etching time: 15 minutes. Inset: SEM image of a textured surface.

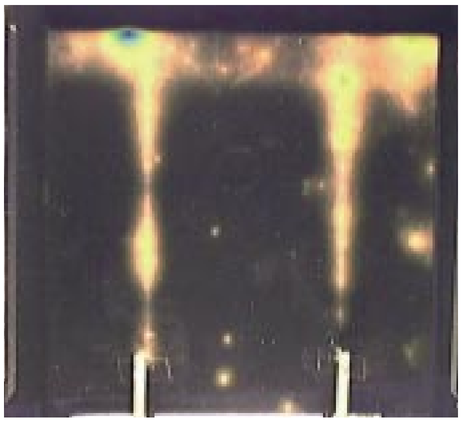
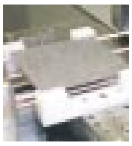


Fig. 2: Example illustrating our measurement system to detect shunts in a multicrystalline silicon solar cell with an area of 12.5 x 12.5 cm^2. The temperature-sensitive liquid-crystal film, which was placed on the front surface of the solar cell, shows pronounced changes in colour, particularly near the bus bars. The bright areas are caused by local shunts which were created by firing the cell contacts too strongly.



Dye Solar Cells

Dye solar cells are based on a new type of technology. Completely different materials and production procedures are applied than for conventional solar cells. They have a high potential for cost reduction.

Simone Baumgärtner*, Udo Belledin*, Anneke Hauch*, **Andreas Hinsch**, Sarmimala Hore*, Rainer Kern, Ronald Sastrawan*, Marion Schubert*, Jochen Wagner*, Uli Würfel*

Fig. 1: Production technology for dye solar cells: All layers of the cell are applied by screen-printing.

Dye solar cells are electrochemical solar cells. The production of dye solar cells does not require semiconductor technology, but intrinsically inexpensive thin-film technology, such as is used in the glazing industry. This means that these solar cells could eventually be produced at very low prices. At Fraunhofer ISE, we have set up a pilot production line for dye solar modules with an area of 30 x 30 cm^2. We focussed on:

- accurate screen-printing or stencil printing (fig. 1)
- thermal sealing techniques with glass solder or ionomers
- equipment to structure the glass substrates
- dispersion units to prepare the screen-printing pastes
- filling stations to fill the cells and modules with dye or electrolyte solutions

We have developed a new module concept for dye solar cells which, combined with our know-how in the field of thermal sealing technology with glass solders, enables the development of dye solar modules that are stable on a long-term basis. It is based on the monolithic cell concept for dye solar cells (fig. 2). Both the front electrode and the counter-electrode of the solar cell are deposited as layers on the front pane of TCO-coated glass. The back glass pane serves only to seal the cell and is joined to the front pane with a glass solder seal.

To fill the cells within the modules, we have developed a vacuum back-filling station. One hole in the counter-electrode is sufficient to introduce the electrolyte.

In addition, we are working intensively, together with the Materialforschungszentrum at the University of Freiburg, on increasing the efficiency of dye solar cells. We are co-operating with other leading research groups in this work within the European "NANOMAX" project. We are investigating new cell concepts and materials to raise the efficiency values significantly. The new concepts are to be implemented on a pilot scale with the newly constructed pilot line. Last year, we achieved an efficiency value of 6 % for these cells.

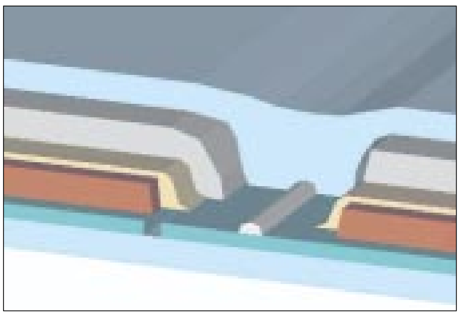
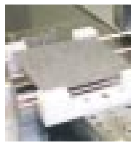


Fig. 2: Schematic diagram of the monolithic cell concept for dye solar cells, developed at Fraunhofer ISE. The photoactive dye (red) is dispersed through a 10 µm thick porous layer consisting of TiO_2 crystallites of about 20 nm diameter. A porous zirconium oxide layer (yellow) serves as an electron barrier between the photo-electrode and the counter-electrode of graphite (grey). The back cover (light blue) and the hermetic seal for the cell consist of thin glass. An electrolyte is contained within the layers to transport the light-generated positive charge. The negative charge is conducted via a transparent conductive oxide of SnO_2:F (green) and a narrow silver conductor (grey) on the front glass cover.

* University of Freiburg, Freiburger Materialforschungszentrum FMF



Organic Solar Cells

As part of the search for inexpensive solar cells, we have recently started also to develop thin-film solar cells of purely organic materials at Fraunhofer ISE.

Simone Baumgärtner*, Markus Glatthaar, **Andreas Hinsch**, Michael Niggemann, Marion Schubert*, Jochen Wagner

There is still a high risk associated with the development of organic solar cells. However, following the breakthrough in organic light-emitting diodes (LED's), the prospects for success with organic solar cells have also improved markedly. Polymer electronics is regarded as one of the key technological areas for the 21st century. The technology is relatively new, and significant advances can be expected in the near future. During the last few years, the selective combination of material with negative and positive charge carriers led to organic solar cells with efficiency values of up to 3 %.

An essential component of our research is reviewing materials with regard to their photoactivity. We investigate whether various materials combinations are suitable as electron donors and electron acceptors - either as layered systems or mixtures. We produce the layers both by vacuum evaporation and by spin-coating. All of the systems have a planar stratified configuration with the active layer between a transparent and a highly reflective electrode. Low charge-carrier mobilities and high recombination rates limit the layer thicknesses to a maximum of 100 – 200 nm. These low thicknesses result in poor light absorption and impose a decisive restriction on the efficiency. The mismatch between the absorption spectrum of the photoactive materials and the solar spectrum further restricts the exploitation of sunlight in the absorber materials currently used.

At Fraunhofer ISE, we are attempting to increase the light absorption by embossing nanostructures onto the surface (fig. 1). In doing so, we benefit from the long years of experience at the Institute in large-area nanostructuring of polymer materials. The experiments are supported by modelling the electric field distribution in the structured absorber layers with rigorous coupled wave analysis, RCWA (fig. 2).

The activities on organic solar cells are integrated into work at the Materials Research Centre at the University of Freiburg. We have taken a glovebox with integrated evaporation equipment into operation there. It is used to deposit the electrode films. The solar cells are also characterised within the glovebox using a solar simulator (fig. 3).

Fraunhofer ISE is co-ordinating two joint and network projects on this topic with research groups from universities and other institutions, which are financially supported by the German Federal Ministry of Education and Research BMBF.

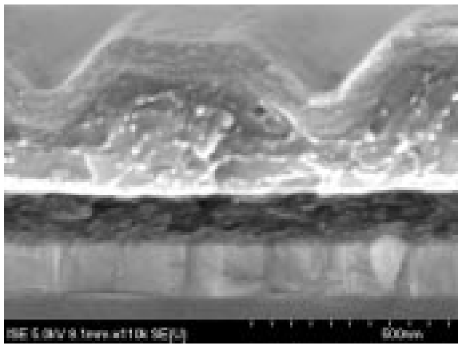


Fig. 1: SEM image of the layered configuration of a structured organic solar cell. The components are, from the bottom to the top: Glass, transparent conductive ITO, polythiophene (PEDOT) as an electric hole conductor, active absorber layer (bucky ball polymer mixture), aluminium as the counter-electrode. The absorber layer was nanostructured by embossing.

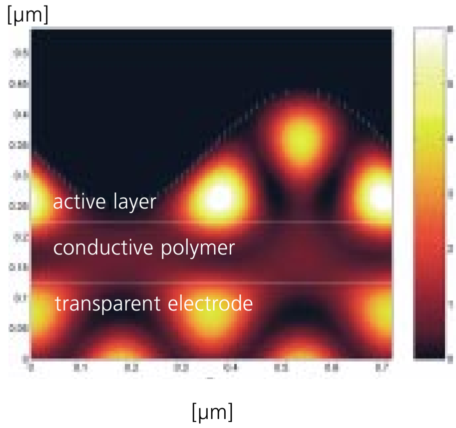
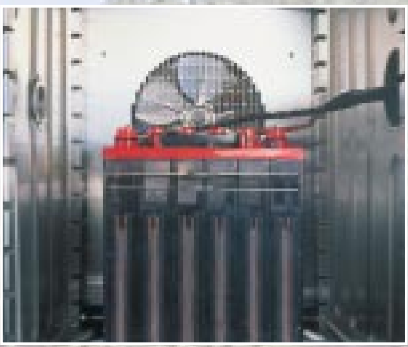


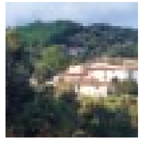
Fig. 2: Calculated distribution of the squared field intensity over a cross-section through a structured organic solar cell (period of the structure = 720 nm). In this case, the maximum light absorption is located in the active layer. The calculation was made for monochromatic light with a wavelength of 500 nm and perpendicular incidence from below.

Fig. 3: Production of organic solar cells in the glovebox.

* University of Freiburg, Freiburger Materialforschungszentrum FMF

Off-Grid Power Supplies



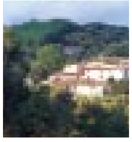


Clean and Available Everywhere – Off-Grid Power Supplies with Regenerative Energy

Two thousand million people without electricity, a multitude of technical power supplies for telematics, telecommunications or environmental measurement technology, and four thousand million portable electronic appliances in the industrialised countries all have one feature in common: They all require off-grid electricity. This is supplied in the required amounts by regenerative energy sources or innovative energy converters like fuel cells. About half of the photovoltaic modules sold world-wide are thus used in off-grid power supplies. This application is currently the largest natural market for photovoltaic systems, which are often already more economic today than batteries, grid extension or diesel generators.

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

The quality of the components and the system design for both rural electrification and technical power supplies has improved notably over the last few years. However, the quality or costs of the power supply are often still unacceptable.Thus, increasing attention is being paid to careful planning, high-quality components and sophisticated operation management. System integrators and component manufacturers often have to estimate the complex interaction of many influences. In doing so, they make use of our expert knowledge on power and control electronics, battery modelling, charging strategies, system operation management, energy management, system simulation or socio-economics.



Fuel cells have a high potential as off-grid power supplies - particularly as miniature fuel cells in portable appliances. Their decisive advantage is the high energy density which can be achieved in the storage units for hydrogen or methanol, compared to today's secondary batteries. This can significantly lengthen the operating time for the appliances, while the volume or mass remains unchanged. Often, mobile power supplies can be optimised by combining different energy converters such as solar cells, fuel cells or secondary batteries.

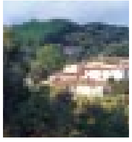
New business models and appropriate market penetration strategies are important for the companies which are involved in rural electrification. Larger electrification programmes are now also taking socio-economic factors increasingly into account. That ensures a sustainable distribution and service network - and thus long-term operation of the installed systems. Anyone who wishes to access the markets for rural electrification must therefore include socio-economic methods and knowledge in business planning and product design.

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

- electronics development
- battery modelling
- small fuel cells
- highly efficient solar modules for integration into appliances
- system dimensioning and optimisation
- system operation management and energy management systems
- water treatment systems and technology for drinking and other water supplies
- socio-economics

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

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



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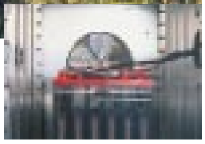
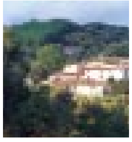
Photovoltaic hybrid village power supply in Cal Peraire in Spain. The system was planned and implemented with a socio-technological strategy as part of the EU-funded MSG project (Multi-User Solar Hybrid Grids).



Battery measurements in the test laboratory, for development of battery operation strategies (articles on pp. 55 and 90).

Controls circuit board with a 50 W fuel cell as a stand-alone power supply for a laptop (article on p. 56, example of integration into a laptop - see cover illustration).

Proof of the disinfection and desalination performance of a decentralised drinking water treatment system.



Ergonomic Communications Interface for Photovoltaic Systems - the Display for a Prepayment System as an Example

We have designed a display unit for a compact photovoltaic system that is being developed for energy services in regions remote from the grid. It satisfies the criteria of perception psychology and ergonomics, and serves as the interface between the technical system and the user. Both the requirements of the user and of the technical system were taken equally into account by combining sociological and technical competence.

Norbert Pfanner, Maria Xesus Bello Rivas, Dirk Uwe Sauer, **Sebastian Will***

The Solar Home Compact System consists of one external module, and a battery integrated into a casing together with the associated charging electronics. This allows the charge control to be adapted to the battery, the system to be protected against manipulation and the installation effort to be reduced considerably. Installation errors are practically eliminated. The system operates according to the prepayment principle: The energy user pays for the service in advance, just as with a telephone card, which is then booked from a chip card.

One essential aspect is communication with the user, to inform him/her about the state of the system. The display designed for this purpose is intended to be very convenient to use and to visualise the necessary information about the operating condition:

- In order to optimise consumption, the user needs information about the technical state of the system (battery and charging state).
- A display for diagnosis of faults can reduce the costs for repairs and maintenance (travel costs). If the user can clearly recognise the reason for a system breakdown, acceptance of the system also increases.
- Users can adjust their energy consumption according to their available financial resources if the prepayment credit is displayed.
- Feedback on the positive or negative effects of their behaviour allow users to learn about appropriate system operation.

The display was designed according to ergonomic and perception-psychological criteria. In doing so, we particularly aimed to draw on existing user knowledge in visualising the information. We wanted to make the display surface compatible with concepts which are already familiar to the users. We understand "compatibility" to mean the extent of agreement between structures in the semantic memory of the user and the actions required of him/her. A training session when the photovoltaic systems are taken into operation strengthens this compatibility.

The display is designed such that the user can absorb all relevant information at one glance. Confusion of the user by unintended displays is avoided.

The development work on the photovoltaic compact system is being led by the Steca company. To achieve a balance between production costs and ergonomics, Steca decided, in consultation with Fraunhofer ISE and the energy utility, Afrisol (Morocco), on a display in which pictograms display the state of the battery, the maintenance service and the account status, and green, yellow and red LED's indicate the instantaneous state of the system (preliminary design in fig. 1).

As the next step of our socio-technical strategy, we will accompany the pilot field introduction by studying the acceptance of the compact system and the client-specific display. This procedure will allow the product to be optimised and then introduced on a more widespread basis.

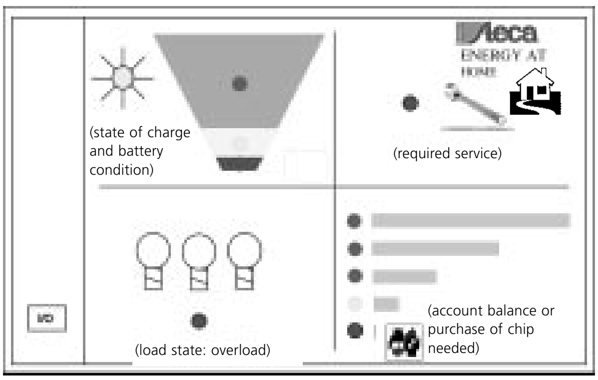
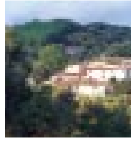


Fig. 1: Draft layout for the customised system display.

* PSE GmbH Forschung Entwicklung Marketing, Freiburg



Export Campaign for Products and Services for Rural Electrification

The Johannesburg summit meeting brought rural electrification into the centre of global development politics. With regard to this challenge on the one hand, and rapidly increasing production capacity for photovoltaic modules on the other, it is time to open these export markets more effectively to German industry. Two activities supported by Fraunhofer ISE are dedicated to this goal.

Sven Kreitz, **Werner Roth**, **Dirk Uwe Sauer**, Nicole Seibel, Irina Wellige

Supplying energy and water to rural areas was identified as a central task for the global community in the immediate future at the summit meeting in Johannesburg. Today, around two thousand million people live without access to these resources.

German industry and research can offer excellent products to solve these supply tasks. However, access to the markets in developing and threshold countries is still difficult, particularly for small and medium-sized enterprises (SME). This is partly due to the difficult market conditions, which demand high investment and initial costs that can hardly be met by SME's. Another reason is international competition from many industrialised countries, which are intensively supported by the corresponding national politics, creating considerable market advantages. A central element of this support is a close connection between development aid and support for the national economy.

For many years, Fraunhofer ISE has been developing technology and socio-economic methods for use in developing and threshold countries, and has implemented them in projects there.

We now use the experience gained to support companies in penetrating the markets for rural electrification. The work is streamed into two central activities:

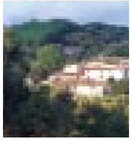
1. Club zur ländlichen Elektrifizierung C.L.E. (Club for Rural Electrification)
2. Access to the World Bank for business consortia

C.L.E. is an association primarily of SME's from German-speaking countries. Membership of C.L.E. is open to all enterprises which are interested in operating within the rural electrification sector, today or in future, particularly in southern countries outside of Europe. The main activities are political lobby work, internal communication, acquisition of information, support in applying for World Bank projects and the establishment of long-term contacts in the target countries.

Fraunhofer ISE is a member of C.L.E. and manages the day-to-day operations in the headquarters. In this role, we are constantly in contact with ministries, the development aid organisations and the export initiative established by the German Federal Government. In this way, we act as a spokesperson for the companies and the specific market segment. The aim of the activities is to improve the market situation for German businesses and simultaneously to develop sustainable concepts for rural electrification. In our opinion, this can be achieved only by close co-operation between public development aid and involvement of the private sector. You can find further information on C.L.E. under www.cle-export.de

In particular, SME's find it difficult to apply successfully for World Bank projects. With an annual credit volume between 700 and 1000 million US dollars, which the World Bank provides for rural electrification, this represents a large untapped economic potential. Therefore, the Fraunhofer Gesellschaft, with seven of its Institutes and the support of the Bavarian State Ministry for Economics, Transport and Technology, has founded the joint initiative on “Access to the World Bank for Business Consortia“, which started operation at the beginning of 2002. Within this initiative, the pool of member companies is supported in identifying promising calls for project applications and matching the expertise of the enterprise to the specifications of World Bank projects.

A joint presentation brochure is intended to simplify contact to the target countries and representatives of the World Bank. Complete applications are prepared and submitted with direct support from Fraunhofer ISE. Further information on the initiative can be found at the Internet site, wb.iitb.fhg.de .



Passing on Experience from Ten Years of Rural Electrification for Use by Commercial Enterprises

New energy technology can be successfully integrated in rural areas only if the cultural and socio-economic conditions are taken into account right from the beginning. Businesses must be able to assess these conditions and take account of them in their project work. In order to pass on this know-how to participants from the solar industry, sociologists and European companies involved in rural electrification are co-operating to prepare a relevant training programme. The programme is being run and evaluated in commercial companies.

Dirk Uwe Sauer, Mark Ullrich, Gisela Vogt, **Sebastian Will***

The rural electrification market for off-grid photovoltaic systems offers a theoretical market potential today of several hundred million euros.

Up to now, technocratic approaches have often dominated the rural electrification process. "Technology" and "rural electrification" have often been understood as synonyms. Accordingly, the attitude to users in such projects has been characterised by a functional-deterministic view of people. However, most often it is specifically the non-technical problems which prevent more rapid dissemination of photovoltaic power supplies. A central reason is lack of adaptation by photovoltaic technology and market penetration strategies to the existing social, cultural and socio-economic structures.

Fig. 1: Installation of a photovoltaic hybrid system in Indonesia.

An analysis of project reports from the last 10 years identifies many cases of the following deficits:

- Inadequate knowledge of the local culture and social conditions leads to a discrepancy between the energy demand and the supply potential of the installed photovoltaic systems.
- Inadequate analysis of the income structures leads to high-risk financing models.
- Insufficient instruction of the final users leads to incorrect use such as deactivation of components to limit consumption or excessive use of individual components.
- Lack of investment in the infrastructure and training of local staff for service, maintenance and distribution leads to massive restrictions in long-term operation.

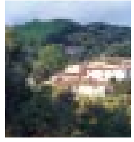
In order to eliminate these deficits, Fraunhofer ISE co-operated with partners[1] from sociology, implementation managers and the industry to develop a "Train the Trainer" concept, in which business representatives learn the skills required to assess socio-economic and cultural conditions. Furthermore, we teach how they can use the results of the assessment to implement photovoltaic systems in a sustainable and socio-economically appropriate fashion. Co-operation between sociologists with field experience and technicians with relevant practical experience was the pre-requisite for developing the content of the training course to meet the specific needs of the target group.

The training courses are initially being held at the premises of each industrial partner and scientifically evaluated. Then the training programme will be opened to all companies, which can make a selection from a choice of topics. One example is "Local Energy Demand". In the past, this has been estimated by surveying the existing electric appliances. As this method is unable to provide reliable estimates, the participants learn to judge the relevant energy demand by taking the local socio-economic context into account. Another example is "Selection of Personnel". Qualified analysis and evaluation of the local conditions and the project concept help the enterprise to select the most suitable staff for local installation and maintenance. The course contents include well-tested recommendations for marketing and an introduction to the operation of photovoltaic systems, as well as the establishment of trusting relationships between the project partners. Finally, approaches and "tools" for on-going monitoring and follow-up studies are presented, so that the companies can judge the technical, social and financial success for themselves.

The work is being carried out within the "SOPRA-RE" project, which is financially supported by the European Union.

* PSE GmbH Forschung Entwicklung Marketing, Freiburg

[1] The partners in the SOPRA-RE project are: BP Solar, Total Energie, ATERSA, Trama Tecno Ambiental, Vergnet, ECN and the Carlos III University in Madrid.



New Charging Procedure for Batteries in Stand-Alone Power Supplies

Batteries are central components in stand-alone and off-grid power supply systems. Lead-acid batteries are still most commonly used. We develop highly efficient charging procedures to lengthen the battery lifetime, which is often unacceptably short.

Georg Bopp, Rudi Kaiser,
Dirk Uwe Sauer

At present and in the foreseeable future, lead-acid batteries will continue to be the most commonly used type of battery in stand-alone power supply systems, due to their good cost-performance ratio. Considerable loads in partial cycling operation, irregular complete charging and unsuitable charging procedures often needlessly shorten the battery lifetime.

Many batteries are replaced today, not only in stand-alone power supplies, although the irreversible loss of capacity is not yet critical. However, the concentration of reversible sulphates can increase significantly, and cannot be decreased by conventional IV charging procedures (constant current / constant voltage). As a result, the instantaneous capacity available to the user is reduced significantly.

Both in the field and in our laboratory, we were able to show that the reversible losses of capacity can be almost completely compensated with constant-current recharging (I_a phase), particularly for lead-acid batteries with immobilised electrolytes. Figure 1 shows this clearly: Three constant-current recharging processes (I_a phase) are needed to bring the capacity of an old battery back to its rated value. The capacity remains stable at the rated value during further operation with the standard charging procedure. The test object here was a battery that had been stored for five years without being operated. The resulting sulphation is similar to the problems that also occur during typical operation in the field, e.g. when batteries are only partly charged during partial cycling operation.

We were also able to extend the lifetime with improved charging procedures in field investigations in co-operation with the battery manufacturer, Deutsche Exide Standby. In a field test comprising 16 systems with sealed lead-acid batteries, we investigated different IV and IVI_a charging procedures. Only the IVI_a charging procedures resulted in complete charging of the battery. Depending on the type of battery and the season, between 5 and 20 % more charge than with the best IV procedure could be stored in the battery and drawn again. High-quality batteries, which were completely charged twice a year with an IVI_a charging procedure, hardly showed any loss of capacity, even after four years of operation.

The constant-current charging procedure extends the battery lifetime appreciably, but only a few charging devices are able to apply this procedure, and the exact specifications of the charging procedure must be adapted according to the application and type of battery.

In the EU project on "Reducing electricity storage costs", we intensively investigated charging procedures with pulsed current in the frequency range from 10 Hz to 10 kHz and amplitudes up to I_1. We did not discover any significant effect on the charging behaviour of lead-acid batteries with liquid electrolytes in general. Only batteries with liquid electrolytes but without electrolyte circulation showed poor lifetime values after pulsed current loads, as occur in stand-alone power supplies.

Electrolyte circulation systems significantly extend the lifetime of lead-acid batteries with liquid electrolytes. For instance, a recently investigated OPzS battery proved to have an only slightly reduced capacity after ten years of operation in the field.

On the basis of our investigations, we can extend the battery lifetime in stand-alone power supplies by 30 to 70 % compared to the present status. We thus offer the development of optimised, customised charging devices and total storage concepts that are optimised according to energy and economic criteria to manufacturers and users. In particular, these concepts and devices include our precise self-adjusting algorithms to determine the state of charge and ageing effects.

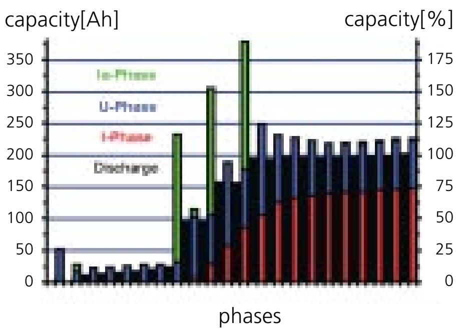
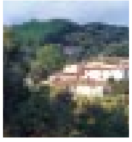


Fig. 1: Cycling to refresh an OPzV battery after five years' storage without operation. Each coloured bar represents one charging process, the following black bar shows how much capacity could be discharged. Blue and red bars correspond to conventional charging with constant voltage and constant current, respectively. Three constant-current recharging processes (I_a phase, green bars) are needed before the capacity of the battery regains its rated value of 200 Ah.



Micro-Energy Technology

The energy demand for appliances in the 4C market (cell phones, camcorders, computers, cordless tools) is increasing rapidly due to the integration of additional functions. A stand-alone power supply is often desired for dispersed electrical appliances, e.g. measurement or signal systems. In the group addressing micro-energy technology, we are developing reliable miniaturised power generators to replace or complement batteries.

Johannes Aschaber, Ulf Groos, **Christopher Hebling**, Helge Schmidhuber, Jürgen Schumacher, Mario Zedda

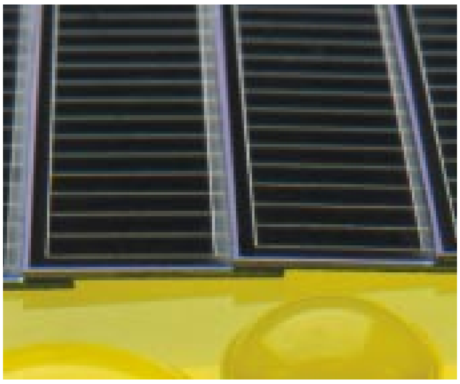


Fig. 1: Shingle technology for solar modules with highest efficiency values. Combined with the high-efficiency solar cells from Fraunhofer ISE, a module efficiency value of 20 % is achieved.

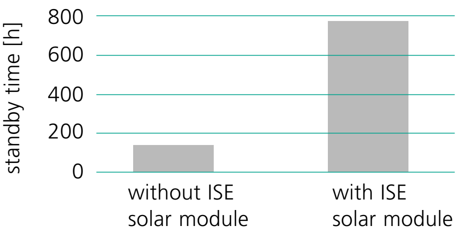


Fig. 2: Extension of the standby time for a mobile phone at the window of an interior room by the application of highly efficient solar technology.

High-efficiency solar modules

Solar cells are well known from everyday applications e.g. in pocket calculators. However, conventional photovoltaic technology does not provide sufficient power for palmtops, mobile phones or notebooks. High-efficiency solar cells can supply sufficient autonomous power for these appliances or appreciably lengthen their operating or standby times.

Our module technology distinguishes itself from the state of the art by its significantly higher efficiency value of 20 %. Particularly when appliances are operated under dim lighting conditions such as found indoors, the high level of the cell voltage and thus the efficiency that has been achieved at Fraunhofer ISE is decisive. We obtain high reliability for the power supply by accurately matching the solar module technology and the charging electronics for the device-integrated rechargeable battery.

In order to reduce the mass production costs, and increase the throughput and long-term stability, we are investigating new materials to laminate the solar cells. In addition, we have set up a pilot production line for our high-efficiency solar cells. This guarantees that we can transfer the technology directly to our clients.

As an example, an organiser was equipped with our solar technology, which operated for two months indoors without connection to an external power supply. Another development is illustrated by a solar rechargeable battery for a mobile phone, which has achieved practically unlimited standby times with our high-efficiency solar cells. The user can thus dispense with charging devices, cables and grid adapters, and instead simply recharge the battery at the window of the car or the hotel.

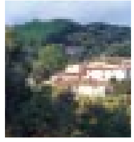
Miniature fuel cells

The high energy density of the storage units for hydrogen or methanol makes miniature fuel cells particularly suitable for electric appliances with long operating times. Separation of the electricity generation (fuel cell) and fuel storage allows ideal adaptation to the required specifications. The modularity of fuel cells offers a wide choice in their construction.

We develop membrane fuel cells and highly efficient voltage converters for a power range up to app. 200 W. The components are integrated as a complete system, including the energy storage unit, electronics and peripheral components, into portable appliances.

Led by Fraunhofer ISE, the Fraunhofer Initiative on Miniature Fuel Cells is developing innovative energy systems, in which materials development, production technology and assembly aspects are taken into account. In this way, we improve the product safety and reduce the costs in preparation for entry into the market. To demonstrate our development expertise, we have constructed a miniaturised fuel-cell system with a power of 10 W to operate a commercially available DV camcorder. We developed production procedures for the bipolar plates, new bipolar materials with conductive polymers and an automated assembly unit.

On commission to a computer manufacturer, a fuel-cell system was integrated into the battery compartment of a laptop. The fuel cell



supplies power of maximally 50 W to the laptop; three metal hydride storage units provide electrical energy reserves of app. 40 Wh. This completely replaces the rechargeable battery that is normally installed (cover photo).

Electronics for fuel cells

In future, powerful fuel cells will supply increasing numbers of stand-alone measurement instruments, laptops or mobile phones with energy. In doing so, they will replace or complement conventional primary and secondary batteries. We develop DC/DC converters which transform the energy from the fuel cells into a form which can be used by commercially available appliances. The electronic circuits provide many functions, such as:

- initial switching
- process control
- highly efficient DC/DC conversion
- hydrogen pressure control
- impedance control
- and humidity control.

At present we are concentrating our research activities on humidity control, in order to ensure stable operation of the fuel cell (see on p. 64).

Thermophotovoltaics

In contrast to solar photovoltaics, thermophotovoltaics (TPV) converts thermal radiation to electricity. This technology allows a reserve energy source, e.g. a gas burner, to be tapped in off-grid applications, independent of the availability of solar radiation.

We develop TPV cells with a spectral response that is matched to the emitted infrared radiation. Additionally, we optimise the material and surface structure of the radiator so that the emission maximum occurs in the desired spectral range. Finally, we develop miniature burners to heat the emitter and the entire systems technology.

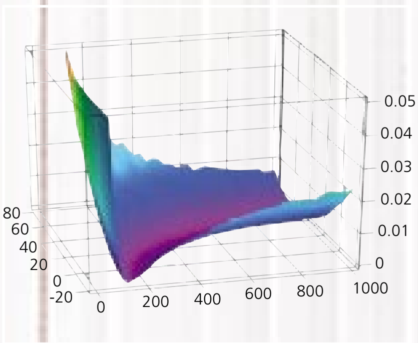
On the medium term, power densities of $1\ W\ cm^{-2}$ and electrical system efficiency values of 10 % are achievable. This makes TPV eminently suitable for co-generation of heat and electricity e.g. in the camping sector, on holiday houses or boats. Other markets can be found in off-grid heating of buildings or standby power supplies for vehicles.

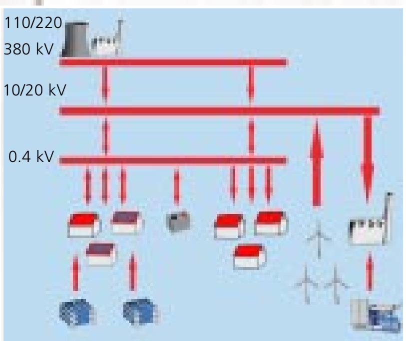
Fig. 3: Completely integrated fuel-cell system for a commercially available DV camcorder. Demonstration system developed by the Fraunhofer Initiative on Miniature Fuel Cells, under the leadership of Fraunhofer ISE.

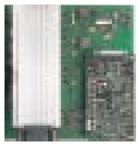
Fig. 4: 50 W fuel cell with a controls circuit board as a stand-alone power supply for a notebook.

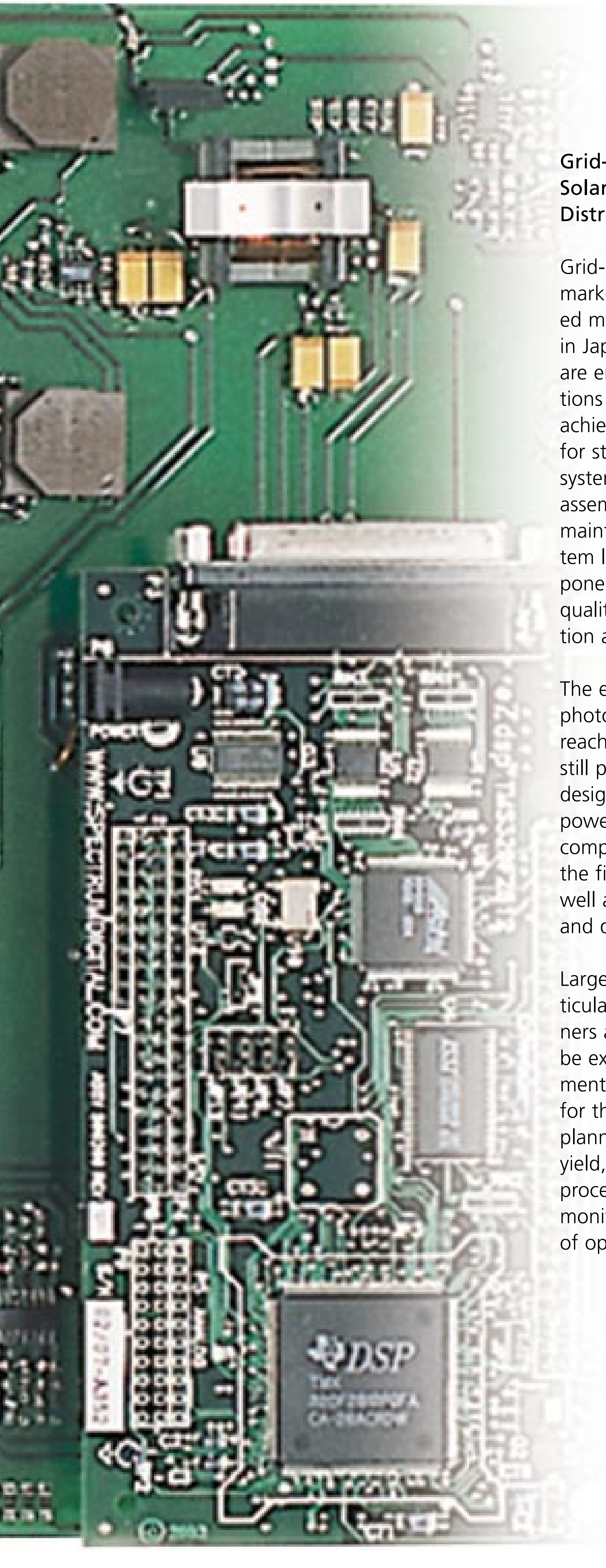
Fig. 5: Cutaway diagram of a TPV reactor with the burner, emitter, vacuum technology, TPV cells and cooling system. The electric power is about 100 W, for an electrical efficiency value of 10 %. The height of the reactor is 245 mm.

Grid-Connected Renewable Power Generation







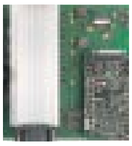


Grid-Connected Photovoltaics, Solar Power Stations and Distributed Electricity Generation

Grid-connected systems represent the largest market for photovoltaics today. Well-implemented market penetration programmes, particularly in Japan, Germany and some States of the USA, are ensuring high growth rates. The cost reductions in photovoltaic systems, which have been achieved so far and which are needed further for stable growth, have mainly occurred in the systems technology: inverters, roof integration, assembly and cabling systems. In order to keep maintenance and repair costs low over the system lifetime of 20 years, the quality of the components must improve. For the same reasons, quality control and monitoring of system operation are playing increasingly significant roles.

The efficiency and quality of inverters for feeding photovoltaic electricity into the grid have reached a high standard. Nevertheless, there is still potential for improvement with new circuit designs, digital controls technology, advances in power semiconductor components and passive components. We offer specialised know-how in the fields of circuit design and dimensioning, as well as configuring and implementing analog and digital controllers.

Large, commercial photovoltaic systems in particular raise questions of quality control for planners and operators: Which electricity yields can be expected, to pay back the system investment? Are the specifications actually met, e.g. for the solar modules? We advise on system planning, write expert reports analysing the yield, carry out measurements for authorisation procedures and develop concepts for system monitoring in operation or the visualisation of operating data, e.g. in the Internet.



On the medium term, solar thermal power stations such as the successful systems with parabolic troughs can make an important contribution to regenerative generation of electricity. We develop materials, optimise the controls and carry out system simulations.

Optically concentrating photovoltaic systems can also reduce the price of solar electricity. For instance, we are developing an inexpensive procedure to manufacture Fresnel lenses in concentrator modules and have constructed complete modules for use in the field.

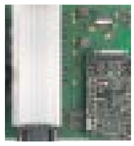
Photovoltaic systems and other decentralised electricity generators such as heat/electricity cogeneration plants interact with the electricity grids into which they are integrated. The liberalisation of the electricity markets and the entry of CO_2-saving energy technology to the market means that these decentralised generators are increasingly penetrating the low-voltage grids. Questions concerning operating safety, supply reliability and voltage quality will become a growing priority. Thus, utilities are already exploring these questions today. At the end of the process, the structure of distribution grids will have changed significantly: Many small generators will interact and be actively controlled. This results in completely new demands on controls, operation management, communication and data management in electricity grids. We prepare concepts, electronics, planning instruments and management tools to meet these questions of distributed generation.

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

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

The facilities we use for this work include:

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



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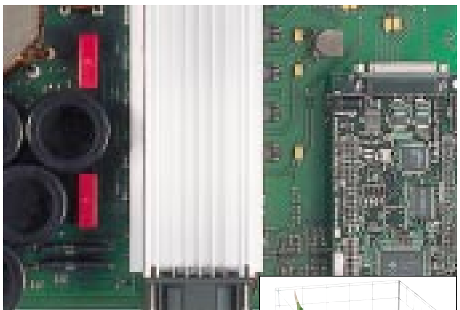
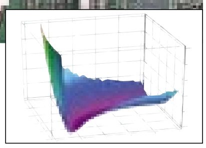
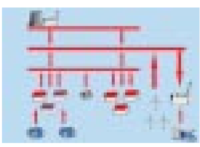


Platform for inverters of the next generation, developed at Fraunhofer ISE. It uses the HERIC® circuit topology (article on p. 64).

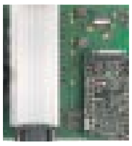


Simulation of a photovoltaic system with MPP tracking. The additional losses of a static MPP tracker compared to a dynamic MPP tracker are shown (article on p. 65).

Computer visualisation of a Fresnel collector array for solar thermal power stations (article on p. 67).



Dispersed structure of an electricity grid of the future (article on p. 62).



Electricity Grids with a Large Input from Fluctuating Renewable Energy Sources

The integration of many dispersed electricity generators in low–voltage grids demands new technical concepts and optimisation tools on the medium term. Even today in some weak grids, complicated extension of the grid can be avoided by the less expensive option of integrating new electricity generators or storage units. We develop concepts and tools for the monitoring, improved planning and operation management of such grids.

Thomas Erge, Martin Jantsch, Hermann Laukamp, **Tim Meyer**, Dirk Uwe Sauer, Heribert Schmidt

The global liberalisation of energy markets, and the deliberate expansion of renewable energy use and heat/electricity co-generation, are already leading today to noticeable changes in the composition of the power generation mixture and grid structures. Overcapacity is being reduced and the potential for cost minimisation is exploited better. However, a danger of these savings is that less care is taken to ensure high-quality supply to the final customer. Simultaneously, private generation systems are becoming increasingly economical.

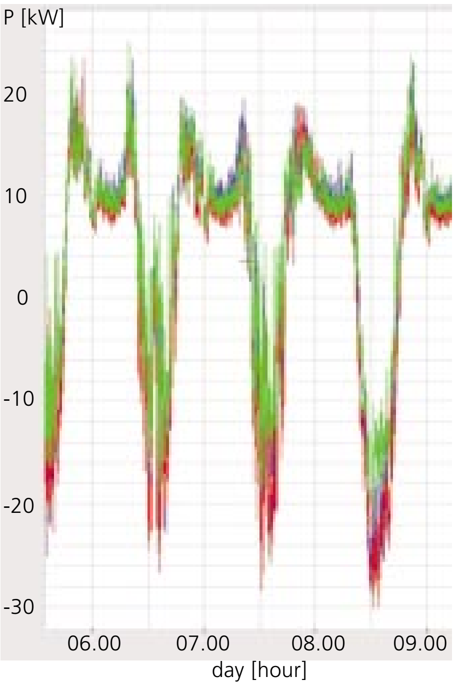


Fig. 1: Variation in the power drawn from or supplied to the grid for the three phases of the triple-phase grid (red: phase 1, blue: phase 2, green: phase 3) at the transformer of a solar settlement. Existing grids are often not designed for reverse power flows.

Against this background and the new legal boundary conditions, new markets are opening to private companies for building and operating small, decentralised power stations. At the same time, integration into buildings and building services technology on the one hand, and into electricity grids on the other, is gaining in importance. In parallel, large wind parks and heat/electricity co-generation plants are placing new demands on the operation management of transport and distribution grids.

In developing concepts and technology to integrate dispersed generators into electricity grids, we draw on knowledge gained in the "Edison" project. The concept of "dispersed power stations" was implemented with a series of decentralised heat/electricity co-generation plants and battery storage banks in the power range of up to several hundred kW.

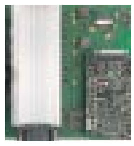
Now we are taking the next step. We are concentrating on technological and socio-economic questions of integrating dispersed generators and storage units into low-voltage grids, and options to influence distributed loads. The structure of low-voltage grids has much in common with hybrid systems for village power supplies, so that we can build on our experience in this area.

For example, we develop monitoring concepts for large pilot installations. Data is acquired on voltages, power flows and grid quality parameters such as harmonics, flicker, etc., and is stored in a common data bank. The communications and data structures are designed such that many components and measurement sites can be included. Using remote control, the data bank computers can be controlled or reconfigured, and data can be transferred. In our scientific analysis, we then investigate the interaction between the dispersed generators and the grid into which they are integrated:

- effects on the grid of large numbers of dispersed generators
- possible effects of specific grid operating states on the dispersed generators
- identification of operating parameters for active grid management
- assessment and evaluation of the effect on the grid achieved by active management

In this way, we gain fundamental understanding of processes in low-voltage grids, which have hardly been systematically investigated to date.

Existing low-voltage grids that are being operated at the limits of their capacity can be strengthened by selective integration of photovoltaic systems, heat/electricity co-generation plants or battery storage units. This applies particularly for weak grids or island grids in regions with little infrastructure, e.g. in developing and threshold countries. In this way, at least some of the investment in operating equipment, such as cabling or transformers, can be postponed or even avoided. We are extending our design tool, TALCO (Technical and



Least Cost Optimisation), to provide support for making relevant decisions in the planning phase. TALCO includes models of all components, based on their technical and economic parameters such as power, control dynamics, thermal limitations for co-generation plants, investment and capital costs, operating and maintenance expense, and operation management strategies. We optimise lifetime costs, so refer to long periods such as 20 years.

We are developing a management system to optimise the operation of low-voltage grids or island grids with respect to economic and energy-relevant criteria. It communicates with the higher-level control centre, the dispersed generators and storage units in the grid and with controllable loads, if present. It constantly receives information about prices and technical restrictions. These can include, for example, the state of charge of the thermal storage unit for co-generation plants, which restricts operation of the plant at times. Loads and generators can then be specifically controlled, based on such information and integrated models to predict the expected load profiles.

Actions controlling the operation of private generation systems are of course only possible if the operator of the management system (e.g. the grid operator) and the system owners have made corresponding contracts or if the grid operators draw more strongly on the operation of their own dispersed generators. The application potential and optimisation goals vary from country to country depending on the legal boundary conditions.

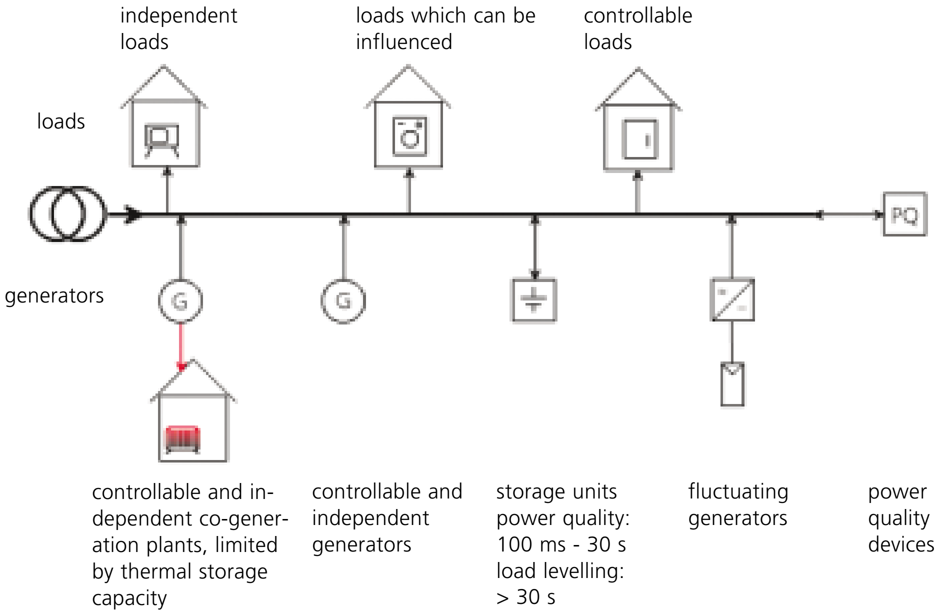


Fig. 2: Categories of dispersed generators, which must be taken into account in active grid management. Independent loads include e.g. electronic consumer appliances for entertainment such as television. The operating times for washing machines and similar appliances can e.g. be influenced by variable tariffs. Loads with a high thermal inertia (e.g. refrigerators) can be actively controlled. Their periods of operation can be shifted within certain limits. Power quality devices specifically improve the quality of the voltage.

The management system will be introduced in different pilot installations. The largest is the solar settlement in Querdeich, which is currently being constructed by the MVV utility. Many photovoltaic systems, a heat/electricity co-generation plant and possibly a battery bank will be installed in Querdeich. The aim is to optimise operation technically and economically, while maintaining highest standards of supply quality.

This work is being done within the European "DISPOWER" project (Distributed Generation with High Penetration of Renewable Energy Sources). In it, we are co-operating with 36 partners to develop concepts and technology for the integration of distributed generators into electricity grids. The Institute for Solar Energy Supply Technology (ISET) in Kassel and Fraunhofer ISE are co-ordinating the project.

Fig. 3: Plan of the solar settlement in Querdeich, where the low-voltage grid is to be actively managed within the DISPOWER project.

Development of Electronics

Power-electronics circuits represent the decisive link between electricity generators, storage units and consumers. On commission to industry, we are developing customised electronic circuits and controls for photovoltaics, fuel cells and batteries.

Jochen Benz, **Bruno Burger**, Jürgen Ketterer, Heribert Schmidt, Christoph Siedle

In industrial projects, we develop highly efficient DC/DC converters and inverters in the power range from a few milliwatts to several kilowatts. The work ranges from circuit design through layout to analog or digital controls. In simulation, we apply the newest programs and methods to simulate circuits and controls. Finite element programs are available to simulate inductive components and the thermal behaviour of individual component groups.

We develop the hardware to meet our clients' specifications: For instance, our development goals for device-integrated fuel cells are high power density or an appropriate geometrical configuration. High efficiency and low costs are always primary objectives. Our software developments range from rapid, stable controls for grid and stand-alone inverters, through MPP trackers, to controls for specific input and output characteristics of stationary fuel cells.

We develop complete devices or just individual components such as power components or controller structures, including the implementation in DSP's and microcontrollers. Last year, we made many such developments for industry, as the following examples show.

Inverter

Photovoltaic modules or fuel cells supply DC electricity, which cannot be used directly by conventional electric appliances. Inverters convert this DC electricity into AC electricity. Grid-connected inverters feed this AC electricity into the public electricity grid. Stand-alone inverters supply appliances in remote areas without a grid connection.

The major goals in the development of new grid inverters are cost optimisation, weight reduction and efficiency improvement.

In order to reach these goals, last year we developed a new inverter topology and filed a patent claim for it. The brand name, HERIC® (Highly Efficient & Reliable Inverter Concept), reflects the excellent properties of the new topology. At present, HERIC® is being integrated into an existing series of inverters. Measurements on prototypes have resulted in efficiency values of up to 97 %.

Fuel cells in grids

Increasing numbers of fuel cells are being tested and applied in grids. They can be controlled e.g. to generate electricity when the local demand is greatest. The local demand peaks can be minimised so that the maximum power consumption from the grid is reduced.
We develop controls to integrate fuel cells into grids. Our highly efficient DC/DC converters act as a link between the fuel cells and the grid-connected inverters. The developed electronic components include many functions such as:

- process control
- highly efficient DC/DC converters
- highly efficient inverters
- power control
- hydrogen pressure control
- oxygen or ventilator control
- impedance control and
- humidity control.

At present, in addition to developing new converter circuits, we are concentrating our research activities on humidity control for fuel cells, which is very important to ensure their stable operation (see on p. 57).

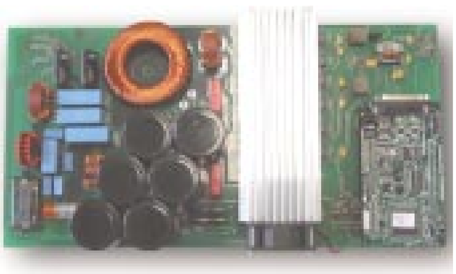


Fig. 1: Platform for inverters of the next generation, developed at Fraunhofer ISE. It uses the HERIC® topology.

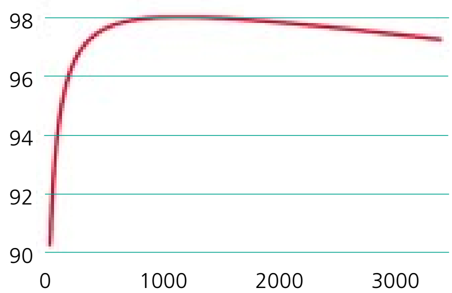
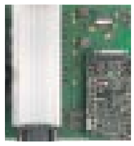


Fig. 2: Percentage efficiency of an inverter with the HERIC® topology as a function of the output power in W.



Battery periphery

Energy storage plays an essential role in uninterruptible power supplies, but also represents one of the weak points. Two aspects are important for a long lifetime: careful selection of appropriate storage technology for the specific requirements and good operation management. We develop automatic equalisation systems to ensure that all battery cells or blocks within a series connection are operated within allowable limits. These CHarge EQualizers prevent overcharging or deep discharge of individual cells. They have been tested in many pilot systems and have proven themselves excellently. Figure 3 shows their application in an uninterruptible power supply for the Stuttgart tram network.

We prepare an individual solution for each application (photovoltaic and uninterruptible power supplies, electric vehicles, grid backup, etc.) and each storage system (lead-acid, Li ion, double-layer capacitors, etc.).

Fig. 3: Uninterruptible power supply (UPS) at the Ruit tram stop in Stuttgart.

MPP tracking

The output power of a solar generator depends on the voltage at which it is operated. The output power is greatest at the so-called maximum power point (MPP). However, the associated voltage V_{MPP} is not constant, but depends on the solar radiation, the temperature and internal parameters of the solar cell. An MPP-tracking algorithm which we developed determines the MPP of a solar generator based solely on simply measured values such as the voltage and current of the generator. It is thus suited for crystalline, amorphous and thin-film solar cells. The MPP tracking algorithm is applied in grid-connected inverters and charge controllers.

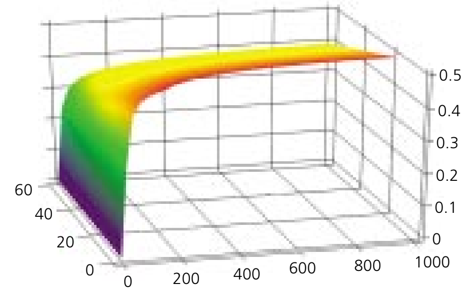


Fig. 4: Voltage of a crystalline silicon solar cell at the maximum power point, plotted against the solar irradiance in Wm^{-2} and the temperature in °C.

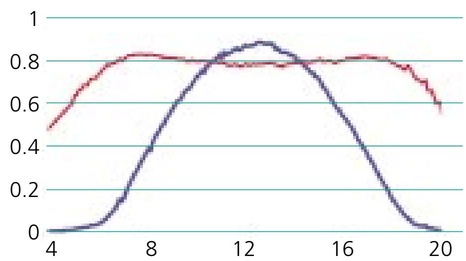


Fig. 5: Output power of a solar generator (blue) and ratio of the MPP voltage to the open-circuit voltage (red) versus the time of day on a sunny day.

Modelling and simulation

To design controllers for inverters or DC/DC converters optimally, we set up control-technology models of the power electronics. The pulse-width modulated (PWM) circuit is converted to a linear model with "state space averaging". Bode diagrams can then be calculated for this linear model, and the controllers dimensioned. The computing time for simulating the circuits is significantly reduced by use of the model.

We develop controls mainly for switch-mode circuits. Major areas include:

- model development
- Laplace transformation
- Z transformation
- cascade controls
- state controls
- analog controls and
- digital controls in microcontrollers and DSP's.

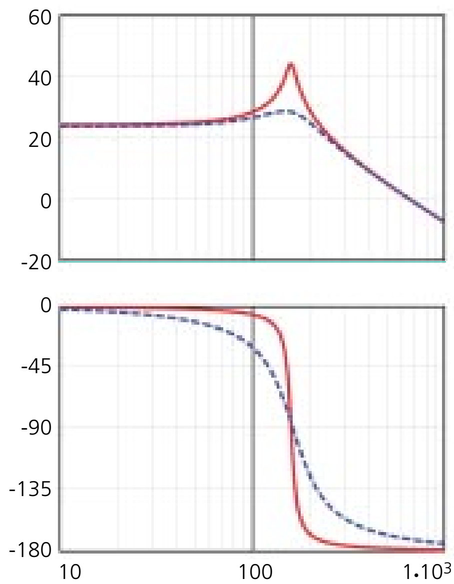
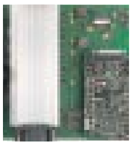


Fig. 6: Gain characteristics in dB and phase characteristics in degrees versus the frequency in Hz for a power-electronic converter under open-circuit conditions (red) and with a load (blue).



Malaysia: Grid-Connected Photovoltaics in South-East Asia

Most of the photovoltaic systems that have been installed in Malaysia to date are stand-alone systems. Together with local partners, we are using a house prototype to test and demonstrate various components and system concepts for grid-connected, roof-integrated photovoltaic systems on typical houses.

Thomas Erge, Klaus Kiefer, Frank Neuberger, Eberhard Rössler*

* free-lance

Photovoltaics can make an important contribution to the energy mix in the South-East Asian country of Malaysia. Extensive efforts have already been made in this direction with stand-alone systems, whereas only a few grid-connected systems have been constructed for test purposes over the last few years. If grid-connected photovoltaics is to make a breakthrough in Malaysia, not only must appropriate economic boundary conditions be created, but many technical issues must also be addressed.

In close co-operation with NLCC Architects Malaysia, we have developed and built a "solar house prototype" (figures 1 and 2). It demonstrates different types of technology to integrate grid-connected photovoltaic systems into typical houses. Because very different components and system concepts have been used at one site, the systems can be compared directly with each other. At the same time, the solar house is demonstrating how technical requirements for photovoltaics can be harmonised with architectural criteria. The total installed power of about 4 kW_p is supplied by standard monocrystalline silicon modules, thin-film modules and photovoltaic roofing tiles.

In addition, a photovoltaic test stand has been built, where modules can easily be mounted and dismounted. It is intended for testing and training purposes. The various systems feed via inverters into the domestic circuit or the local low-voltage grid.

Fig. 1: View of the "solar house prototype". Standard silicon modules are located on the upper roof, silicon thin-film modules are mounted on the middle roof and the lower roof is covered with photovoltaic polycrystalline roofing tiles.

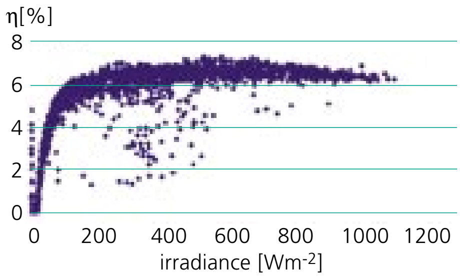


Fig. 3: Dependence of the generator efficiency on the solar radiation for the system with photovoltaic roofing tiles. Points documenting low efficiency between 200 and 400 Wm^{-2} indicate that there is partial shading.

Fig. 2: View into the plant room with switchboxes and inverters. The switchboxes contain data loggers, all power meters and some of the inverters.

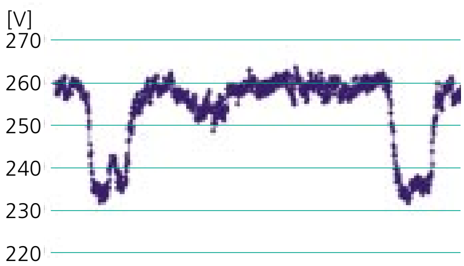
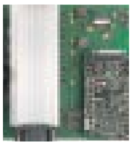


Fig. 4: Fluctuations in the AC grid voltage at the connection point, caused by load variation in the relevant low-voltage grid segment. A period of four days including a weekend is shown.

Parameters characterising the individual systems and the ambient conditions are recorded in a comprehensive measurement programme (example of results in fig. 3). We use it to continuously monitor and analyse operation, to gain reliable information on optimal system concepts for grid-connected photovoltaics in Malaysia. At the same time, we are studying aspects of the integration and mutual influences of the electricity grid and the photovoltaic system (fig. 4).

Initial analysis shows that the systems are operating reliably and efficiently. However, unexpectedly large fluctuations in the local grid voltage (fig. 4) cause the inverter in one system to switch off at times.

The Ministry of Science, Technology and the Environment of Malaysia financed the project.



Solar Thermal Generation of Electricity

Solar thermal power stations can make an important contribution in future to electricity generated from renewable energy sources. We develop materials and optimise controls to reduce the electricity generation costs, and carry out system simulation on solar power stations.

Wolfgang Graf, Andreas Häberle*, Michael Köhl,
Hansjörg Lerchenmüller,
Max Mertins, Christof Wittwer

Solar thermal power stations generate electricity indirectly by first converting solar radiation to heat: Direct solar radiation is concentrated optically onto an absorber. Water is evaporated at the resulting high temperatures. The steam is used in conventional steam turbines to generate electricity.

Already today in California, nine parabolic-trough power stations with a total installed capacity of 354 MW_p are successfully generating solar electricity economically on a utility scale. A legislative initiative in Spain stipulating payment of 0.16 €/kWh for solar thermal power generation has given it new impetus. Many power station projects are currently being planned in Spain and other countries with abundant solar resources. With projected electricity generation costs, based on today's technology, of 0.10 to 0.16 €/kWh depending on the site, there is great potential for cost-effective savings in CO_2 emission on a large scale. It is anticipated that the electricity generation costs can still be reduced significantly by increasing the efficiency and reducing the investment costs. We are working on a number of relevant topics, drawing on long experience in optics, materials research, thermal flux calculation and system simulation and controls.

For example, the durability of selective solar absorber coatings plays a central role. Degradation of the coatings, which are subjected to very high temperatures, would result in high repair costs or lower solar yields. We offer investigations on durability and lifetime predictions for selective absorber coatings and support industrial clients in the development of such coatings.

The reflectors are another key component in concentrating solar power stations. High solar reflectance, good durability and low costs are decisive criteria. We also offer durability testing for solar reflectors and the development of new concepts for highly reflective mirrors.

Optical Fresnel collectors, in which horizontally mounted mirror facets track the sun, represent an interesting alternative to the parabolic trough. The simple construction of the Fresnel collector, the use of inexpensive materials and the possibility of using the space under the collector offer interesting perspectives for further cost reduction.

The ColSim simulation environment that we have developed allows solar array yields to be calculated for given radiation data with high temporal resolution. Using this, we can optimise complete system concepts. The results flow into innovative control concepts, which can be implemented with “distributed intelligence“ in embedded systems. The aim is to optimise the interaction between all control parameters and thus to maximise the solar output.

With financial support from the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety BMU, we are cooperating with the utility, E.ON Energie AG and the German Centre for Air and Space Travel (DLR) to prepare studies on power stations. Their subject is the systematic investigation and comparison of the various possibilities to couple solar-produced steam into conventional power station technology.

* PSE GmbH Forschung Entwicklung Marketing, Freiburg

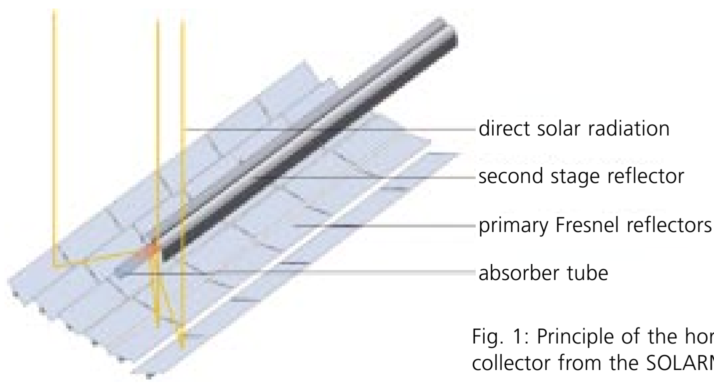


Fig. 1: Principle of the horizontal Fresnel collector from the SOLARMUNDO company.

Photovoltaics - Safety Aspects

The growing numbers of photovoltaic systems raise new questions for grid operators concerning quality and safety. We have the tools, simulations, field experiments and laboratories, to give answers. For instance, we have developed a methodology to investigate the risk of "islanding" among grid-connected photovoltaic systems.

Thomas Erge, **Hermann Laukamp**, Edo Wiemken

"Islanding" of sub-grids

"Islanding" is understood to mean the uncontrolled presence of a voltage in a sub-grid, although there has been a power cut in the main grid. Islanding is caused by a flow of locally generated electricity into the grid.

Protection against islanding is an acute problem for inverter manufacturers: Inverters must meet different safety criteria, depending on the country where they are used.

The load and generation conditions that can lead to unwanted islanding are extremely improbable. Recent measurements by Dutch scientists in the local grid of the city of Arnhem, the Netherlands, showed that the highest value for this probability is about 10^{-4}. This was based on the assumption of a penetration of 1 kW_p per household. We then developed a methodology to calculate the islanding risk simply from measured data (fig. 1).

The risk of a fatal electricity accident due to islanding is less than 10^{-10}. This is orders of magnitude less than accepted risks of civilisation such as driving a car.

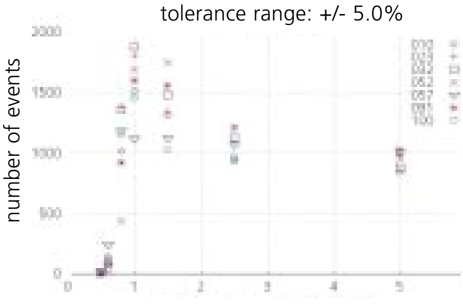


Fig. 1: Using data from the 1000 Roofs Programme, we investigated how often the electricity consumption and the photovoltaically generated power of a solar settlement were equal over the course of one year (an "event" in the graph). This investigation was carried out for seven locations and six different photovoltaic system dimensions per house. Below a threshold of about 500 W_p per household, the load is always larger than the generated power. Above 1 kW_p per household, the frequency for equal load and generation declines again.

An average connection density of about 400 W_p per household must be reached for islanding to occur at all. At present, the connection density in Germany is about 6 W_p per household.

The work was done as part of the research programme on "Photovoltaic Power Systems" of the International Energy Agency (IEA), Task 5: "Grid Connection of Many Dispersed Individual Generation Systems" (www.iea-pvps.org).

In Task 5, experts from twelve countries studied topics including connection and construction regulations, the risk of islanding and the effects of a high density of dispersed photovoltaic systems on grid operation.

With this know-how, we can give comprehensive advice to grid and system operators on all questions

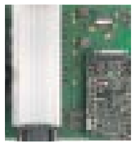
Fig. 2: In the "Solarsiedlung Schlierberg", about 130 inverters feed electricity from about 330 kW_p of installed photovoltaics into the low-voltage grid.
Photo: Andreas Weindel

concerning the grid connection of photovoltaics and other distributed generation equipment. National boundaries can be overcome with the help of our international contacts.

Thus, we can support inverter manufacturers who want to adapt their export products to comply with the newest regulations and who have the following questions, for example:

- What are the normal limits for the grid voltage?
- How quickly must an inverter switch off if the grid voltage deviates from the allowed range?
- Which measures are specified to protect against islanding?
- Are there special requirements for inverters without transformers?
- How much room is there for interpretation of certain specifications?

Several inverter manufacturers have already taken advantage of our consultancy offer in their new developments.



Satellite Data for Quality Control and Operation Management

Meteorological satellite data also allow the solar radiation on the earth's surface to be determined economically at all locations. We use these data to estimate yields, check functionality and soon to manage the operation of solar systems.

Christian Reise, Edo Wiemken

Solar radiation maps can be generated with high temporal and spatial resolution from the image data of the geostationary METEOSAT satellites. Long-term, archived data sets are already being used to estimate the potential of solar systems; rapidly available current data allow economic monitoring of dispersed solar systems.

One example of operational use at Fraunhofer ISE follows:

Quality control for small photovoltaic systems

Grid-connected photovoltaic systems are contributing to the energy supply in an increasing number of residential buildings. With the current rates for electricity fed into the grid, it is worth controlling the quality and yield continuously, both from a financial and an energy viewpoint. Since the middle of 2001, we have been controlling the yield from all newly installed Shell photovoltaic systems on commission to Shell Solar, with the aid of satellite data – the SAT WATCH project. After installation, Shell passes on the technical data of each system to Fraunhofer ISE. In co-operation with the University of Oldenburg, we determine the individual values for the solar radiation at each location from the METEOSAT images. On this basis, we can predict the yield, and send it directly to the system operators by email, fax or postcard. They can then compare the predicted yield with the reading on their meter. If larger deviations are found, the local Shell partner can be contacted.

The current extension of the procedure includes additional use of inexpensive data acquisition on site, which is in contact with the analysis server via Internet. In this way, the system monitoring would be further automated. The procedure can also be applied to other renewable sources of energy, and thus supports the safe integration of renewable energy sources into existing supply grids.

Outlook: energy-weather predictions

Extension of the satellite data analysis is planned to allow prediction of the solar radiation (as well as other energy-relevant quantities) for periods up to two days. There are many ways of using such "energy-weather predictions", e.g. in building management. Building concepts with high thermal inertia and small specific heating and cooling capacity require predictive controls. Co-operation with manufacturers of building management technology is sought for integration of the meteorological information into this technology.

Fig. 1: METEOSAT 7 is the currently active, European geostationary meteorological satellite. Solar radiation maps with a resolution of about 5 x 5 km^2 in Central Europe are generated from its image data.

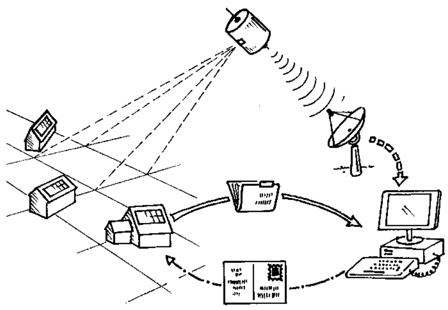
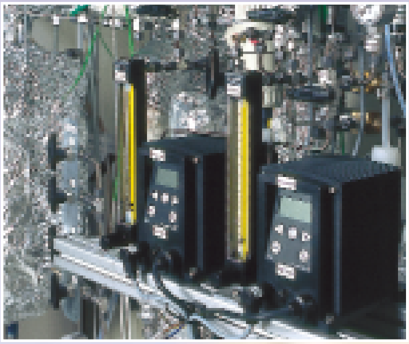
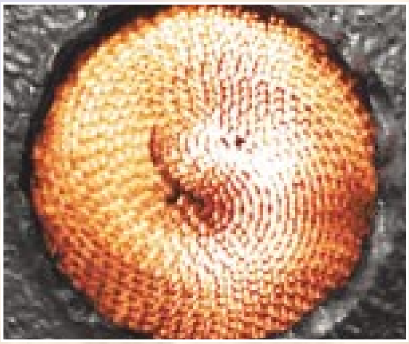
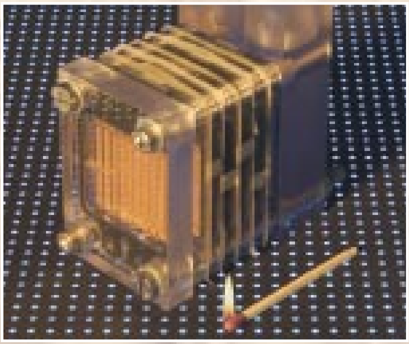


Fig. 2: Operating principle of SAT WATCH: The basic specifications of each monitored system are recorded once. The expected yields are calculated monthly from the continuously updated satellite images and the individual system data, and sent to the system operators.

Hydrogen Technology







Hydrogen - Fuel of the Future

Hydrogen releases usable energy when it reacts with oxygen. Thus, fuel cells convert hydrogen into electricity and heat. As hydrogen is not found in its pure form in nature, it must be obtained from its chemical compounds. That occurs when energy is applied – ideally renewable energy – e.g. in electrolysis with photovoltaic electricity or by reforming biogenic and fossil fuels.

Although hydrogen is not a source of energy, as a universal fuel it will be an important component in the low-emission energy economy of the future. By using hydrogen, fluctuating forms of renewable energy will be processed such that all desired energy services can be provided with the accustomed reliability. Scientists and technologists are working intensively on realising this vision.

The application potential of hydrogen is enormous: In building services technology, fuel cells can supply heat and electricity with a total efficiency value of up to 80 %. The hydrogen required is produced e.g. in the building by reforming natural gas. A “distributed power station” then consists of thousands of such fuel-cell co-generation plants. Mobile applications of fuel cells, combined with electric motors, serve as non-polluting engines for cars, trucks and buses. In addition, fuel cells in auxiliary power units (APU) provide electricity for aeroplane cabin services. Finally, miniature fuel cells are excellent alternatives or complements to primary and secondary batteries in electronic devices, due to the high energy density of the fuel storage units.

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

We produce reformers to convert liquid or gaseous fuels. To obtain hydrogen from water, we construct electrolysers up to 2 kW. In addition, we conduct research on the catalytic conversion of hydrogen to generate heat. The membrane fuel cell is our favoured energy converter in the low power range, being efficient, environmentally friendly, quiet and requiring little maintenance. We also develop miniature fuel cells as power supplies for portable electric appliances. They complement our activities on device-integrated solar modules and thermophotovoltaic systems.

In addition to developing components and hydrogen-conversion systems, we also work on their integration into higher-order systems. We design and implement the electric infrastructure, including power conditioning and safety technology. In this way, we create the basis for a commercially viable hydrogen economy with hydrogen service stations, fuel-cell co-generation plants producing heat and electricity, stand-alone power supplies for applications remote from the grid, and miniature systems as portable power supplies.

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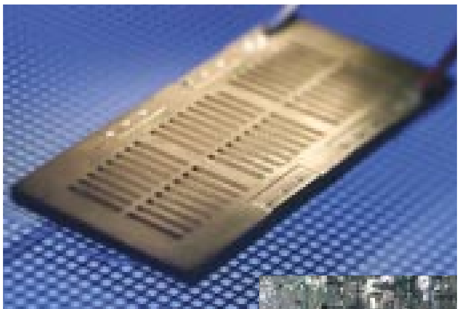
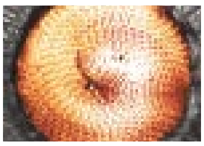
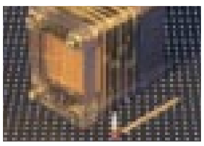


Planar, series-connected fuel cell constructed of printed circuit boards (article on p. 78).

Test stand for a kerosene reformer, detail (article on p. 75).



Catalyst honeycomb for gas-processing technology, enlarged (article on p. 76).



Miniature electrolyser for gaschromic windows.

Fuel Cells Operating with Reformate Gas – Optimisation of Operation Management and Components

On the medium term, hydrogen-rich reformate gas will be the fuel supply for polymer-electrolyte membrane (PEM) fuel cells in a decentralised power supply. We investigate how the composition of the reformate gas affects PEM fuel cells, and optimise their components and operation modes.

Peter Gesikiewicz, Tom Smolinka, **Ursula Wittstadt**, Mario Zedda

The product of reforming hydrocarbons with integrated gas purification is a hydrogen-rich gas with varying proportions of carbon dioxide and carbon monoxide, and also nitrogen, depending on the reforming process. Compared to the use of pure hydrogen, supplying PEM fuel cells with this reformate gas leads to considerable reduction in performance. Whereas nitrogen, as an inert gas, has a purely diluting effect on the anode side, even the smallest traces of carbon monoxide poison the catalyst. The effect of carbon dioxide is contentious. It is presumed that CO is also created from CO_2 in the cell via the inverse shift reaction.

In order to keep the gas purification process as simple as possible and still retain the highest possible power output from the cell, we are systematically investigating the effect of individual components of the reformate gas on the fuel cell. To do this, we have set up a test stand for laboratory cells and fuel-cell stacks of up to 250 W_{el}. It can supply reformate gas as fuel with any composition and well-defined humidity even at high temperatures (up to 130 °C). To characterise the cells, we can measure not only the voltage and temperature but also impedance spectra at different operating points.

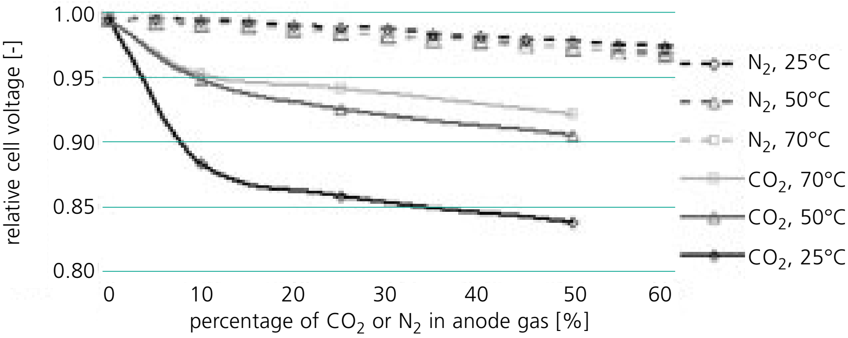


Fig. 1: Effect of CO_2 and N_2 on the cell voltage (with reference to V_0 for operation with pure H_2), for a current density of 400 mA cm^{-2} and temperatures of 25, 50 and 70 °C.

Figure 1 shows the reduction in cell performance at different temperatures as an example. When nitrogen is added on the anode side, the cell voltage for a constant current density falls from 100 % for operation in pure hydrogen to values around 97 %. Adding carbon dioxide has a much larger negative effect. The voltage sinks to values of less than 85 %.

We use the insight gained from these measurements to develop improved components for fuel cells or to optimise their mode of operation. In addition, we support our clients in screening commercially available membrane electrode assemblies and gas diffusion coatings, to select the most appropriate ones for their purposes. We are also involved in characterising new membrane materials based on polyarylene for use at high temperatures.

Further development of flowfield structures and the sealing of fuel-cell stacks are topics that we are currently addressing very intensively. Figure 2 shows a detailed view of a bipolar plate for a stack with an active area of 100 cm^2 which is suitable for use with reformate gas.

The work is being carried out within a joint project together with the Centre for Solar Energy and Hydrogen Research (ZSW) in Ulm, and is financially supported by the Ministry for Economics of Baden-Württemberg.

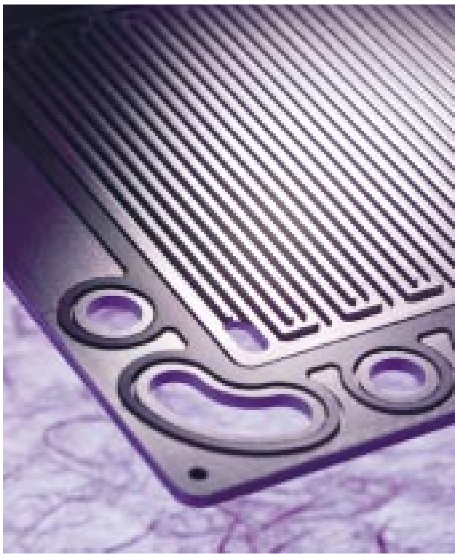


Fig. 2: Detail of a bipolar plate.

Reformers Take Off – Efficient Power Supplies in Aircraft

In large passenger planes of the future, the aim is to reduce the energy demand for auxiliary power units, despite increasing expectations on in-flight comfort. For this purpose, we are developing a compact kerosene reformer, which efficiently supplies heat and electricity when combined with a solid–oxide fuel cell (SOFC).

Peter Hübner, Bettina Lenz

Auxiliary power units for the cabin services in large passenger planes generally operate with a very low efficiency value, i.e. less than 10 %. If they are to be improved, some completely new concepts need to be tested. The goal of the project on "Power Optimised Aircraft (POA)" is to save energy in large passenger planes of the future. In particular, the energy which is not required for propulsion is to be saved, by up to 25 %. This goal should be reached by saving weight and intelligently combining improved individual components. Together with our project partners, we are initially optimising the individual components and their interaction with the help of dynamic simulation.

We are developing a kerosene reformer as a component for future auxiliary power units of aeroplanes. The reformer processes the fuel for a high-temperature fuel cell, which supplies 50 kW electric power. The waste heat can be used e.g. to keep the wings free of ice.

Reforming kerosene is particularly challenging, as according to the standards, kerosene can contain a high concentration of sulphur (e.g. maximally 0.3 wt % in jet fuel A-1 according to ASTM D1655). The sulphur can be present in different compounds, e.g. mercaptan, sulphide or thiophene compounds. As sulphur acts as a catalyst poison for the fuel cell, and also affects the conversion of kerosene in the reforming process, we are developing a compact sulphur-removal unit. Kerosene is autothermally reformed to supply hydrogen for a 5 kW fuel cell in our test stand (fig. 1).

Experiments on the autothermal reforming of individual constituents that are found in kerosene show that the conversion can proceed with an efficiency value of about 80 % (Table 1). In combination with a high-temperature fuel cell, electricity can be generated with an efficiency value of about 40 %.

This work is supported as part of the EU project on "Power Optimised Aircraft (POA)".

Fig. 1: Test stand for the POA kerosene reformer. The photo shows the educt inlets and the reactor.

compound	efficiency value [%]	
	experimental	calculated
C_7H_8 (toluene)	83	88
C_8H_{16}	79	91
$C_{13}H_{26}$	76	90

Table 1: Reforming efficiency values for autothermal reforming of selected components of kerosene.

Selection of Catalysts for Gas-Processing Technology

Hydrogen is needed to operate fuel cells. At present, the most economic method to obtain it is by reforming carbonaceous fuels. Depending on the type of fuel cell, the hydrogen-rich gas must then be purified further. These are the central tasks of gas-processing technology. We are investigating which catalysts are most suitable.

Peter Hübner, Alexander Susdorf, Alexander Di Bella, Britta Hund, Thomas Rampe

Efficient and economic production of hydrogen for fuel cells is decisive for the further development of fuel-cell technology. We are screening catalysts to ensure that hydrogen production and gas purification is as simple and efficient as possible.

To find the optimal catalyst for our clients, our measurements must be both highly accurate and allow flexible variation of parameters. We have constructed several test stands to achieve this – one of them can be seen in the photo of fig. 4. Using this test stand, we can investigate each individual reaction of the gas-processing technology, as it is equipped with gas flow controllers and different types of reactors that can be substituted as needed. The composition of the product and educt gases is measured by gas chromatography (equipment at the right of fig. 4).

The choice of catalytic steps in producing hydrogen from carbonaceous fuels is determined by the fuel on the one hand and the type of fuel cell on the other. The hydrogen generation steps are shown in fig. 1 for two high-temperature fuel cells, molten-carbonate fuel cells (MCFC) and solid-oxide fuel cells (SOFC), and in fig. 2 for proton-exchange membrane fuel cells (PEMFC).

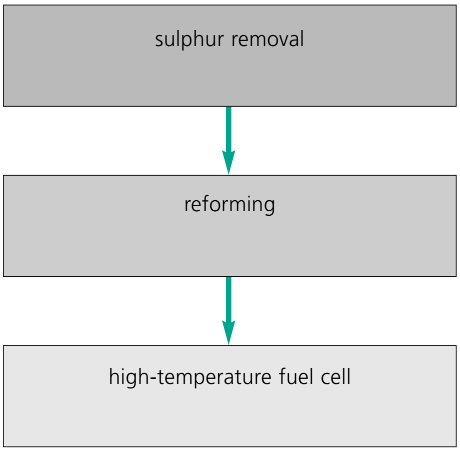


Fig. 1: Hydrogen production for high-temperature fuel cells, MCFC and SOFC.

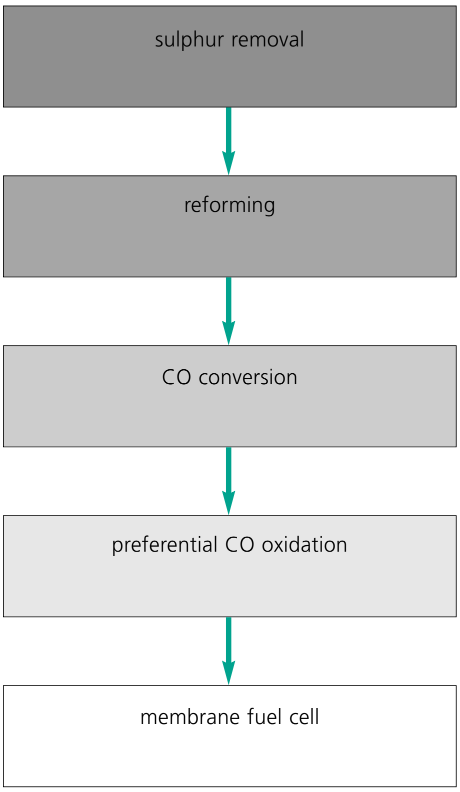


Fig. 2: Hydrogen production for membrane fuel cells, PEMFC.

The first step is purification, with the complexity depending on the fuel used. In general, a catalytic step to remove sulphur is sufficient.

For gaseous fuels, e.g. natural gas or camping gas, the sulphur can be removed in the gas phase. Most often, active charcoal is used, as it does not adsorb hydrogen and removes the most important sulphur compounds, including hydrogen sulphide, at room temperature.

It is more difficult to remove sulphur from liquid hydrocarbons such as petrol, kerosene or diesel. Either the fuel must first be evaporated, so that sulphur can again be removed in the gas phase, or special adsorbers must be used. At Fraunhofer ISE, we are investigating both procedures within the project on "Power Optimised Aircraft" (see the previous article).

Fundamentally different procedures such as steam reforming, partial oxidation or autothermal reforming can be applied for reforming. We are transferring these procedures, which are well established on a large scale, to small, compact units to produce hydrogen for fuel cells from 1 kW to 100 kW.

We use laboratory test stands for catalyst screening and further investigation of reaction kinetics as a basis for reactor design. On commission to clients, we investigate both loose catalysts in powder or pellet form and catalysts that are already mounted on honeycomb substrates, as shown in fig. 3.

If the hydrogen-rich gas mixture is used for membrane fuel cells, carbon monoxide must be removed after reforming (fig. 2), as CO is a catalyst poison for the electrodes of the fuel cell. Most of it is converted to hydrogen and CO_2 in a conversion step. After this reaction, the remaining concentration of CO in the reformate is typically 0.1 vol. % to 0.5 vol. %.

The procedure can be carried out in a single step or in two steps. The two-step procedure exploits the fact that the reaction speed at the high-temperature step (app. 320 °C to 400 °C) is so high that a compact reactor design can be used. However, the thermodynamic equilibrium of the conversion reaction is not shifted sufficiently to the product side to reach a CO concentration of 0.1 vol. % until the low-temperature step (at 180 °C to 240 °C) is run. More recent developments foresee only a single-step CO conversion step, which operates at medium temperatures (250 °C).
The CO concentration is then about 0.5 vol. %, representing a compromise between process simplification and processing efficiency.

In a CO fine purification step, the remaining CO concentration is reduced to 10 – 100 ppm. Various procedures can be applied, including pressure-swing adsorption, gas cleaning with metal membranes, methanisation or preferential CO oxidation. We favour the last procedure at Fraunhofer ISE. It preferentially oxidises the CO to CO_2 in the presence of oxygen or air with the aid of a catalyst. The hydrogen content of the reformate should be maintained as far as possible.

The advantages of preferential CO oxidation in comparison to pressure-swing adsorption are that it requires less room and that practically no pressure has to be applied. In comparison to methanisation, preferential oxidation needs more sophisticated control of the air input. However, the measures needed to ensure operating safety are more complex for selective methanisation.

After co-operating with our industrial partners to develop efficient catalysts based on noble metals for individual reaction steps and prove their functionality, the next investigations aim to reduce the catalyst costs by reducing the noble-metal content or replacing it with less expensive materials.

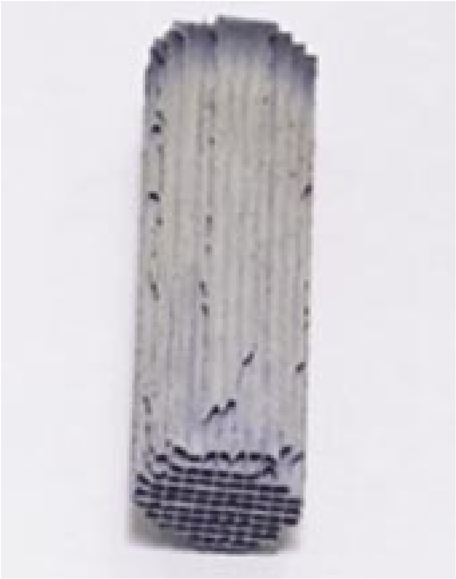


Fig. 3: Ceramic honeycomb to hold catalysts for screening tests for reforming liquid hydrocarbons.

Fig. 4: Test stand to characterise catalysts for gas-processing technology. The gas chromatography equipment to the right of the photo is used to measure the composition of product and educt gases.

Flat Miniature Fuel Cell

Flat fuel cells are particularly easy to integrate into appliances. Furthermore, they can be constructed in the same way as circuit boards, with the potential for cost-reducing mass production. The group working on micro-energy technology is developing this type of planar fuel cell, in which the casing consists of circuit boards. Air is to be supplied passively to it via an open cathode.

Christopher Hebling,
Andreas Schmitz, Marco Tranitz

Miniature fuel cells for the low power range make a new, more powerful generation of mobile applications feasible, such as notebooks and mobile phones. Hydrogen (in PEMFC with metal hydride storage units) or methanol (in DMFC) is used as the fuel. The equivalent energy densities are appreciably higher than for conventional rechargeable batteries. Miniature fuel cells are particularly interesting for applications that were previously impossible because the energy density of the rechargeable batteries was inadequate. We are developing reliable and attractively priced miniature fuel cells for these applications.

In addition to the usual stack design, we are concentrating particularly on miniature fuel cells with a planar configuration. This technology is excellently suited for integration into the housing of an appliance and gives the client considerable freedom in the product design. As the fuel cell can also function as the housing wall, optimal use is made of the required volume. The integration of a planar fuel cell into e.g. the back of a notebook screen or an organiser is also conceivable.

Our planar fuel cell will have a cathode which is open to the air. This means that the oxygen supply can be obtained completely passively from the air, without active components such as ventilators or pumps.

Planar fuel cells are constructed in the same way as printed circuit boards. The particular charm of this approach is that circuit board technology is a well-proven procedure for mass production. It will allow economic production of miniature fuel cells in large numbers.

Several fuel cells are connected in series to supply electricity for appliances. The circuit-board construction with multi-layer contacting is an ideal configuration for this. In addition, the electronic controls for the fuel cell and an electric consumer can be mounted on the circuit board of the fuel cell.

We have constructed a series connection of three individual fuel cells as an initial prototype. It supplies power of 1.2 W when operated with hydrogen at room temperature. In measurements over more than 1500 hours of operation, we have demonstrated that stable operation can be guaranteed over long periods even with the air side open.

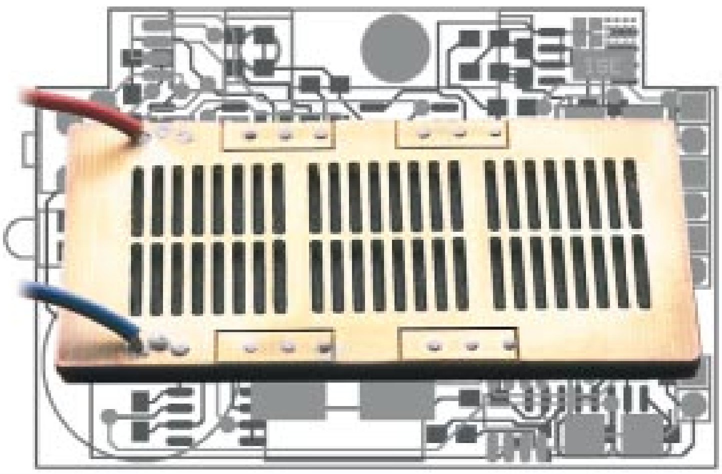


Fig. 1: Planar, series-connected fuel cell constructed of printed circuit boards. Its area is 40 mm x 75 mm. The cell is only 3 mm thick.

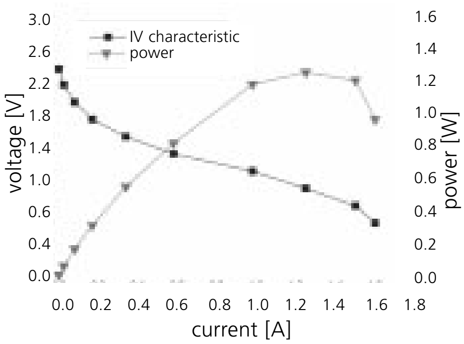


Fig. 2: Electric characteristic curve of the planar, series-connected fuel cell constructed of printed circuit boards (area 40 x 75 mm^2).

Control and Simulation of Fuel Cells

We develop control concepts for various applications, including portable fuel-cell systems, and provide the complete controls hardware for our clients. In addition, we use spatially resolved numerical simulations to support optimisation of the cells.

Bruno Burger, Peter Gemmar*, Alexander Hakenjos, Christopher Hebling, Karsten Kühn, Mario Ohlberger**, Andreas Schmitz, **Jürgen Schumacher**, Mario Zedda

The controls for portable fuel cells should guarantee stable operation, even when the load from the appliance changes. This includes thermal and water management. We use prototypes to develop control concepts to the marketable stage.

We have made detailed investigations of the dynamic operation of the fuel-cell stack developed by the "Fraunhofer Initiative on Miniature Fuel Cells". Arrays of characteristics for the fuel-cell stack were generated from the measurement data. We applied fuzzy logic to make empirical models for the water budget and analyse them. A stable response by the stack to changes in the consumer load was demonstrated.

We develop detailed fuel-cell models (fig. 1) to analyse the losses and optimise low-temperature fuel cells for portable applications. They calculate the mass, heat and charge transport with spatial resolution by applying the finite-element method. Figure 2 is a schematic diagram of a planar, portable PEM fuel cell. Pressure is applied to press the hydrogen through the diffusion layer on the left-hand side. Air diffuses to the open diffusion layer of the cathode side (right-hand side of fig. 2). A result from the time-dependent numerical simulation for this geometry is shown in fig. 3. The oxygen distribution in the diffusion layers of the cathode can be seen for two different cell voltages.

At present, we are working on a dynamic fuel-cell model to calculate the distribution of steam and liquid water in the cell. We will use it to understand the effect of the cell-stack construction on its operational dynamics and develop the control algorithms further. The models are validated by measurements at Fraunhofer ISE and then used to optimise our cells.

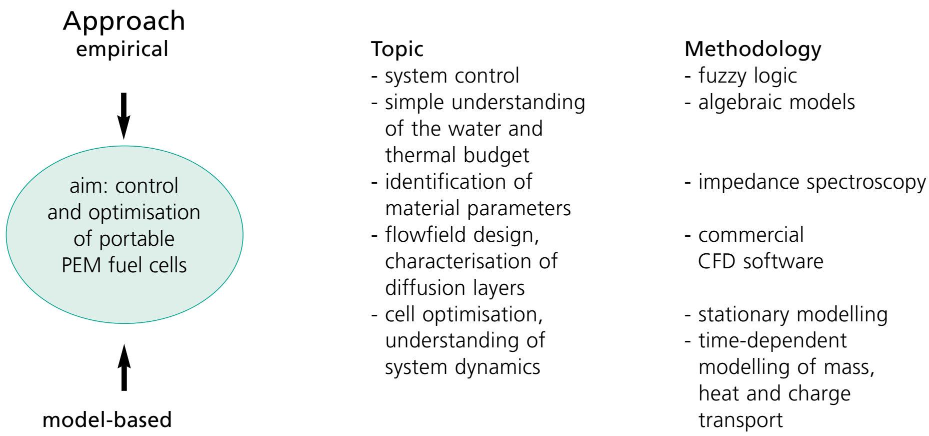


Fig. 1: Empirical models are applied to control portable PEM fuel cells. To optimise the cells, detailed models are being established, which calculate the mass and charge transport with high spatial and temporal resolution.

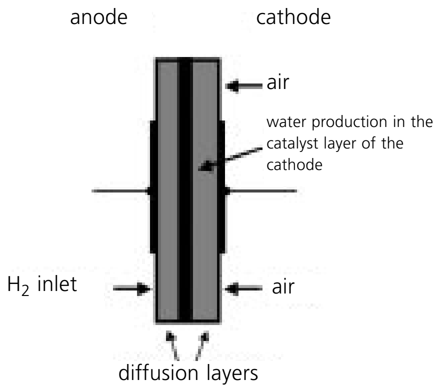


Fig. 2: Schematic diagram of a planar, portable PEM fuel cell.

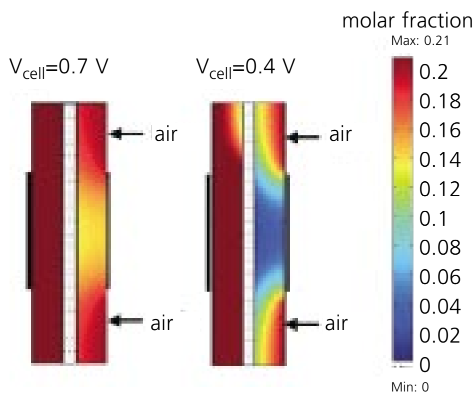
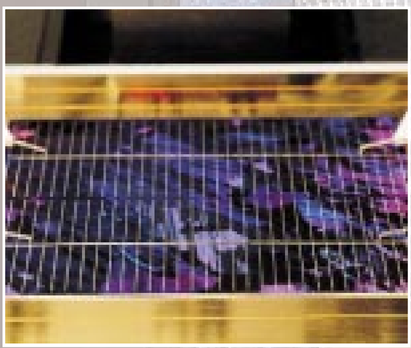
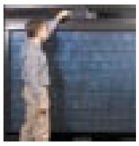


Fig. 3: Distribution of the oxygen molar fraction on the cathode side of a planar PEM fuel cell for different cell voltages.

* Institute for Innovative IT Applications, Fachhochschule Trier
** Institute for Applied Mathematics, Freiburg

Service Units



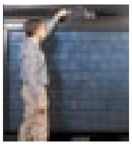


Quality Brings Success – We Help it on its Way

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

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

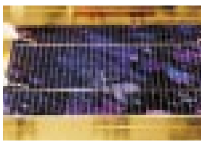
Our spectrum of services includes a calibration laboratory for solar cells and modules, a thermal/optical testing laboratory, a lighting measurement laboratory, daylighting measurement rooms, a facade testing facility, a test stand for solar desiccant cooling, a testing centre for thermal solar systems, a battery testing laboratory and an inverter characterisation stand.



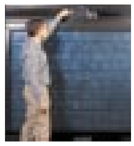
Precision measurement of a 3 m² solar module (article on p. 84).

Test stand for solar desiccant cooling systems (article on p. 86).

Indoor collector test stand with solar simulator (article on p. 85).



Precision measurement of a solar cell (article on p. 84).



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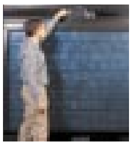


ISE CalLab – Calibration of Solar Cells and Modules

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

Britta Hund, Klaus Kiefer, Frank Neuberger, Wilhelm Warta, Jürgen Weber

The PV Calibration Laboratory at Fraunhofer ISE (ISE CalLab) is one of the internationally leading laboratories in this field. Round-robin comparisons between these laboratories and the Physikalisch-Technische Bundesanstalt (German Standards Institute) in Braunschweig ensure constant quality control. Internationally renowned manufacturers and also TÜV Rheinland, the German technical authorisation body, have their reference cells measured by ISE CalLab. Scientists come with their new developments from all over the world to Freiburg, for a measurement from ISE CalLab is recognised by scientific journals and at conferences.

Thanks to our long years of experience in PV measurement technology and the extensive research background at the Institute, we offer excellent service and security to our clients:

- accurate and reliable results, which are guaranteed by regular participation in round-robin tests with other internationally recognised measurement laboratories
- observation of international standards in all calibration steps and in the use of reference elements and measurement facilities
- rapid, non-bureaucratic processing
- confidentiality guaranteed

Cell calibration – references for research and industry

We undertake complete characterisation of solar cells and detectors with areas up to 30 x 30 cm^2:

- calibration of standard solar cells
- calibration of concentrator cells and tandem cells
- calibration of reference cells
- spectral response measurement
- determination of the temperature dependence of the current
- determination of the annual efficiency value of solar cells

Module calibration – an efficient quality control method

Increasing numbers of wholesalers and installation firms commission measurements of random samples from large orders of solar modules. The primary aim is to check compliance with the manufacturers' specifications. If the solar modules are already mounted on the roof and electrically connected, later characterisation is usually very complicated.

We characterise PV modules up to an area of 2 x 2 m^2:

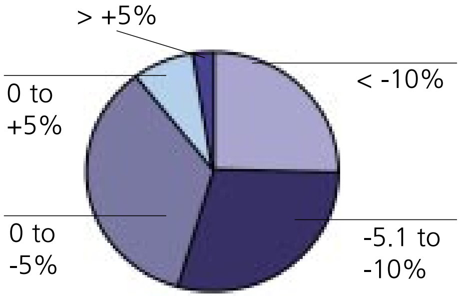
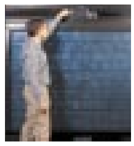


Fig. 1: 55 % of the modules measured deviated by more than the customary manufacturer's tolerance of ± 5 %.

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

Internet

For detailed information, simply consult our Internet site at www.callab.de. From there, you can also place measurement orders very simply by email.



Testing Centre for Thermal Solar Systems

We operate an outdoor test stand and are authorised as a testing centre by DIN CERTCO. We certify solar collectors and support our clients in developing solar thermal system components. For one year now, we have also made measurements using an indoor test stand with a solar simulator.

Carsten Hindenburg, Volker Kallwellis, Joachim Koschikowski, Flaviu Marton, Matthias Rommel, Arim Schäfer, Vitali Schmidt, Yan Schmitt, Thorsten Siems

Certification of solar collectors

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

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

Collector and system development

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

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

Indoor collector test stand with a solar simulator

For one year now, we have operated a solar-simulator test stand. We constructed it to simulate outdoor conditions as closely as possible. Its great advantage, particularly for collector development, is the high reproducibility of the measurement conditions.

The most important technical data are:

- test plane dimensions: 2.4 x 2 m^2. Other configurations of the test plane are possible (up to 3.5 x 3 m^2).
- irradiance: 1200 Wm^{-2} without the artificial sky, 1000 Wm^{-2} with the artificial sky
- homogeneity: ± 10 %
- lamp array tilt angle: 0 – 90 °
- angular divergence: so small, that we can determine the incidence angle modifier IAM even for collectors with integrated reflectors.

The construction of the test stand opens up the following options:

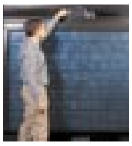
- measurement of the collector efficiency characteristic curve
- determination of the incidence angle modifier for collectors
- measurement of wall elements
- conduction of internal thermal shock tests
- determination of the collector capacity from measurements of the dynamic response to rapid changes in irradiance
- development work dedicated to improving collector constructions

Test stand for solar air collectors

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

Beyond that, we offer the following services:

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



Test Stand for Desiccant-Cooling Air-Conditioning Systems

For two years, we have been running a test stand for desiccant cooling systems. The integration of two solar collector arrays and a buffer storage tank means that the interaction with solar radiation can be investigated under realistic conditions. We support equipment manufacturers in developing components and systems and optimise different connection options according to energy-relevant criteria. Flexible hydraulics and the option of adding outdoor air-conditioning mean that we can investigate very diverse hydraulic configurations and optimise their energy consumption. The test stand makes rapid measurements feasible, which are independent of user behaviour.

Carsten Hindenburg,
Volker Kallwellis, Mario Motta,
Thorsten Siems

Fig. 1: The air-handling unit is the core of the test stand for desiccant cooling systems.

Component development

The modular construction of the test stand means that different components, such as sorption wheels, heat recovery rotors or humidifiers, can be exchanged independently of each other. Depending on the client's requirements, we can develop these components further or measure them in situ. We can also draw on results from our thermo-analytical laboratory, where sorption materials are characterised and optimised.

Optimisation of complete systems

Extensive measurement and controls technology also allows us to characterise and improve desiccant cooling systems as complete units. We can then optimise these with respect to their energy and water consumption. Simulation programs, some of which were developed at the Institute, shorten the measurement cycles and thus the total development time.

Development of standard controllers

The control performance of five different system concepts can be investigated simultaneously with the test stand due to the flexibility of the hydraulic circuit – ideal conditions for developing standard controllers for desiccant-cooling air-conditioning systems.

Field tests of solar collector arrays

Using the test stand, we can also measure complete arrays of solar hot-water collectors or solar air collectors with an area of up to 20 m^2. We offer the following services:

- measurement of the system efficiency value of solar collector arrays for defined loads. This enables realistic yield prediction for air-conditioning applications, domestic hot water or space-heating support.
- specific development of collectors for air conditioning.

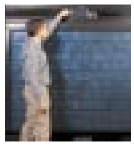
Customised design software

We develop design and simulation software on commission to clients. In doing so, we continually draw on our experience with the test stand and in demonstration projects. The programs can be used to calculate air-conditioning systems, both of the conventional type and those applying desiccant cooling. If desired, hydraulic circuits including solar energy components or connections specified by the client can be modelled. Program modules for cost calculations are used to compare different configurations not only with regard to energy but also economically.

Test stand specifications

- rated air flow rate: 4000 m^{3}h^{-1}
- 20 m^2 flat-plate collectors with liquid heat-transfer media
- 20 m^2 solar air collectors
- 2 m^3 buffer storage tank
- auxiliary heating with a gas boiler
- simulation of any outdoor air conditions
- simulation of room loads.

For further information, see also www.solar-cooling.de



Measurement of Building Facades and Transparent Components

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

Ulrich Amann, Georg Bopp,
Sebastian Bundy, Angelika Helde,
Tilmann Kuhn, Werner Platzer,
Christian Reise, Jan Wienold,
Helen Rose Wilson*

Thermal-optical measurement laboratory TOPLAB

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

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

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

Examples of equipment:

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

Standard testing procedures round off our range of services. We determine the spectral properties of glazing, films and surfaces for our clients.

The German building code recognises our laboratory's determination of the g value (total solar energy transmittance).

Some of the development of testing procedures was publicly funded.

Daylighting measurement rooms

The daylighting measurement rooms consist of two identical office rooms, located side-by-side in a container. They can be rotated, so that any desired facade orientation can be chosen. The following investigations have been made in the measurement rooms to date:

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

Facade testing facility, FASTEST

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

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

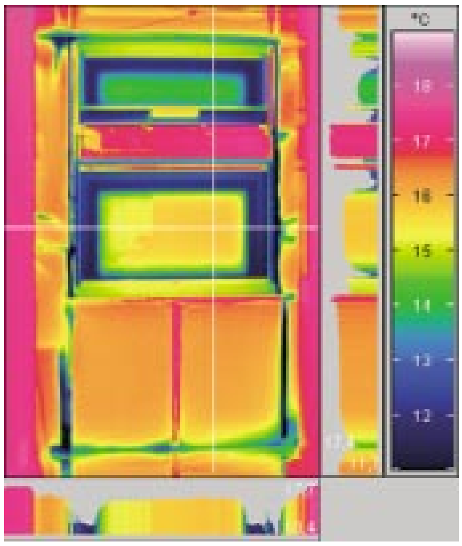
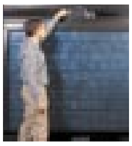


Fig. 1: Thermographic image of a facade module occupying the full height of a test cabin (viewed from indoors).

* Interpane E&BmbH, Lauenförde



Building Concepts and Simulation

We support our clients in designing buildings and technical building services with simulation calculations and special planning services. For thermal simulations, we use ESP-r, ColSim and TRNSYS as software. Lighting technology planning and evaluation is based on the RADIANCE program. Our on-site measurements and expert reports support quality control.

Andreas Bühring, Sebastian Bundy, Sebastian Herkel, Jens Pfafferott, Christian Reise, Jan Wienold

Lighting planning and consultancy

By running simulations with validated models, we evaluate various design options with regard to:

- glare (regulation on lighting conditions for work with computer monitors)
- daylighting quotients (daylighting autonomy)

We determine daylighting quotients and evaluate glare with mobile daylighting measurement technology.

Air-exchange measurements with tracer gas

To ensure good room air quality, it is important that the specified air-exchange rates in buildings and air flow rates in ventilation systems be observed.

Using gas chromatography to measure the decrease in concentration of a tracer gas, we determine the air-exchange rates of rooms during operation. We measure the air flow rate with the constant injection method to analyse ventilation systems.

Our measurement method meets the specifications of VDI 4300, sheet 7. It allows SF_6 to be used as the tracer gas, even in occupied buildings, if an electron capture detector is used for the gas chromatography.

Test stand for compact heating and ventilation units

We support our clients in developing compact heating and ventilation units with integrated exhaust-air heat pumps.

Laboratory testing

Using our test stand for ventilation equipment, we measure the energy efficiency of the complete units and their components. Stationary test conditions can be selected within a wide range. As the test stand has been automated, we can also set dynamic, changing conditions, e.g. according to the standard, EN 255-3. Based on the measurements, we make recommendations to optimise the components and their interaction.

Monitoring

We are measuring the performance of compact heating and ventilation units from different manufacturers in a field test in various occupied solar passive houses. The data is analysed daily, so that we can immediately recommend how operation can be optimised. Possible faults are identified quickly, and corrected. We make suggestions to optimise equipment and the controls on the basis of these measurements.

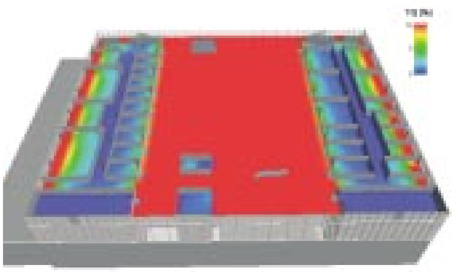
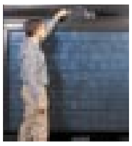


Fig. 1: Representation of the daylighting quotient in the first storey of the Design Centre at EXPO 2000.

Fig. 2: Glare-protection investigation of a daylighting system in an office (simulation analysis).

Fig. 3: Automated test stand for simultaneous measurement of two ventilation units with integrated exhaust-air heat pumps.



Characterisation of Inverters

Inverters represent the link between DC voltage sources such as photovoltaic generators or fuel cells on the one hand, and the public AC grid or an island grid on the other. The control behaviour and efficiency of the inverter have considerable influence on the performance of the system. In addition, many standards have to be observed, which ensure the safety of service personnel, guarantee reliable grid operation and prevent electromagnetic disturbance of other electric equipment. We offer the characterisation of inverters as a service to our clients.

Bruno Burger, Jürgen Ketterer,
Rainer Schätzle, Heribert Schmidt

We characterise inverters in our laboratory with respect to:

- efficiency
- MPP tracking performance
- electromagnetic compatibility (EMC)
- burst and surge tests
- compliance with the relevant standards
- user friendliness

The following energy sources are available for testing the inverters:

- various freely configurable solar generators up to 10 kW
- six programmable solar simulators and
- four DC power supplies with different voltage ranges up to a power of 21 kW.

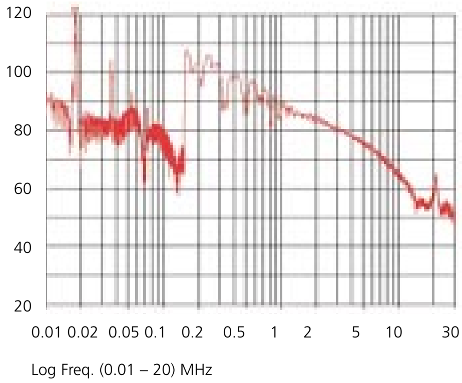


Fig. 1: EMC measurement of the AC side of an inverter without a transformer. The interference voltage generated by this inverter exceeds the allowable limits.
x axis: frequency in MHz
y axis: interference voltage in dBµV

Using precise power analysers, we can accurately measure the efficiency of the inverters. A well-equipped EMC measurement chamber, with a floor area of 4.8 m x 3.1 m and a height of 3 m is available to characterise the EMC behaviour. If desired, experienced power-electronics engineers can modify the inverters during the measurements so that they comply with the EMC standards. Our staff, who work in standardisation committees, are happy to advise you on technical questions or clarification of the standards which must be observed.

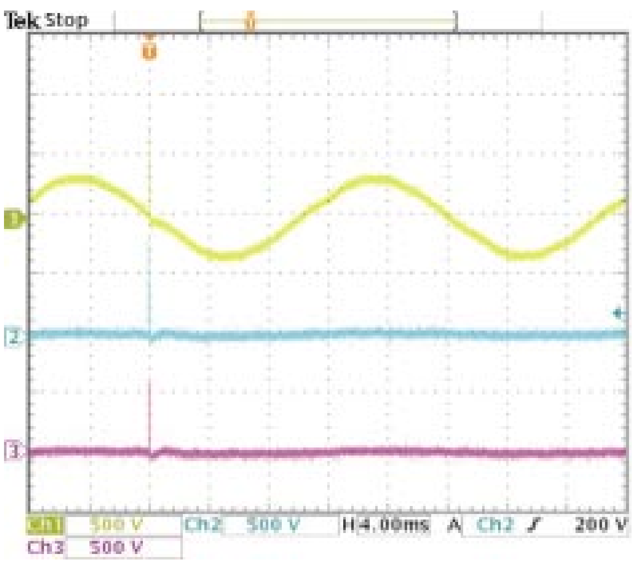
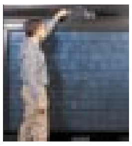


Fig. 2: Surge pulse with an amplitude of 1000 V (spike in all three curves) in the grid voltage (yellow sinusoidal curve, top), and its effect on the DC-link voltage of the inverter (blue, centre) and the voltage at the power semiconductor components (pink, bottom). Result: This equipment is not adequately protected against disturbance pulses. The external disturbance enters the unit unhindered and can destroy the power semiconductor components.
x axis: 4 ms/div
y axis: 500 V/div
The top curve is the grid voltage with 230 V_{eff}. The zero line is indicated at the left for each of the three curves.



Qualification Testing and Optimisation of DC Components for Photovoltaic Systems

Technical reliability and low costs are the key to long-term success for photovoltaically powered DC voltage systems. Commercially available appliances, such as camping lamps, portable radios and television sets, but also certain system components, often prove not to be sufficiently well adapted for use in photovoltaic systems. Experience shows that maintenance and repair of these system components make up a large share of the operating costs.

We offer our clients measurements, qualification testing and optimisation of DC appliances, photovoltaic components and photovoltaic systems in three laboratories which are equipped with high-quality instruments and test stands.

Rudi Kaiser, Norbert Pfanner,
Dirk Uwe Sauer

DC testing and development laboratory

We measure, test and evaluate complete photovoltaic systems or individual components with respect to quality criteria such as:

- energy consumption and efficiency
- operation management performance
- fault performance
- protection against incorrect operation
- electromagnetic compatibility

Long-term tests and stress tests are the basis for making predictions of the lifetime and reliability with practical relevance. As a further service, we offer training courses on measurement and testing in our DC laboratory for technicians and engineers.

Fig. 1: Integrating-sphere photometer to measure the luminous flux of DC lamps and light sources.

Lighting measurement laboratory

We investigate electrical characteristics of PV-powered light sources and lighting systems, such as:

- efficiency
- operation management performance (pre-heating, ignition voltage, operating current and waveforms, etc.)
- fault occurrence.

We also make precise measurements of lighting-technology parameters:

- luminous flux and luminous efficacy
- luminance
- lighting technology performance in operation

A switching cycle test provides information on the anticipated lifetime of the lighting system in practical use.

Battery testing laboratory

By conducting comprehensive qualification tests for battery storage units, we support our clients in selecting a suitable battery type, and optimal operation management and charging strategies. In the tests, we determine the following characteristics for all common types of battery technology:

- capacity of new and used batteries
- charging and discharging curves
- charging performance
- temperature dependence
- efficiency
- self-discharge

Long-term tests in the laboratory or in real systems allow realistic appraisal of the storage unit lifetime.

Facts and Figures

Visiting Scientists

Participation in National and International Associations

Congresses, Conferences and Seminars organised by the Institute

Lecture Courses and Seminars

Trade Fairs and Exhibitions

Patents

Doctoral Theses

Press Releases

Lectures

Publications

Visiting Scientists

Antonio Buonassisi
University of California
Berkeley, USA
1.6.2002 – 31.7.2002
Research area: defect analysis in monocrystalline silicon

Prof. Andres Cuevas
Australian National University
Canberra, Australia
12. – 27.9.2002
Research area: analysis of defects in monocrystalline silicon

José Roberto Flores Hernández
Instituto de Investigaciones Electricas (IEE)
Madrid, Spain
1.10.2001 – 30.9.2004
Research area: fuel cells and electrolysis

Prof. Joachim Lämmel
Fachhochschule Frankfurt a.M.
Frankfurt, Germany
16.9. – 31.12.2002
Research area: photovoltaic systems technology

Zongcun Liang
Guangzhou Institute of Energy Conversion
Guangzhou, China
1.1.2001 – 31.5.2002
Research area: GKSD solar cells

Dr Daniel Macdonald
Australian National University
Canberra, Australia
2. – 14.5.2002
Research area: analysis of defects in monocrystalline silicon

Prof. Manfred von Mende
Fachhochschule Konstanz
Constance, Germany
1.10.2001 – 28.2.2002
Research area: solar building

Anders Ødegård
Norwegian University for Science and Technology (NTNU)
Trondheim, Norway
21.8.2000 – 28.2.2003
Research area: micro-energy technology

Prof. Valeri Rumyantsev
Ioffe Physico-Technical Institute
St Petersburg, Russia
20.2. – 20.4.2002
Research area: III-V concentrator module development

Dr Nicolay Sadchikov
Ioffe Physico-Technical Institute
St Petersburg, Russia
20.5. – 20.7.2002
Research area: III-V concentrator module development

Dr Mazim Shvarts
Ioffe Physico-Technical Institute
St Petersburg, Russia
14.1. – 22.3.2002
Research area: III-V concentrator solar cell measurement technology

Gaute Stokkan
University of Trondheim
Trondheim, Norway
1.9.2002 – 28.2.2003
Research area: characterisation of mc silicon

Participation in National and International Associations

Bundesministerium für Wirtschaft und Technologie BMWi
- Lenkungsausschuss "Solar optimiertes Bauen"

Club zur Ländlichen Elektrifizierung C.L.E.
- Geschäftsführung

Deutsche Elektrotechnische Kommission DKE
- Komitee 221: "Elektrische Anlagen von Gebäuden"
- Komitee 373: "Photovoltaische Solarenergiesysteme"
- Komitee 384: Brennstoffzellen + Arbeitsgruppe Portable Fuel Cell Systems

Deutsche Gesellschaft für Galvano- und Oberflächentechnik DGO
- Fachausschuss "Mikrosysteme und Oberflächentechnik"

Deutsche Gesellschaft für Sonnenenergie DGS
- Vorstand der Sektion Südbaden

Deutsche Physikalische Gesellschaft
- Arbeitskreis Energie

Deutscher Wasserstoff-Verein

European Photovoltaic Industry Association EPIA
- Associate member

EUREC Agency, The European Association of Renewable Energy Research Centers
- President

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

European Fuel Cell Group

Exportinitiative Erneuerbare Energien
- Kontaktgruppe Verbände

Fachverband Transparente Wärmedämmung
- Fachausschuss "Produktkennwerte"

Fachinstitut Gebäude-Klima FGK
- Arbeitskreis "Sorptionsgestützte Klimatisierung"

FitLicht – Fördergemeinschaft innovative Tageslichtnutzung
- Mitglied

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

Forschungsallianz "Brennstoffzellen", Baden-Württemberg

Forschungsverbund Sonnenenergie FVS
- Direktorium, Tagungsbeirat

German Advisory Council on Global Change
- Member

Hahn-Meitner-Institut (HMI)
- Wissenschaftlicher Beirat

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

Institut für Solare Energieversorgungstechnik (ISET)
- Wissenschaftlicher Beirat

International Solar Energy Society Europe (ISES-Europe)
- Governing Board

ISO/TC 197 Hydrogen Technologies (NA Gas),
- Standardisation Committee, Gas Technology

Kompetenznetzwerk Brennstoffzelle NRW (Nordrhein Westfalen)

Nationales Symposium Photovoltaische Solarenergie
- Wissenschaftlicher Beirat

Passivhaustagung 2003
- Wissenschaftlicher Beirat

Progress in Photovoltaics
- Editorial Board

Senat der Fraunhofer-Gesellschaft
- Mitglied

"Solar Energy" Journal , Elsevier
- Editor-in-Chief

Verein Deutscher Elektrotechniker
- ETG-Fachausschuss "Brennstoffzellen"

Verein Deutscher Ingenieure, VDI-Gesellschaft Energietechnik
- Fachausschuss "Regenerative Energien"

VMPA Verband der Materialprüfämter e.V.
- Sektorgruppe "Türen, Fenster und Glasprodukte"

WBZU, Weiterbildungszentrum Brennstoffzelle in Ulm

Zeitschrift "Physikalische Blätter", Wiley-VCH
- Kuratorium

Zentrum für Solarenergie und Wasserstoff (ZSW)
- Kuratorium

Congresses, Conferences and Seminars organised by the Institute

OTTI Energie-Kolleg Regensburg
8. Symposium Innovative Lichttechnik in Gebäuden
Bad Staffelstein, Kloster Banz, 24./25.1.2002

OTTI Energie-Kolleg Regensburg
Fachseminar Dezentrale Stromversorgung mit Photovoltaik
Freiburg, 30./31.1.2002

SolarBau:MONITOR
Workshop "Strategien und Konzepte für schlanke Gebäude"
Zwingenberg, 21. – 22.2.2002

OTTI Energie-Kolleg Regensburg
5. Fachforum Innovative Wohnungslüftung
Regensburg, 20./21.3.2002

Fachinstitut Gebäude-Klima FGK, IEA Task 25
Industrial-Workshop "Solar Assisted Air Conditioning of Buildings" as part of Light&Building – AirConTec
Frankfurt, 17.4.2002

OTTI Energie-Kolleg Regensburg
12. Symposium Thermische Solarenergie
Bad Staffelstein, Kloster Banz, 24. – 26.04.2002

OTTI Energie-Kolleg Regensburg
Fachseminar Netzgekoppelte Photovoltaik-Anlagen
Freiburg, 11./12.6.2002

Intersolar Freiburg
Professional Seminar "Solar Assisted Air-Conditioning of Buildings"
Freiburg, 26./27.6.2002

Intersolar Freiburg
Technologie-Seminar
Freiburg, 28. – 30.6.2002

OTTI Energie-Kolleg Regensburg
Fachseminar EMV und Blitzschutz in Photovoltaik-Anlagen
Freiburg, 26./27.9.2002

5th TPV Conference
"International Workshop on the Integration of Social Aspect Tools in Commercial Rural Electrification Activities"
Rome, Italy, 6.10.2002

International Energy Agency, SHCP Task 28 / ECBCS Annex 38
Expert Meeting "Energy Supply for High Performance Houses"
Freiburg, 10. – 13.10.2002

SolarBau:MONITOR
Workshop "Nutzerakzeptanz – Erfassen-Bewerten-Planen"
Creuzburg, 21./22.11.2002

Lecture Courses and Seminars

Dr Dietmar Borchert
Photovoltaik
Vorlesung SS 2002
Technische Fachhochschule Georg Agricola, Bochum

Dr Bruno Burger
Leistungselektronische Systeme für regenerative Energiequellen
Vorlesung WS 02/03
Universität Karlsruhe

Dr Andreas Gombert
Mikrostrukturierte Oberflächen mit optischen Funktionen
Vorlesung WS 02/03
Albert-Ludwigs-Universität Freiburg, Fakultät für Angewandte Wissenschaften

Sebastian Herkel
Bauökologie/Solarenergienutzung
Vorlesung SS 02
Staatliche Akademie der Bildenden Künste, Stuttgart

Prof. Joachim Luther
Photovoltaische Energiekonversion
Vorlesung SS 02
Aktuelle Fragen der Sonnenenergiekonversion
Seminar SS 02
Thermische Solarenergiewandlung
Vorlesung WS 02/03
Aktuelle Fragen der Sonnenenergiekonversion
Seminar WS 02/03
Albert-Ludwigs-Universität Freiburg, Fakultät für Physik

Jens Pfafferott
Konventionelle und regenerative Energiewirtschaft
Vorlesung SS 02 / WS 02/03
Fachhochschule Biberach

Dr Christel Russ
Modernisierung und Sanierung von Gebäuden
Vorlesung SS 02 / WS 02/03
Fachhochschule Biberach

Prof. Roland Schindler
Halbleitertechnologie I (Technologie), Photovoltaik I
Vorlesung WS 02/03
Halbleitertechnologie II (Bauelemente), Photovoltaik II
Vorlesung SS 02
FernUniversität, Hagen

Dr Heribert Schmidt
Photovoltaik Systemtechnik
Vorlesung SS 02
Universität Karlsruhe

Dr Gerhard Willeke
Grundlagen von Halbleiterbauelementen und der optischen Datenübertragung
Vorlesung SS 02
Universität Konstanz

Dr Volker Wittwer
Energieversorgung für Mikrosysteme
Vorlesung SS 02
Albert-Ludwigs-Universität Freiburg, Fakultät für Angewandte Wissenschaften

Trade Fairs and Exhibitions

Industrieausstellung im Rahmen des 17. Symposiums Photovoltaische Solarenergie
Bad Staffelstein, Kloster Banz, 13. – 15.3.2002

Light&Building – AirConTec
Frankfurt/M., 13 – 18.4.2002

Hanover Trade Fair, HMI 2002
Hanover, 15. – 20.4.2002

Intersolar 2002,
Freiburg, 28. – 30.6.2002

H2-Expo
Hamburg, 10. – 12.10.2002

f-cell
Stuttgart, 14./15.10.2002

Patents

Patent Applications

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

Ulrich Hofmann, Markus Löhr, Dieter Schlegel, Marc Straub, Robert Szolak, Bernd Tischhauser, William Wiesner
"Device for procedure for reforming hydrocarbons from an input gas"

Axel Heitzler, Dr Christopher Hebling, Andreas Schmitz
"Fuel cell configuration"

Dr Benedikt Bläsi, Christopher Bühler, Dr Andreas Georg, Dr Andreas Gombert, Wolfgang Graf, Dr Peter Nitz, Dr Volker Wittwer
"Switchable solar-control device"

Dr Alexander Susdorf, Dr Jürgen Koy, Dr Albert Chigapov, Dr Klaus Wanninger, Prof. Angelika Heinzel, Dr Peter Hübner
"Ce/Cu/Mn catalyst to remove CO from hydrogen-rich gas mixtures"

Andreas Schmitz, Dr Robert Hahn, Dr Christopher Hebling, Dr Bruno Burger
"Fuel-cell system constructed of circuit boards"

Dr Andreas Gombert, Volkmar Boerner, Dr Benedikt Bläsi, Ilka Gehrke, Michael Niggemann, Josef Robert, Christian Schlemmer
"Procedure to produce micro-sieves"

Dr Heribert Schmidt, Jürgen Ketterer, Dr Christoph Siedle
"Inverter and procedure to convert DC electricity to AC electricity"

Carsten Hindenburg, Volker Kallwellis, Wolfgang Dotzler, Gerd Renner
"Procedure to produce radiation absorbers with heat-conducting fins"

Dr Andreas Gombert, Wolfgang Graf, Dr Andreas Hinsch, Michael Niggemann
"Optoelectronic component with electrically conductive organic material and procedure to produce the component"

Prof. Adolf Goetzberger
"Procedure for large-area production of thin-film Si solar cells"

Tilmann Kuhn, Dr Peter Nitz, Dr Benedikt Bläsi, Christopher Bühler, Dr Andreas Gombert, Dr Werner Platzer, Dr Volker Wittwer
"Solar-shading device with a multitude of parallel slats"

Dr Benedikt Bläsi, Christopher Bühler, Dr Andreas Gombert, Wolfgang Hoßfeld, Jörg Mick, Dr Peter Nitz
"Device for light redirection and procedure to produce the device"

Jörg Isenberg, Stephan Riepe, Dr Wilhelm Warta
"Procedure and configuration to measure light-induced temperature changes and power losses in semi-conductor components"

Uwe Armbruster, Dr Peter Hübner, Helga Ströhl
"Procedure to switch off a reformer fuel-cell system"

Dr Heribert Schmidt
"End-plate"

Dr Heribert Schmidt
"Radiation sensor with reduced sensitivity to interference signals"

Dr Bruno Burger, Dr Heribert Schmidt
"Device and procedure to suppress a DC component in the output current of inverters"

Christian Schlemmer, Dr Andreas Georg, Dr Andreas Gombert, Wolfgang Graf
"Procedure to produce high-temperature resistant, micro-structured selective metal emitters"

Alexander Hakenjos
"Procedure to measure series-connected electrochemical cells"

Patents Granted

Michael Hermann, Joachim Koschikowski
"Procedure to produce formed bodies from paste and device to accomplish the procedure"

Klaus Preiser, Jérôme Kuhmann
"Device to test stand-alone solar systems"

Orlando Parodi, Konstanze Fleige, Ulrike Seibert
"Device to transport untreated and treated water"

Dr Harry Wirth, Dr Volker Wittwer
"Solar-control device for buildings"

Dr Andreas Georg
"Optical component"

Dr Andreas Gombert, Michael Niggemann, Hansjörg Lerchenmüller
"Procedure and device to produce a coupling grating for a waveguide"

Doctoral Theses

Konrad Lustig
"Experimentelle Untersuchungen zum Stillstandsverhalten thermischer Solaranlagen"
(Experimental Investigations of the Stagnation Behaviour of Thermal Solar Systems)
Doctoral thesis, University of Karlsruhe
Karlsruhe, 2002

Mario Motta
"Thermodynamic design and optimisation of solar assisted desiccant cooling cycles for Italian climates"
Doctoral thesis, University of Genoa
Genoa, 2002

Tomas Núñez
"Charakterisierung und Bewertung von Adsorbentien für Wärmetransformationsanwendungen"
(Characterisation and Assessment of Adsorbing Materials for Thermal Transformation Applications)
Doctoral thesis, University of Freiburg
Freiburg, 2002

Mathias Hein
"Entwicklung und Vergleich zweier konzentrierender Photovoltaik-Systeme für den wirtschaftlichen Einsatz von hocheffizienten III-V Solarzellen"
(Development and Comparison of two Concentrating Photovoltaic Systems for Economic Application of Highly Efficient III-V Solar Cells)
Doctoral thesis, University of Oldenburg
Oldenburg, 2002

Press Releases

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

25.3.2002
Fraunhofer Institutes demonstrate economical series production for micro fuel cells

8.4.2002
Air-conditioning with the sun – World-wide unique exhibit and IEA-workshop at the "aircontec" in Frankfurt

11.4.2002
Fuel cell system integrated in laptops for the first time

22.5.2002
Tested reference cells reduce uncertainty in generating electricity from the sun – Fraunhofer ISE measurement technology for highest accuracy now also available for field use

29.6.2002
Fraunhofer ISE wins praise of WORLD TECHNOLOGY NETWORK

27.8.2002
Independent power supply using hydrogen from renewable sources of energy

5.12.2002
Driving with low exhaust emission in spite of gasoline use? – Fraunhofer ISE develops autothermal gasoline reforming for fuel cells

Lectures

Lectures with published manuscripts are listed under "Publications".

Agert, C.
"The Future of Renewable Energy", Northern African Power Industry Convention, 27.10.2002, Casablanca, Morocco

Agert, C.; Beckert, R.; Bett, A.W.; Dimroth, F.; Heuken, M.[1]; Giesen, C.[1]; Dauelsberg, M.[1]; Hannappel, T.[2]; Kollonitsch, Z.[2]; Möller, K.[2]; Seip, M.[3]; Greiling, A.[3]
"Sb-Based Semiconductors for TPV Application Grown in an Industrial Sized MOVPE Reactor", 5th Conference on Thermophotovoltaic Generation of Electricity, Rome, Italy, 15. – 19.9.2002
([1]: AIXTRON AG, Aachen)
([2]: Hahn-Meitner-Institut, Berlin)
([3]: MOCHEM, Marburg)

Bett, A.W.
"Tandem Cells for Very High Concentration", 3rd Generation PV Workshop for High Efficiency through Full Spectrum Utilization, Cercedilla, Madrid, Spain, 21. – 23.3.2002

Bopp, G.; v. Dohlen, K.[1]
"Normkonforme Einbindung von PV-Anlagen in Gebäude mit und ohne äußeren Blitzschutz", Fachseminar Blitzschutz und Potenzialausgleich in der Solartechnik, Cölbe, 22.3.2002
([1]: Erhardt & Leimer Elektroanlagen, Augsburg)

Bopp, G.
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Abbreviations

AC	alternating current
Ag	silver
Al	aluminium
AlGaAs	aluminium gallium arsenide
AM	air mass
APCVD	atmospheric pressure chemical vapour deposition
ASTM	American Society for Testing and Materials
Bi	bismuth
BFC	bifacial cell
BMBF	Bundesministerium für Bildung und Forschung (German Federal Ministry of Education and Research)
BMWi	Bundesministerium für Wirtschaft und Technologie (German Federal Ministry of Economics and Technology)
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (German Federal Ministry of Economic Co-operation and Development)
BSF	back surface field
CDI	carrier density imaging
CFD	computational fluid dynamics
CIS	copper indium diselenide
CNRS	Centre Nationale de la Recherche Scientifique
CO	carbon monoxide
CO_2	carbon dioxide
CPC	compound parabolic concentrator
c-Si	crystalline silicon
CV	capacitance/voltage
CVD	chemical vapour deposition
Cz	Czochralski
DC	direct current
DIN	Deutsches Institut für Normung (German Standards Institute)
DLTS	deep level transient spectroscopy
DMFC	direct methanol fuel cell
EBIC	electron beam induced current
EBR	etchback regrowth
ECR	electron cyclotron resonance
EFG	edge-defined film-fed growth
EMC	electromagnetic compatibility
EN	European Norm (European Standard)
EU	European Union
FF	fill factor
FhG	Fraunhofer-Gesellschaft
FCHC	fluorinated/chlorinated hydrocarbons
FZ	float zone
GaAs	gallium arsenide
GaInP	gallium indium phosphide
GaSb	gallium antimonide
Ge	germanium
GSM	Global System for Mobile Communication
IEA	International Energy Agency
IR	infrared
K	Kelvin
kW_p	kilowatt peak
LBIC	light beam induced current
LBSF	local back surface field
LED	light-emitting diode
LPE	liquid phase epitaxy
mc	multicrystalline
MCFC	molten carbonate fuel cell
mc-Si	multicrystalline silicon
MFCA	modulated free carrier absorption
MgF_2	magnesium fluoride
MOCVD	metal organic chemical vapour deposition
MOVPE	metal organic vapour phase epitaxy
MPP	maximum power point
MSCM	miniature solar cell mapping
MW-PCD	microwave-detected photo-conductance decay
N_2	nitrogen
NOCT	nominal operating cell temperature
PCM	phase-change material
PCVD	photocurrent and voltage decay
Pd	palladium
PDA	personal digital assistant
PECVD	plasma enhanced chemical vapour deposition
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
PERC	passivated emitter and rear cell
POA	power optimised aircraft
PV	photovoltaic
RCC	rear contacted cell
RCWA	rigorous coupled wave analysis
RIE	reactive ion etching
RPHP	remote plasma hydrogen passivation
RP-PERC	random pyramid, passivated emitter and rear cell
RRC	realistic reporting conditions
RTCVD	rapid thermal chemical vapour deposition
RTP	rapid thermal processing
S/C	steam/carbon ratio
SDCS	solar desiccant cooling system
SEM	scanning electron microscope
Si	silicon
SIMOX	separation by implanted oxygen
SiN_x	silicon nitride
SiO_2	silicon dioxide
SIR	simultaneous infiltration and recrystallisation
SME	small and medium-sized enterprises
Sn	tin
SOFC	solid oxide fuel cell
SPV	surface photovoltage
SSP	silicon sheets from powder
SR	spectral response
SR-LBIC	spatially resolved light beam induced current
TCO	transparent conducting oxide
TDLS	temperature-dependent lifetime spectroscopy
TI	transparent insulation
Ti	titanium
TiO_2	titanium dioxide
TPV	thermophotovoltaics
V_{OC}	open circuit voltage
WO_3	tungsten trioxide
WPVS	world photovoltaic scale
Zn	zinc
η	efficiency value

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